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Potential of Energy Willow Plantations for Biological Reclamation of Soils Polluted by ^{137}Cs and Heavy Metals, and for Control of Nutrients Leaking into Water Systems

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Abstract **– Willow is a low-maintenance crop that has potential for energy production and enhancing the local environment. The area of commercial plantations of willow in Europe is mostly concentrated in Sweden, with more than 20 000 ha. Willow trees are used not only for energy production, but also for reclamation of polluted soils because a plantation may grow for 20–25 years, with a three-year period of harvesting. Our research covers issues of reclamation of soils contaminated by radionuclides and heavy metals, and decreasing of eutrophication of water ecosystems with using willow plantations. The field studies of phytoremediation of soil contaminated by ^{137}Cs by willow plants were conducted in eastern Belarus, in the area where agricultural activity was banned after Chernobyl disaster. This region is heavily polluted with ^{137}Cs (from 185 to 555 kBq/m^2) and heavy metals. The transferring factors of accumulated ^{137}Cs and heavy metals from the soil to willow biomass were determined. The field experiments showed that willow does not accumulate actively Cd and Pb, but it accumulates Zn, Cu and Mn intensively. The potassium application decreases the accumulation of ^{137}Cs in willow biomass and increases accumulation of Cu, Zn and Mn, but has no influence on accumulation of Cd and Pb. Our results confirmed that soils polluted with radionuclide and heavy metals could be used for willow cultivation as energy crop, if adequate management is applied. The different potential of the willow species concerning heavy metals accumulation was also established. The yield of willow biomass on polluted soils achieved 11.5–12.8 DMg ha^{-1} per year, depending on variety, that is competitive with the ordinary yield of willow on mineral fertile soils. Willow plantations also may be used for accumulations of nutrients like nitrogen and phosphorus in watersheds. It enables to decrease impact for water ecosystems and to control eutrophication.**

Keywords **– Energy willow; eutrophication; heavy metals; pollution; radionuclide; reclamation**

1. INTRODUCTION

Pollution by heavy metals, radionuclides and other chemicals is one of the key factors of degradation and decreasing of fertility of soils. In the Republic of Belarus, level of the soil pollution by heavy metals, which exceeded maximum allowable concentration, took place in

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areas close to the cities, livestock complexes, motorways. The extra high level of agricultural soil pollution with Zn have been observed on the area about 180 000 hectares, with Cu on the area 260 000 ha, with Pb – 100 000 ha and with Cd – 45 000 ha. Other problem concerning Belarus is radioactive contamination of soils after Chernobyl disaster [1]. Natural radioactivity is also problem caused by the presence of ^{40}K and other elements. As a result, radioactivity concentrations of nuclides may be surveyed in agricultural products for instance in Vietnam [2]. Heavy metal contaminated soils are also serious environmental problem for other countries [3]. It is possible to use different methods for soils rehabilitation or reclamation. Biological reclamation of polluted soils is based on using of plants. The ability of elements accumulation depends on environmental conditions and crop species. Some kinds of plants may accumulate especially high quantity of heavy metals [4]. At the result concentration of metals in biomass plants, which may be named "hyperaccumulators" in hundreds times higher to compare with others [5]. As an example may be selected plants of Brassicaceae family [6]. Species of plants, which belong to this family may accumulate high levels of Zn, Cd and other elements in biomass [7]. For example, *Brassica napus* may accumulate extra high rates of Zn in roots. Other species of Brassicaceae also has potential for metals accumulation [8]. *Brassica napus* plants may not only accumulate metals, but grow successfully on polluted soils [9].

Nevertheless, practical using of "hyperaccumulators" is limited. It is a fact that those species typically do not produce high yield of biomass, and cost of extraction of pollutants from biomass may be extra high.

From this point of view, more perspective for practical purpose, may be the usage of crops which are not hyperaccumulators, but may produce high biomass. It is a rule that biomass growing on heavy metals polluted areas must not be used as a food for people or as a livestock forage, but for energy production on renewable base. Energy crops may have both environmental and energy profit. Energy crops, which may be used for growing on polluted soils belong to different species. *Miscanthus giganteus* or giant reed may grow successfully on the soils polluted by Cd, Pb, and Zn [10]. It was established that most part of metals was accumulated in roots. There were no significant differences in metal concentrations and shoot yields after treatments of plants by different doses of metals.

Some crops, for instance potato may be used as a source of several valuable products: starch, proteins, ascorbic acid, carbohydrates, minerals, vitamins and fibre, alkaloids, flavonoids, phenolic compounds [11]. As a result, potato is perspective crop not only for food production, but pharmacy, medicine applications and other fields.

Forest residues and even invasive species, like *Solidago canadensis* (goldenrod) and *Herecleum Sosnowskyi* (hogweed) is also a valid bioresource that may be used for cellulosic production [12].

One of the healthiest and most nutritious food products is fish [13]. Therefore, the growing demand for fish feed and omega-3 rich oils is stimulating the aspiration to find alternatives and aquaculture, agriculture, genetically modified plants and various microorganisms are considered as the most promising source.

The perspective direction is using fast-growing trees with high yield of biomass such as poplar (*Populus* spp.) or willow (*Salix* spp.) [14], [15]. These trees, may reach the height of 4–5 meters after 3 years of growing. The yield of trees may reach 10–15 tonnes of dry biomass per hectare [16]. The plantations of energy trees also named short rotation coppice (SRC) crops, because they have a lifetime of 20–25 years, with harvests every 3–5 years. The basic goal of SRC trees growing is bioenergy production. Nowadays energy plantations introduced in Sweden [17], USA [18], Germany [19] and other countries. SRC trees may be also used for rehabilitation of polluted areas. In experiments in the area located close to Chernobyl, willow biomass and transfer factor of ^{137}Cs from the soil to wood were estimated [20]. The results showed that biomass, which was produced on loamy sand, sandy loam and loamy soils is suitable for energy purpose without any limits. Radionuclide pollution it is actual problem not only for Ukraine and Belarus, but for other European countries. After Chernobyl disaster, some areas in Europe are contaminated by ^{137}Cs. Radionuclide was deposited to the soils from atmosphere. At the result, for instance, the density of contamination in Central Serbia is from 15.5 to 236 Bk/kg^{-1} [21].

The complicated environmental problem for water ecosystems is eutrophication at the result of leaking nitrogen and especially phosphorus from ashore. In accordance with basic conception, the limitation factor for eutrophication is concentration of phosphorus in water is 0.005 mg per litre of water, while nitrogen – 0.020 mg/l [22]. It was established that algal biomass increased as a function of increased total phosphorus and total nitrogen in waters. The results of algal biomass increasing is deterioration of water ecosystems [23]. EU gives special attention to water protection as an element of environmental policy [24]. And control of eutrophication is part of the Integrated River Basin Management (IRBM) paradigm.

It is possible to use several ways to control of nutrients leaking into water systems. One of them is limitation of using mineral fertilizer in the area of watersheds. This program was introduced by Sweden [25]. The main purpose of program was decreasing the volume of nitrogen, which goes to the Baltic Sea. Another way is using of special vegetative filters. For instance, Aronsson and Perttu researched perspective of willow planting as vegetation filters for wastewater treatment and soil remediation combined with biomass production [26]. Experiments showed high potential of willow plants for accumulation of N and P in biomass. Willows and other trees may be also used as barriers for cleaning of polluted water from agricultural land. The appropriate field experiments were successfully carried out by Elowson [27].

The goal of our investigation was estimation of potential of SRC willow for accumulation of heavy metals, radionuclides and nutrients from contaminated agricultural soil.

2. MATERIALS AND METHOD

2.1. Study Site

Two experimental fields of willow plantations have been planted. Experimental field 1 (EF 1) is located at Krichev district of Mogilev region, in eastern Belarus, close to the Russian border (Fig. 1). This region is characterized by high level of ^{137}Cs contamination, mostly for the reason of precipitating from clouds after the Chernobyl accident. As a result, the level of contamination at the place of our experiment varied from 5 to 15 Ci/km^2 or 185–555 kBq/m^2. Experimental field 2 (EF 2) is located at Volma Field Station in Minsk region, in the central part of Belarus which is not polluted by radionuclides and close to the lake Volma, which has the area of 10 650 m^2. The area of the watershed around lake about 16 km^2. It includes 55 % of agricultural lands, 40 % of forests, 1.5 % of pastures, 3.5 % is settlement zone.

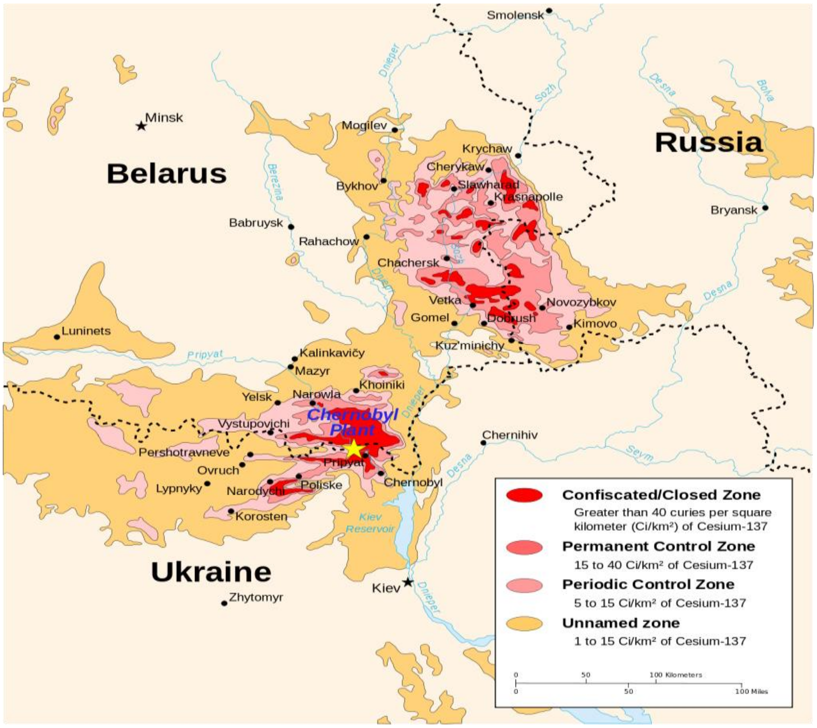

Fig. 1. Allocation of experimental fields [28].

Properties of soil on the experimental fields are presented in Table 1.

TABLE 1. CHEMICAL PROPERTIES OF SOIL ON THE EXPERIMENTAL PLOTS

Experimental field	Properties				
	Soil structure	Humus, %	P_2O_5, mg/kg	K_2O, mg/kg	pH
EF 1	Sandy-loam	2.2	60.2	148.5	5.6
EF 2	Sandy-loam	2.0	76.2	96.9	6.05

2.2. Experimental Design

The experiments were placed in 4 randomized complete block design. Each elementary plot was 7 m long by 7.2 m wide (50 m^2) and contained 4 double rows of plants. The densest plantation (e.g. 15500 trees ha^{-1}) had been established according to the twin-row system. Before planting the plots, the soil received 150 kg ha^{-1} N as ammonium nitrate, 120 kg ha^{-1} P as double superphosphate, and 150 kg ha^{-1} K as of potassium salt. The clone Jorr (*Salix viminalis*) and clones Drina, Volmianka, Bachka (*Salix alba*) were planted.

2.3. Sampling and Analyses

Samples of soil and willow biomass were collected and analysed from 2010 to 2015. Air-dried soil samples were analysed for pH by using a glass electrode of Ionanalyser. Contents of metals in soil and biomass (Pb, Cd, Zn, Cu, Ni, Mn) were determined by X-ray fluorescence method (RFA). Activity contents of ^{137}Cs in plant and soil samples were determined by means of gamma-spectrometer *ADCAM*-100, ORTEC Company, USA. The error of determination was 10 %. Concentrations of nitrogen in soils and willow biomass were determined by Kjeldahl method and concentrations of phosphorus by means of photoelectric calorimeter.

A completely randomized design was used for statistical analysis. The experimental data obtained as a result of the studies were processed using the methods of dispersion, correlation and regression analysis on the basis of the statistical programs *Excel* and *Statistica* 10.

3. RESULTS

3.1. Phytoremediation of Radionuclide Polluted Areas

At the area polluted by ^{137}Cs (experimental field 1), the willow trees of clone Jorr (*Salix viminalis*) were planted. For the assessment of radionuclide accumulation, the experiment with 7 variants of mineral fertilizer application (kg of active substance per hectare) was set up. In accordance with our hypothesis the additional application of potassium enables to decrease the level of accumulation of ^{137}Cs in willow biomass. High doses of potassium application is method, which successfully used in agricultural practice in radionuclide polluted area for other crops, because K it is chemical analog of Cs [29]. The contents of ^{137}Cs had been measured separately for leaves, roots and wood because of two reasons. The first, it was established that ^{137}Cs has different rates of accumulation in different parts of plants, and the basic quantity of radionuclide as a rule accumulates in the root system. And the second reason is life cycle of the biomass. The leaves fall off every autumn, the wood is harvested and used as energy every 3 years, while roots remain in the soils as long as willow plantation exists. The transferring factor (TF), as index of difference in radionuclide activity in the biomass and in the soil was calculated, to assess the movement of ^{137}Cs from the soil to the plants. The results of TF calculation in the willow biomass after the first-year growing are presented in the Table 2.

The highest TF of ^{137}Cs from soils was observed in roots. TF for leaves was approximately twice time higher in comparison with wood. After potassium application with doses 90 kg/ha, accumulation of ^{137}Cs in leaves decreased in 1.6 times, in wood in 3.4 times and in roots in 4.2 times. The permitted rate of ^{137}Cs level in the firewood in Belarus was established by special Decree of Ministry of Health at the rate of 740 Bq/kg. In accordance with experimental data the models of ^{137}Cs accumulation in willow biomass was developed for the total time of plantation existing (22 years). On the base of TF determination, the prognoses model of ^{137}Cs accumulation for the roots and wood of willow was developed. The results of modeling have identified that level of ^{137}Cs in wood was several times lower, than the highest legal limit. The biomass of root may be used for energy production in accordance with permitted standards from the soils contaminated by ^{137}Cs with the density not more than 370 kBq/m^2 (10 Ci/km^2), but biomass of wood with density contamination 1017 kBq/m^2 (27.5 Ci/km^2) and more. As a rule, the level of soil contamination more than 370 kBq/m^2 is extreme for most kinds of agricultural crops, but those soils may be effectively used for SCR willow plantations.

TABLE 2. TRANSFERRING FACTORS OF ^{137}Cs FOR WILLOW BIOMASS X_I, $x \cdot 10^{-3}$ m^{2}kg^{-1}

Variant	Leaves	Wood	Roots	Branches
Control	0.052	0.031	0.939	0.061
$N_{30}P_{60}K_{30}$	0.030	0.025	0.612	0.047
K_{30}	0.051	0.0243	0.564	0.042
K_{60}	0.041	0.015	0.393	0.026
K_{90}	0.032	0.009	0.229	0.019
N_{30}	0.048	0.028	0.693	0.055
N_{60}	0.052	0.030	0.634	0.052
LSD*	0.011	0.010	0.237	0.021

*LSD Fisher's protected least significant difference ($\alpha = 0.05$) in TF between the variants.

The models of ^{137}Cs accumulation in willow wood and roots were using for creation of GIS map of Mogilev region. The models enable to predict levels of ^{137}Cs radioactivity in biomass depending to the type of soil and density of pollution after every willow harvesting cycle. About 25 % of Mogilev region is an area polluted by radionuclides. In accordance with this model, it is possible to use willow wood from 98.7 % of radionuclides polluted area of Mogilev region.

3.2. Phytoremediation of Soils Polluted by Heavy Metals

Mogilev region is characterized by significant industrial activity. As a result of this, soil of the region was polluted not only by radionuclides, but heavy metals as well. For instance, content of cadmium in the soil of EF 1 was higher than permitted level for Belarus. The measurements for assessment of heavy metals accumulation in willow biomass have been done with samples of leaves. The leaves may be used as an indicator, because the direct correlation between accumulation of heavy metals in willow leaves and wood was established [30]. Therefore, the measurement of heavy metals in leaves could be used as an indicator for assessment of tendency of their accumulation also for wood. The results of measurement for heavy metals content in soil and willow leaves, as well as calculation of transferring factors (TF) are represented in the Table 3.

TABLE 3. CONTENTS OF HEAVY METALS IN SOIL AND LEAVES AND TRANSFERRING FACTORS, $\bar{X} \pm S_X$

	Contents of heavy metals, mg/kg					
	Cd	Zn	Pb	Cu	Ni	Mn
Soil	2.02 ± 0.35	43.9 ± 4.12	18.46 ± 3.76	9.35 ± 1.19	5.99 ± 0.87	661.76 ± 28.98
Leaves	0.12 ± 0.02	141.75 ± 12.92	0.98 ± 0.11	12.55 ± 1.77	0.41 ± 0.04	86.14 ± 9.12
TF	0.06	3.23	0.05	1.34	0.07	0.13
Permission limit for Belarus soils	2.0	220.0	32.0	132.0	80.0	1500

It is established that the usage of high doses of potassium is necessary in order to decrease the rates of ^{137}Cs accumulated in willow biomass grown on radionuclide polluted areas.

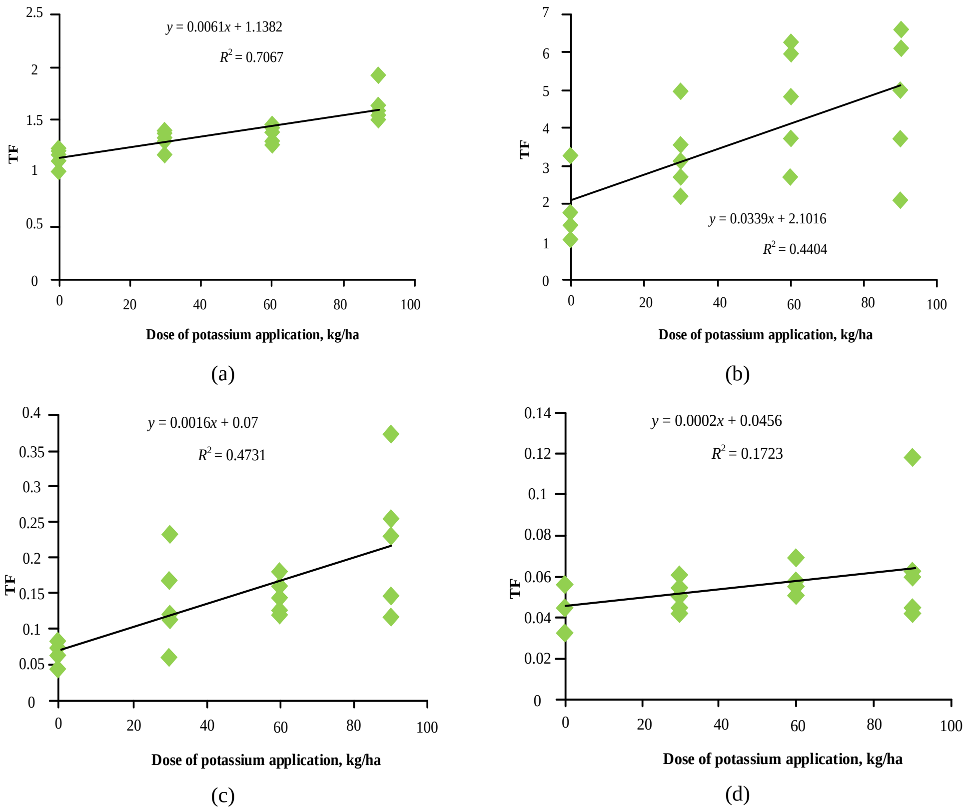

Fig. 2. The diagram of dose-response relationship of: (a) Cu; (b) Zn; (c) Mn; (d) Pb accumulation (TF) and potassium application rate for willow leaves.

Hence, it is reasonable to take into the consideration the influence of potassium application on accumulation of heavy metals on radionuclide polluted soils. The highest positive coefficient of determination between potassium application and transferring factor in willow leaves was established for Cu – 0.71 (Fig. 2). The middle level of correlation between potassium application and transferring factor in leaves was obtained for Zn (coefficient of determination – 0.44) and Mn (coefficient of determination – 0.47), and the low coefficients of determination for Cd (0.12) and Pb (0.17).

Our research task was also assessment the phytoremediation potential of different willow species. Selection of willow for energy purposes started after 1970's. The most actively in selection process were involved following species: *Salix viminalis, Salix dasyclados* and *Salix schwerini* [31]. In our experiments three clones of Serbian selection were tested, which were obtained on the base of specie *Salix alba*, which belong to woody type and has several positive physiological properties [32]. These clones were included in State register of Republic of Belarus in 2013 as Backa, Volmianka and Drina and it was reasonable to compare them with traditional European clone Jorr (*Salix viminalis*) [33].

The results of experiments, which were fulfilled at the EF 2 (Volma Field Station) are presented in the Table 4.

TABLE 4. CONTENTS OF HEAVY METALS IN SOILS AND LEAVES AND TRANSFERRING FACTORS

	Contents of heavy metals, mg/kg					
	Cd	Zn	Pb	Cu	Ni	Mn
Soil	1.50	45.11	10.17	34.74	34.21	650.83
Backa	0.07	109.87	0.62	83.47	1.96	77.29
Volmianka	0.09	176.42	1.07	85.52	1.28	29.04
Drina	0.05	95.52	0.26	97.30	1.03	24.53
Jorr	0.09	183.08	0.67	52.89	1.73	122.01
LSD*	0.02	9.23	0.36	10.92	0.05	8.5
Transferring factors of heavy metals into the leaves						
Backa	0.05	2.43	0.06	2.40	0.06	0.11
Volmianka	0.06	3.91	0.10	2.46	0.04	0.04
Drina	0.03	2.11	0.02	2.80	0.03	0.03
Jorr	0.06	4.05	0.06	1.52	0.05	0.18

*LSD Fisher's protected least significant difference ($\alpha = 0.05$) in contents of heavy metals between the varieties.

Willow is an energy crop and one of the most important factors for establishing a plantation is a yield of the biomass. Willow wood is harvested every three years. The yield of dry biomass of willow varieties in calculation for one year is presented in Table 5.

TABLE 5. THE YIELD OF WILLOW VARIETIES IN EF 2

	Variety			
	Backa	Volmianka	Drina	Jorr
Yield of biomass DMg ha^{-1} per year	12.8	12.3	11.9	11.5
LSD*	0.6			

*LSD Fisher's protected least significant difference ($\alpha = 0.05$) in contents of yield between the varieties.

In order to assess potential of willow plantations for vegetative filters, 4 clones of willows were planted in downy slope, close to the lake (10–15 meters). The measurement of nitrogen and phosphorus has been done for leaves and wood of willow. Monitoring of nutrients accumulation in willow leaves during vegetation period showed that maximal level on nitrogen contents was at the beginning of vegetation (May). In the middle of vegetation period nitrogen contents gradually decreased, and small increasing took place in September. The minimal level of phosphorus contents in willow leaves took place at the beginning of vegetation, and gradually increased till September.

The measurements of average contents of nitrogen in willow wood after 2 years of vegetation in depends of clone presented on Fig. 3.

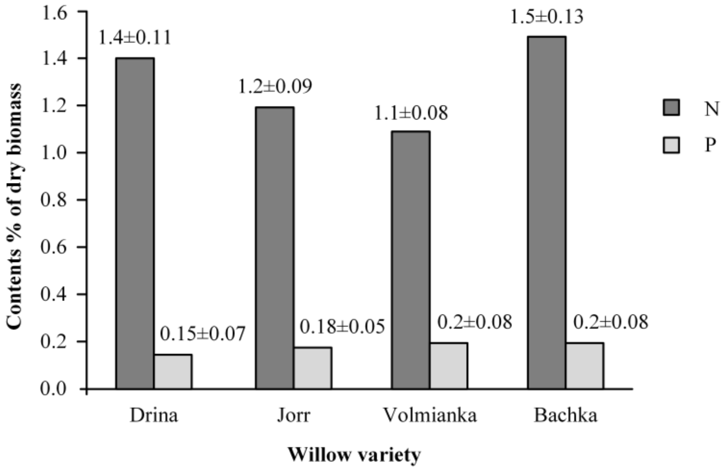

Fig. 3. The content of nitrogen and phosphorus in willow wood, $\bar{X} \pm S_x$, November 2015.

4. DISCUSSION

In our experiments the highest TF of ^{137}Cs accumulation was defined in roots (0.229–0.939·10^{-3} m^2 kg^{-1}) and leaves (0.032–0.052·10^{-3} m^2 kg^{-1}), while minimal one was in wood (0.009–0.031·10^{-3} m^2 kg^{-1}). Similar results were obtained in Sweden by Rosen [34]. Roots and leaves had relatively high rate of ^{137}Cs accumulation comparing to stems and cuttings, also the TF of ^{137}Cs in different plant organs varied between 0.1·10^{-3} and 2.6·10^{-3} m^2 kg^{-1} that in 2–3 times higher than in our experiments. The experimental site was located in east-central Sweden and density of ^{137}Cs contamination of soil was about 141 kBq m^2 which is lower than in Mogilev region. The difference in accumulation may be explained by soil characteristics. In Sweden, the experiment was set up on a sandy soil, while in Belarus in sandy-loam soils. The transfer factor for sandy soil in 2 times higher in compare with loam-sandy soils for the most agricultural crops, including willow. In experiments that were carried out at a field experimental station of Swedish University of Agricultural Sciences (SLU) in Uppsala, ^{137}Cs activity concentration in the different plant parts is ranked in the following falling order: roots > leaves > cuttings > stems [35]. The highest active concentrations of ^{137}Cs were found in the fine roots (0–1 mm). The transfer factor of ^{137}Cs was lower in compare to Rosen results and varied from 0.02·10^{-3} to 0.1·10^{-3} in stems, 0.05·10^{-3} to 0.2·10^{-3} in leaves, 0.03·10^{-3} to 0.08·10^{-3} in cuttings and 0.1·10^{-3} to 1.3·10^{-3} in roots. ^{137}Cs contamination of sandy-loam soil was about 16.68 MBq m^{-2}.

Contents of ^{137}Cs in firewood is limited to level of 740 Bq/kg by special Decree of Ministry of Health of Belarus. In accordance with permitted level established in Belarus and our results, willow could be grown for energy purposes without additional potassium application on soils with density of ^{137}Cs contamination up 370 kBq/m^2, and with additional potassium application in the dose 90 kg/ha for the density of ^{137}Cs contamination up 990 kBq/m^2. The correlation between TF of ^{137}Cs and potassium application established in several earlier mentioned experiments showed that potassium reduces transfer of ^{137}Cs from contaminated soils to plants [36]–[38]. From this point of view, it is better to use willow biomass for energy, than to collect it and bury it after ^{137}Cs accumulation.

In our experiments, the content of Cd in willow leaves was lower than 0.1 mg/kg. In accordance with other experiments, it may range in very broad diapason from 0.08 mg/kg to 55 mg/kg [39], [40]. Phytoremediation of heavy metals depends on a lot of factors: growing conditions, soils properties, contents of elements in the soil and others. For instance, high level of Cd in biomass was detected in the areas, which situated close to the landfills [41], [42].

Contents of Pb in our experiments varied from 0.36 mg/kg to 1.07 mg/kg. In other experiments results also ranged in very broad limits: from 0.68 [43] to 13 mg/kg and more [44]. Concentration of Ni in willow leaves in our experiments was 1–2 mg/kg. In accordance with results of other researchers it varied from 1.97 mg/kg [45], to 10 and more mg/kg [46]. Thus, our results are closer to the lowest limits of heavy metals contents in willow biomass. It may be explained by fact that our experimental plots were set up on ordinary agricultural soils, without special addition of heavy metals. As a rule, transferring factors of Cd, Pb, Ni in our experiments varied from 0.05 to 0.1. Of course, this level is not as high, as it would be effective for soils cleaning. In other experiments was established that the transferring factor for Cd may reach about 4 units [30]. But we should bear in mind that content of Cd in soil for this experiment was 18 mg/kg, which in 9–10 times higher in comparison with our experiments. In accordance with our and others results, we could conclude that willow is not plant – hyperaccumulator of ^{137}Cs, Cd, Pb and Ni, and its biomass could be used as energy source without limit. It is therefore plausible and also very effective to grow willow plantations during 20–25 years' period on soils with extra high level of pollutants content in order to acquire energy source, since it is not possible to grow common agricultural crops there. The content of Cu in willow leaves in our experiments was 50–97 mg/kg and Zn – 95–180 mg/kg. It is rather close to other results [47], [48].

The aspect which we should also keep in mind it is antagonism and synergism of metals. For example, in experiments in Serbia a positive coefficient of correlation between Pb and other metals accumulation in willow biomass (for Fe – 0.4; for Zn – 0.31) was obtained and also a negative one (for Mn – 0.34 and Ni – 0.50) [30]. In our experiments the highest positive coefficient of correlation between K application into the soil and accumulation of metals in willow biomass were obtained for Cu, Zn and Mn. The correlation between K application and accumulation of Pb and Cd was negligible.

We also established the difference of heavy metals accumulation by willow species. The different potential of species and clones of willow in heavy metals accumulation was also confirmed in other studies [49]–[52]. It means that selection of SRC willows should be focused not only on high productivity, but on environmental aspects as well. For instance, Drina is the variety, which does not uptake heavy metals so intensively, in compare with other varieties of willow. It is necessary to keep in mind if we want to get cleaner biomass. Low rates of heavy metals accumulation for willow species, not correlated with willow productivity in our experiments. The most productive variety was Bachka, not Drina. The yield of wood of variety Jorr for not polluted by ^{137}Cs soils was 11.5 DMg ha^{-1} per year. The yield of wood for Bachka variety on the soils in Mogilev region with close chemical properties, but also polluted by radionuclide ^{137}Cs was 12.3 DMg ha^{-1} per year. It means that radionuclide pollution didn't influence dramatically on willow productivity. Yield of willow which growing on radionuclide and heavy metals polluted soils is close to ordinary yield for mineral fertile soils [53], [54].

The contents of nitrogen in willow dry wood in our experiments varied from 1.1 to 1.5 % and phosphorus from 0.15 to 0.21 % in depends of clone. In experiments with willow plantations in Sweden, the plants were irrigated by wastewater with high level of nitrogen contents. It was established that with biomass production of willow 10 tons of dry matter per hectare, the nitrogen concentration in the willow shoots was 0.5 percent [17]. Research however has shown that the N retention in SRWC can be up to 200 kg N ha^{-1} yr^{-1}, due to denitrification and long-term binding of N into the soil. Survey of experimental results concerning of nutrients accumulation was prepared in the frame AILE – Wilwater project. In accordance with survey nitrogen contents in willow wood are varied from 0.3 till 0.83 % and for phosphorus from 0.04 till 0.13 % [55].

The highest contents of nitrogen and phosphorus in willow wood in our experiments may be explained by the following fact. Willow trees were planted in down part the hill in riparian of lake. The most part of the watershed area was occupied by agricultural fields, where mineral and organic fertilizers were brought in. As the result nutrients from mineral fertilizers were partially running down with snow and rainwater runoff, and captured by willow roots. In accordance with willow yield (45 tons of wood for three years with humidity 50 %) and if the leaves fall off every autumn and staying in ecosystem, but wood is harvested and used as energy every 3 years it is possible to take to take out till 332.5 kg of nitrogen and 46.5 kg of phosphorus from one hectare of plantation. The annual uptake of nitrogen with willow biomass will be from 81 till 111 kg from hectare and phosphorus – from 11 till 15.5 kg from hectare.

The nitrogen fertilizers were applied with doze 150 kg ha^{-1} ammonium nitrate (51 kg of active substance of N), 120 kg ha^{-1} double superphosphate (48 kg of active substance of P), and 150 kg ha^{-1} potassium salt (90 kg of active substance of K) once before planting of the plots. It is not reasonable to apply additional dozes of N and P during life cycle of plantation for willow trees which will be used as vegetative filters. Thus, the volume of uptake and takeaway of nutrients from ecosystems by willow trees during their life cycle, in several times more, in compare with application of nutrients with mineral fertilizers.

5. CONCLUSIONS

Phytoremediation is an effective method, not only for cleaning, but and rehabilitation of polluted soils. Results of our experiments show that a willow doesn’t belong to group of crops – hyperaccumulators of radionuclides and heavy metals. It was established that ^{137}Cs has distinct rates of accumulation in different parts of willow plants, and the biggest quantity of radionuclide accumulates in root system. Transferring factor (TF) of ^{137}Cs in the root is three times greater in comparison with wood. It is the different ways of utilization of willow biomass during life time of plantation. The leaves fall of every year to the ground and decays, wood is harvested and used for energy every 3 year, while roots remain in the soils for 20–25 years. The half-life of ^{137}Cs is about 30 years. For the life cycle of plantation, the radionuclide density will decrease at the result of radionuclides disintegration and uptake by wood and leaves. Furthermore, it is possible to use willow biomass for energy purpose even from the areas with comparatively high level of radionuclide pollution density (370–990 kBq/m^2), in case of potassium application.

The transferring factors of heavy metals into willow biomass were: for Cd, Pb, Ni and Mn smaller than 1, for Cu – 1–2 and for Zn – 2–4. It is doubtful that willow biomass obtained from heavy metals polluted soils may be used as a substrate for metal extraction, but it may be used for energy without limits. Our results showed that it is possible and perspective practice to grow willow on soils polluted both with radionuclides and heavy metals. High doses of K application decrease the ^{137}Cs uptake but accelerate accumulation of Cu, Zn and Mn. The yield of willow wood on polluted soils was not lower in comparison with usual results for mineral fertile soils.

The different potential of willow species in heavy metals accumulation has been established. It implies that selection of short coppice rotation fast growing willows could be focused on varieties which accumulate pollutants extensively. In that case willow wood may be used for energy without any limits and plantation grows in the same field for 20–25 years. On the other hand, it is possible to deliberately select varieties which intake heavy metals, radionuclides and other chemicals faster.

The willow plantations potential as vegetative filters, for control of eutrophication of water ecosystems, was established. It is possible and reasonable to use willow trees for uptake of nutrients from ecosystems of the watersheds.

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