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Studies on the Accumulation, Translocation, and Enrichment Capacity of Soils and the Plant Species Phragmites Australis (Common Reed) with Heavy Metals

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Abstract: In the present study, heavy metal concentrations (Cu, Zn, Pb, As) from former industrial areas were analyzed in soil and the plant species Phragmites Australis (common reed), a plant species found in shallow river banks. The objectives of the study were to determine the accumulation, translocation, and enrichment capacity of soils and plants (root, stem, leaf, and flower) with heavy metals, and to evaluate the potential of the plant species Phragmites Australis (common reed) in the phytoremediation of heavy-metal-polluted soils. The sediments and plants investigated were particularly rich in heavy metals such as Cu, Zn, Pb, and As, and Pb and Zn concentrations were determined to be of phytotoxic level. The highest transfer coefficient of heavy metals from the soil to the root of the plant species Phragmites Australis (common reed) was for the metals Cu and Zn. The transfer of heavy metals from the root of the plant species Phragmites Australis (common reed) to the aerial part of the plant was lowest for Cu. A very low enrichment factor value was recorded for the metal As. The mobility of heavy metals was generally higher from the sediment to the plant roots, with the order of the average transfer coefficient values being Cu > Zn > Pb > As for all three areas analyzed. The translocation of heavy metals from the root to the upper aerial part of the plant was in the form of As > Pb > Zn > Cu in the plant species Phragmites australis (common reed). According to the average values obtained for the three coefficients, the accumulation, translocation, and enrichment capacity of heavy metals in soil and the plant species Phragmites Australis (common reed), it can be stated that the plant species Phragmites Australis (common reed) is very suitable for use in the process of soil remediation by phytoremediation.

Keywords: heavy metals pollution; plant; transfer mechanism; root; steam; leaves; flower

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1. Introduction

Soil pollution is internationally recognized as a major health hazard, leading to the production of unsafe and inadequate food, which in turn threatens global food security [1–5]. Industrial activities, mining, waste treatment, agriculture, fossil fuel extraction and processing, and transport emissions are the main sources of pollutants contributing to soil pollution (in order of importance). However, there is a lack of concrete and comparable data on the actual emissions from the individual sectors. Industrial pollutants are released into the environment throughout their lifecycle, from the production of the materials containing the pollutants, to their shipment, use, and disposal [5–8].

Since the early 21st century, global annual industrial chemical production has doubled to around 2.3 billion tons and is expected to increase by 85% by 2030. In Europe, there are about 650,000 sites identified as potentially polluted and included in national and/or regional inventories, according to regular reports and indicators of the European Environment Agency. Despite decades of research, inventory, and monitoring of point-source polluted soils in a number of countries, there are still significant knowledge gaps and uncertainties about the number and extent of affected areas. The knowledge gap on soils affected by diffuse pollution and its impact on other environmental compartments is even greater [2,5,7].

It is well known that high concentrations of heavy metals affect both soil and plants. According to the Government Decree no. 161 of 16 February 2006, entitled Elements and standards for the chemical quality of alluvia—Section 63 μm, metals with high permissible limits are considered safe. In soils, the acceptable levels for Zn are highest, followed by Pb and Cu, while the acceptable levels for As are lowest. This threshold means that the accumulation of As in soils, even at lower levels, is more toxic than those of Cu, Pb, and Zn. In plants, the As limit is highest, followed by Pb, Zn, and Cd. Contrary to soils, As has the safest thresholds, followed by Zn and Pb, while Cu accumulation in plants is the worst [2,5].

Heavy metals found in the soil in the form of traces are insignificant chemical elements in terms of quantity, but they are necessary as micronutrients for plants [1–7]. Heavy metal behavior in soils varies widely depending on the element and type of soil, and these distinctions must be better understood in order to forecast and manage heavy metals in soils effectively [2,6,8,9]. The degree of pollution in heavy metal soils varies based on a variety of factors, including the degree of industrialization, geographical area, human population size, soil type, type of pollution source, and distance from the pollution source [3,4,9]. Internal factors (plant metabolism, the interaction between the root system and the rhizosphere, and metabolic inhibitors), as well as environmental factors, influence the dynamics of the mobility process of micro, macro, and heavy metals (light, temperature, oxygen, humidity, soil reaction, but also the concentration of ions in the soil solution) [1,2,5,7,9,10]. With regard to metal accumulation by plants, there are three types of plants: heavy-metal accumulators, heavy-metal excluders or non-accumulators, and indicator plants [1,4,5,11–20]. In the case of heavy-metal-accumulating plants, the ratio between the concentration of the metal in the plant and the concentration of the metal in the soil is >1 [11,12,16,19–21]. For non-accumulating plants, this ratio is <<1, and for indicator plants, it is approximately 1 [1,11,12,16,19,21]. The concentrations of heavy metals in the soil, in the soil solution, and in the plant are very variable [3,22–24]. Regardless of the concentration of the metal in the soil, hyperaccumulating plants have an extraordinary ability to absorb metals from the soil and translocate them into their shoots [11–13,16–19]. The majority of heavy metals have a low degree of mobility in the soil and are not easily taken up by the plant [16,19,25]. Some plants (non-hyperaccumulators) may concentrate metals at the same levels in polluted areas. Thus, high levels of any given metal in an accumulating plant should be seen in relation to its levels in other plants grown in the same area. In the uptake of elements by plants, plant-specific differences are common [10–12,26–35]. In some of the heavily polluted areas, the pH value of the soil is in a constant state of flux. Analyses of these polluted areas have shown a decrease in soil calcium and magnesium concentrations and an increase in soil Pb concentrations [5–7,14,15,18,20,27,36]. The response of the soil is very important for plant development, and plant preferences vary greatly in this respect [5,35–41].

Pb is released into the atmosphere in the form of fumes, condensing relatively quickly and settling onto the ground, roofing, vegetation, and streets, where it is carried by even the smallest airflow [2,7,9]. Even if the heavy metal contamination is greatly diminished, it remains in the soil for a long time and the effects may be mitigated by extremely expensive soil clean-up operations [5,42–47]. Depending on physico-geographical and eco-climatic factors, the highest concentrations of heavy metals (Cu, Zn, As, Pb) in soils are deposited near pollution sources [1–8,43]. In a simplified form, the processes of bioaccumulation can be seen as a consequence of the following processes [2,4,7,10–14]:

- The process of uptake by the roots of the surface plants;
- The flow of water that circulates as a carrier through cormophytic plants.

Heavy metals may interfere with other metals both within the soil and within plants and to different degrees within different parts of plants. In vegetation, heavy metals are involved in specific interactions like other nutrients [1,10,16–20]. The similar geochemical behavior of many heavy metals can lead to interfering phenomena that can affect how plants manage these metals [16,25,27]. This is exemplified by high levels of Cu in soils, often co-occurring with Zn [2,4,9]. Many complex interactions of Cu with other elements have been observed in the tissues of plants and in the external environment of roots, particularly in the processes of uptake and transport [2,4,10–18]. Cu-Zn interactions are very common. Each of these metals can competitively inhibit the root absorption of the other because they are absorbed by the same mechanism [4,10–19]. The translocation of each element from the roots to the aerial part is affected by the Zn-Pb antagonism [4,13,16,17,19,22,25,26]. The sources of As contamination are very diverse. Depending on the origin of the inorganic As contaminants, they can be classified as natural sources, ores and groundwater containing As, mining and processing of mining waste, and numerous industrial sources [4,13,16,17,20,21,23,27]. As is not essential for plants and other organisms, unlike iron and Cu. Through active or passive mechanisms, plants accumulate As in the root and transport it to the stem. Exposing plants to even low levels of As can alter their morphology, physiology, and biochemistry [4,13,16,17,23].

In phytoremediation, plants use mechanisms such as phytostabilization, phytoextraction, rhizodegradation, and phytovolatilization to stabilize (passive phytoremediation) or absorb (active phytoremediation) contaminants from their growing environment [4,11–13,16,21,29,33,34]. The macrophyte Phragmites Australis (common reed) is a plant species often proposed for use in the phytoextraction mechanism [1,33–42]. Phragmites Australis (common reed) is a wetland plant species that can cover large areas in shallow beds of water. As a bioindicator/accumulator of heavy metals, this plant species is used [1,33–42,44–47].

Current studies in the field show how pollutants are distributed in different plant species for agricultural soils or accidentally polluted soils. The aim of the study was to evaluate the phytoremediation of soils polluted by heavy metals (As, Zn, Cu, Pb) and to determine the accumulation of metals in different parts of the plant and the transfer of heavy metals (As, Zn, Cu, Pb) from the underground to the above-ground parts of the plant.

2. Materials and Methods

2.1. Experimental Part

When selecting sampling points, we looked at the areas where pollution sources are located. For each sampling section, sediments must be sampled from representative locations so that we have a good understanding of the pollution sources and the hydrological and geomorphological characteristics of the area. The sampling points must represent areas where the sediment layer is thick and its granularity is less than 63 µm, consisting of clay and silt.

Figure 1 shows the sections that were considered when obtaining plant and soil samples. The vegetation was sampled from the banks of the tributaries in three locations/areas along the Siret River banks in the Siret hydrographic basin (Siret River—Bridge Holt region, Siret River—canal UHE, and Siret River—downstream confluence Bistrita/Siret).

The plant species developed in the studied areas are Phragmites Australis (common reed) and Typha Latifolia, especially the species Phragmites Australis (common reed).

Phragmites Australis (common reed, Figure 2) is a Gramineae (Poaceae) perennial herbaceous plant with a rigid stem of about 1–4 m, green-bluish lanceolate leaves, and flowers set out in tassels, and is a good absorber of pollutants.

Three levels of plant and soil samples were gathered:

- Sample point 1: 0 cm of soil–water interface;
- Sample point 2: 50 cm of soil–water interface on the river bank;
- Sample point 3: 100 cm of soil–water interface on the river bank.

The atomic absorption spectrometer was used to analyze the heavy metal content of soil, sediment, and plant samples, which can determine heavy metals down to trace levels. The basic technique for determining heavy metals is atomic spectroscopy. The atomic absorption spectrometer (AAS), version ZEENIT AAS 700, made in the USA, was used to determine the Cu, Pb, As, and Zn content of the soil.

Figure 1. The areas from the Siret hydrographic basin that were taken into consideration for the soil and plant sampling program were those along the Bistriţa and Siret rivers [48].

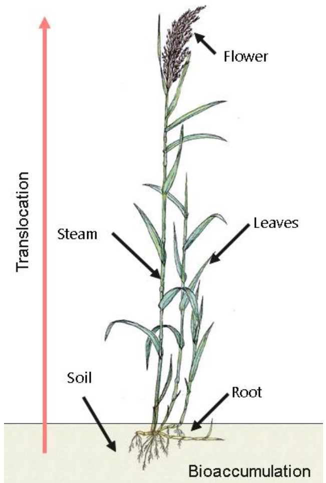

Figure 2. Common reed (Phragmites Australis) [44].

2.2. Data Analysis

To assess the ability of the common reed species to accumulate metals from the soil and translocate them from the root to the aerial part of the plant, the following coefficients were calculated: transfer coefficient (TC), translocation factor (TF), and enrichment coefficient (EC).

The ratio of the concentration of metals in the root to their content in the soil (mg/kg) is defined as the transfer coefficient (TC) (or bioaccumulation factor, Equation (1)). It indicates the plant's ability to accumulate metals from the soil [8,9].

TC > 1: the plant is accumulating metals.

TC < 1: the plant has no metal uptake.

$$TC = \frac{\text{PLANT ROOT METAL CONCENTRATION}}{\text{SOIL METAL CONCENTRATION}}, \quad (1)$$

The ratio of the metal concentration in the aerial part of the plant to that in the roots is calculated as the translocation factor (TF) (Equation (2)) [16,36].

TF > 1: the plant is translocating metals from the roots to the aerial part of the plant.

$$TF = \frac{\text{METAL CONCENTRATION IN THE UPPER PART OF THE PLANT}}{\text{PLANT ROOT METAL CONCENTRATION}}, \quad (2)$$

The enrichment coefficient (EC) can be used to assess the degree of soil contamination and the accumulation of metals in plants growing on contaminated soil compared to soil and plants growing on control soil. The EC is the ratio of the metal concentration in the contaminated soil to the metal concentration in the unpolluted soil, i.e., the metal concentration in plants grown on contaminated soil to the metal concentration in plants grown on unpolluted soil [17,37].

EC > 1 means a higher availability and distribution of metals in the contaminated soil and hence a higher metal accumulation in plant species grown on the contaminated soil compared to the baseline.

3. Results

The experimental values for the four heavy metals in soil (Cu, Pb, As, and Zn) for the control sample of Phragmites Australis (common reed) from unpolluted/polluted soil are shown in Tables 1–4.

Table 1. The experimental average values for the four heavy metals in soil (Cu, Pb, As, and Zn) for the control sample of Phragmites Australis (common reed) from unpolluted soil.

Uncontaminated Location	Cu	Pb	As	Zn
	(mg/kg d.m.)			
Soil	35	80	26	124
Phragmites Australis (common reed) steam + leaves + flower	1.14	2.88	3.17	2.55
Root	1.2	3.86	2.96	3.94
Steam	0.85	3.65	2.81	3.32
Leaves	0.41	2.03	1.73	2.89
Flower	0.06	0.95	0.99	1.75

Table 2. The experimentally determined average values for the four heavy metals in the soil for the three locations/areas along the Siret River banks in the Siret hydrographic basin (Siret River—Bridge Holt region, Siret River—canal UHE, and Siret River—downstream confluence Bistrita/Siret.

Level	Cu	Pb	As	Zn
	(mg/kg d.m.)			
Siret River—Holt Bridge—Pod Holt WP0019 Lat. 46.59010° N/Long. 26.97448° E + 0 m				
minimum level (0 cm) water–soil interface	54.31	151.4	15.65	440.4
medium level (50 cm) water–soil interface	37.63	77.5	12.5	256.4
maximum level (100 cm) water–soil interface	26.55	24.93	14.54	108.5
Siret River—canal UHE—WP0025 Lat. 46.50682° N/Long. 26.97929° E + 176 m				
minimum level (0 cm) water–soil interface	24.52	15.28	15.13	71.3
medium level (50 cm) water–soil interface	29.65	17.25	15.44	74.18
maximum level (100 cm) water–soil interface	30.73	18.6	17.07	81.35
Siret River—downstream confluence Bistrita/Siret—WP0026 Lat. 46.46347° N/Long. 26.96729° E + 157 m				
minimum level (0 cm) water–soil interface	36.03	20.5	18.21	90.3
medium level (50 cm) water–soil interface	38.52	28.14	14.2	120.5
maximum level (100 cm) water–soil interface	30.25	27.2	15.68	102.5

Table 3. The experimentally determined average values for the heavy metals in the plant species Phragmites Australis—common reed (steam + leaves + flower) for the sampling areas along the Siret River banks in the Siret hydrographic basin (Siret River—Bridge Holt region, Siret River—canal UHE, and Siret River—downstream confluence Bistrita/Siret).

Level	Cu	Pb	As	Zn
		(mg/kg d.m.)		
Siret River—Holt Bridge—Pod Holt WP0019 Lat. 46.59010° N/Long. 26.97448° E + 0 m				
minimum level (0 cm) water–soil interface	29.7	40.15	1.23	92.28
medium level (50 cm) water–soil interface	20.9	18.894	0.674	60.88
maximum level (100 cm) water–soil interface	15.751	4.712	1.124	26.55
Siret River—canal UHE—WP0025 Lat. 46.50682° N/Long. 26.97929° E + 176 m				
minimum level (0 cm) water–soil interface	13.55	3.156	0.978	17.54
medium level (50 cm) water–soil interface	15.557	3.658	1.127	17.58
maximum level (100 cm) water–soil interface	17.222	4.887	1.371	20.89
Siret River—downstream confluence Bistrita/Siret—WP0026 Lat. 46.46347° N/Long. 26.96729° E + 157 m				
minimum level (0 cm) water–soil interface	20.2	5.22	1.404	22.889
medium level (50 cm) water–soil interface	22.54	7.32	0.905	25.22
maximum level (100 cm) water–soil interface	14.2	6.92	1.021	24.25

Table 4. The experimentally determined average values for the four heavy metals in the plant species Phragmites Australis—common reed (root, steam, leaves, flower) for the sampling areas along the Siret River banks in the Siret hydrographic basin (Siret River—Bridge Holt region, Siret River—canal UHE, and Siret River—downstream confluence Bistrita/Siret.

Level	Root	Steam	Leaves	Flower	Root	Steam	Leaves	Flower
Siret River—Holt Bridge—Pod Holt WP0019 Lat. 46.59010° N/Long. 26.97448° E + 0 m								
	Cu (mg/kg d.m.)				Pb (mg/kg d.m.)			
0 cm	42.53	26.85	11.95	2.48	42.85	38.61	21	10.7
50 cm	38.51	20.73	8.43	0.95	19.23	16.46	8.9	3.41
100 cm	27.6	12.28	6.9	0.77	4.34	3.1	1.53	0.44
	As (mg/kg d.m.)				Zn (mg/kg d.m.)			
0 cm	11.02	0.86	0.61	0.25	135.94	100.59	88.76	50.14
50 cm	0.59	0.46	0.39	0.14	73.69	65.11	47.39	30.61
100 cm	0.91	0.63	0.27	0.09	30.4	25.68	17.13	10.84
Siret River—canal UHE—WP0025 Lat. 46.50682° N/Long. 26.97929° E + 176 m								
	Cu (mg/kg d.m.)				Pb (mg/kg d.m.)			
0 cm	23.1	12.56	5.39	0.72	3.09	2.84	1.3	0.39
50 cm	24.32	13.95	7.12	1.07	3.74	3.25	1.81	1.03
100 cm	24.98	15.43	7.94	1.22	5.16	4.98	2.46	1.48
	As (mg/kg d.m.)				Zn (mg/kg d.m.)			
0 cm	0.84	0.75	0.24	0.08	31.85	26.99	23.45	14.78
50 cm	1.06	0.82	0.36	0.09	32.1	28.15	25.39	19.56
100 cm	1.29	1.1	0.85	0.31	39.62	32.7	27.56	20.63
Siret River—downstream confluence Bistrita/Siret—WP0026 Lat. 46.46347° N/Long. 26.96729° E + 157 m								
	Cu (mg/kg d.m.)				Pb (mg/kg d.m.)			
0 cm	35.62	19.16	10.54	2.9	5.56	5.37	3.14	1.36
50 cm	36.15	20.07	13.25	2.73	7.89	7.77	3.45	1.59
100 cm	25.38	14.1	7.82	1.49	7.43	7.4	4.26	2.44
	As (mg/kg d.m.)				Zn (mg/kg d.m.)			
0 cm	1.56	1.48	0.83	0.57	39.68	32.19	26.4	18.16
50 cm	1.1	1.05	0.71	0.43	47.15	38.65	31.34	22.19
100 cm	1.089	0.94	0.77	0.5	46.9	38.1	29.59	19.43

The exceeding of limits of heavy metals (Cu, Zn, Pb, and As) in the soil is the result of urban wastewater discharged in Bistrita River by means of water treatment stations, industrial platforms (chemical, mechanical, energy, aviation) from Bacau city, and the inappropriate storage of municipal waste.

The maximum permitted concentrations for heavy metals in soil, according to Government Order No 161 of 16 February 2006, entitled Elements and standards for the chemical quality of alluvium—Section 63 µm [49], were exceeded for Cu, Pb, and Zn for the Siret River—Holt Bridge sampling area, downstream of the city of Bacau, for level 0 cm and level 50 cm (only in the case of Zn).

The high heavy metal values recorded in the plant species Phragmites Australis—common reed (root, stem, leaves, flower) reported in the control samples are mainly due to remnant (historical) soil pollution.

4. Discussion

Phragmites australis (common reed) is a cosmopolitan species plant. It inhabits freshwater and brackish wetlands in different climatic regions of the world [37]. The accumulation of metals in aquatic plants is a function of a number of factors, including the concentration of a metal and its availability in the substrate, the physical and chemical characteristics of the water and sediment, species-specific uptake, the growth requirements of the plants, the sampling time, and the process of translocation within the plants [38]. In the present study, we found a significant linear correlation between concentrations of available metals in soil and the plant species *P. australis* in all three areas analyzed, which is consistent with data previously reported by [46]. The concentration levels of Cu and As in *P. australis* roots followed a positive relationship with their concentration in the soil, which corroborated previous findings [45,45]. The results presented below support previous studies, which indicated that the concentrations of heavy metals are frequently higher in the belowground parts (roots) as compared to the aboveground parts (stems, leaves, and flowers) of wetland plants [41], since belowground parts are the primary sites for the take-up of heavy metals, and the subsequent translocation to aboveground parts may be limited [36,37]. The correlations of heavy metal contents in plants (Cu, Pb, As, and Zn) with those in soil and plant parts (root, stem, leaf, and flower) observed in this study have also been analyzed and demonstrated by other authors [1,4,16,17,19,24].

In the case of the Siret River—Bridge Holt region sampling point, the transfer coefficient (Figure 3) for the metals Pb, As, and Zn had a value less than one, indicating that the plant species Phragmites Australis (common reed) does not accumulate the metals, with the recorded transfer coefficient values ranging from 0.006 to 0.308.

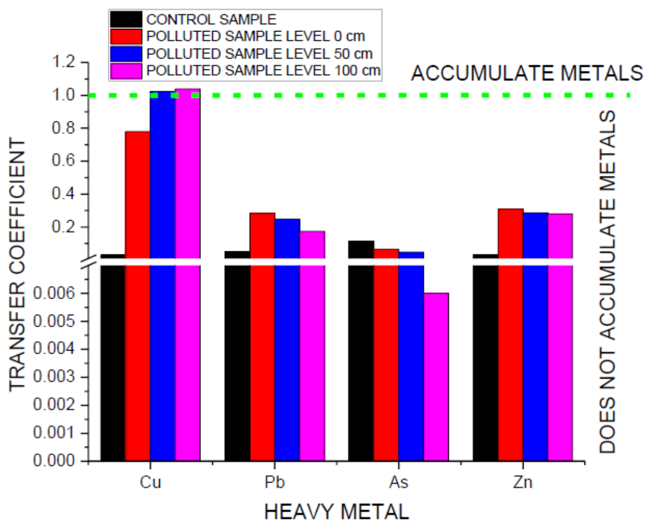

Figure 3. The transfer coefficient of metals in Phragmites Australis (common reed) plant species, control sample and polluted, for location of Siret River—Bridge Holt region.

For the metal Cu, the transfer coefficient value for the sampling point Siret River—Bridge Holt region, for 50 cm and 100 cm levels, had a value greater than one, indicating that the plant species Phragmites Australis (common reed) is a good accumulator of Cu.

The transfer coefficient for all four metals Cu, Pb, As, and Zn had a value less than one for the sampling point Siret River—UHE canal (Figure 4), which indicates that the plant species Phragmites Australis (common reed) does not accumulate the metals, with the recorded transfer coefficient values ranging from 0.055 to 0.942. The highest values of the transfer coefficient for the sampling point Siret River—UHE canal were recorded for the metal Cu, with the recorded values being very close to 1.

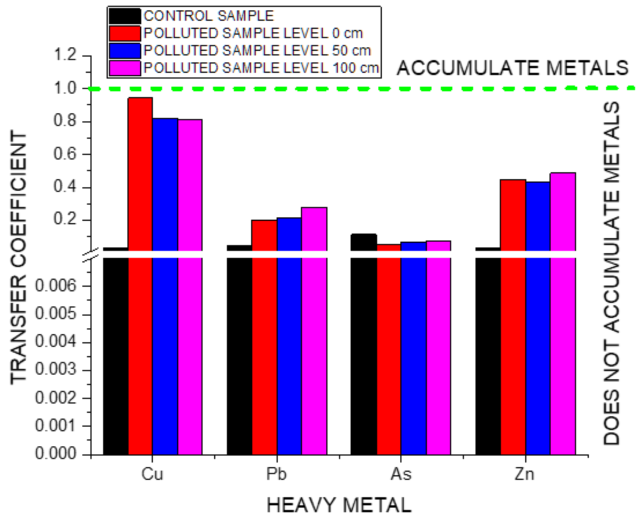

Figure 4. The transfer coefficient of metals in Phragmites Australis (common reed) plant species, control sample and polluted, for location of Siret River—canal UHE.

The transfer coefficient for all metals had a value less than one for the Siret River—downstream confluence Bistrita/Siret sampling point (Figure 5), indicating that the plant species Phragmites Australis (common reed) does not accumulate metals, with the recorded transfer coefficient values ranging from 0.069 to 0.988 (the highest transfer coefficient value for the Siret River—downstream confluence Bistrita/Siret sampling point was recorded for the metal Cu).

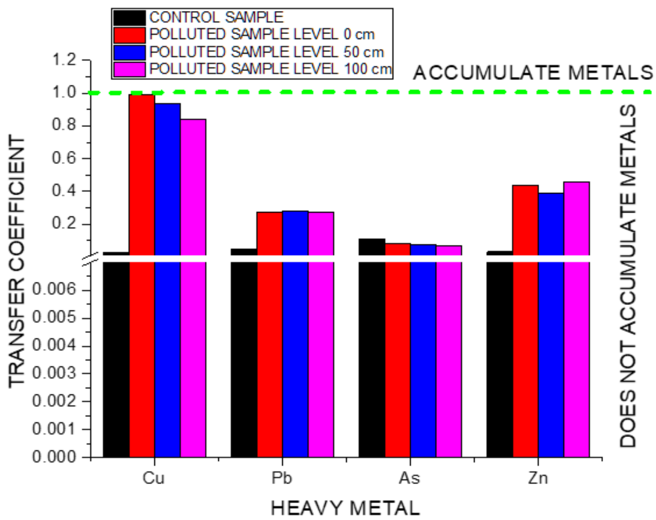

Figure 5. The transfer coefficient of metals in Phragmites Australis (common reed) plant species, control sample and polluted, for location of Siret River—downstream confluence Bistrita/Siret.

The translocation factor was calculated as the ratio of the total metal concentration in the aerial part of the plant (stem, leaves, and flowers) to the metal concentration in the roots.

In the case of the Siret River—Bridge Holt region sampling point, the translocation factor (Figure 6) for the metals Cu and Zn had a value less than one, indicating that the plant species Phragmites Australis (common reed) does not translocate the metals, with translocation factor values recorded ranging from 0.542 to 0.95 for Cu and 0.647 to 0.873 for Zn.

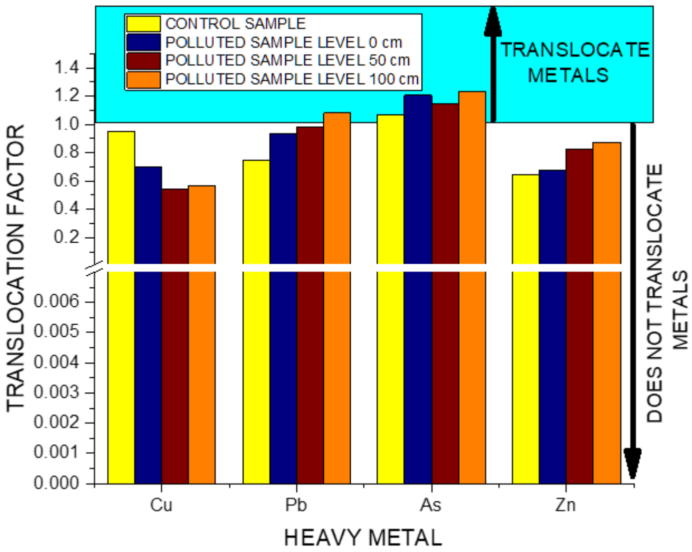

Figure 6. The translocation factor of metals in Phragmites Australis (common reed) plant species, control sample and polluted, for location of Siret River—Bridge Holt region.

For the metal As, the translocation factor value for the sampling point Siret River—Bridge Holt region for all three levels (0 cm, 50 cm, and 100 cm) was greater than one, indicating that the plant species Phragmites Australis (common reed) translocates the As metal very well.

The value of the translocation factor for Pb metal in the case of the sampling point Siret River—Bridge Holt region, for the 100 cm level, was greater than one, and those for the other two levels (0 cm and 50 cm) were also very close to one (0.936 for the 0 cm level and 0.982 for the 50 cm level), indicating that the plant species Phragmites Australis (common reed) also translocates the Pb metal well.

The translocation of As metal from the root to the aerial part of the plant is also significant in uncontaminated soil, with a translocation factor value for As of 1.07.

In the case of the sampling point Siret River—UHE canal, the translocation factor (Figure 7) for the metals Cu and Zn had a value less than one, which indicates that the plant species Phragmites Australis (common reed) does not translocate metals, with the translocation factor values recorded ranging from 0.55 to 0.689. The translocation factor values recorded were also lower than the values recorded in the control sample.

For the metal As, the translocation factor value for the sampling point Siret River—UHE canal, for all three levels, was greater than one (translocation factor values recorded ranged from 1.062 to 1.164), indicating that the plant species Phragmites Australis (common reed) translocates the As metal very well.

The value of the translocation factor for Pb metal in the case of the sampling point Siret River—UHE canal, for the 0 cm level, was greater than one (1.021), and those for the other two levels (50 cm and 100 cm) were also very close to one (0.978 for the 50 cm level and 0.947 for the 100 cm level), which indicates that the plant species Phragmites Australis (common reed) also translocates the Pb metal well.

In the case of the sampling point Siret River—downstream confluence Bistrita/Siret, the translocation factor (Figure 8) for the metals Cu, Pb, As, and Zn had a value less than one, indicating that the plant species Phragmites Australis (common reed) does not translocate metals, with the translocation factor values recorded ranging from 0.567 to 0.938.

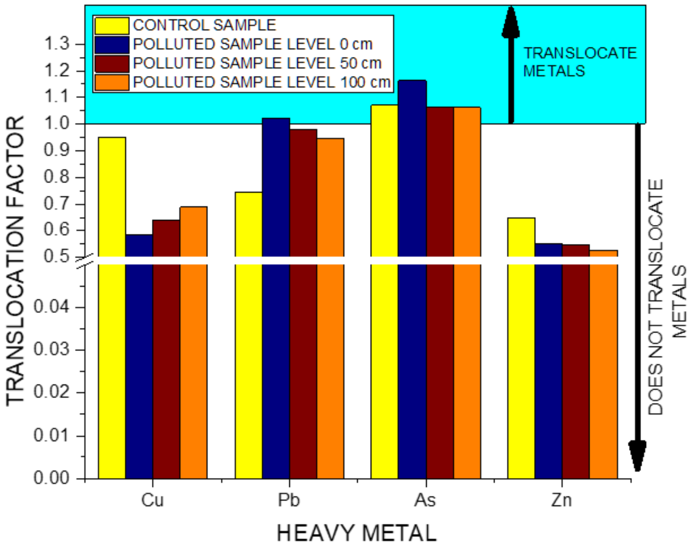

Figure 7. The translocation factor of metals in Phragmites Australis (common reed) plant species, control sample and polluted, for location of Siret River—canal UHE.

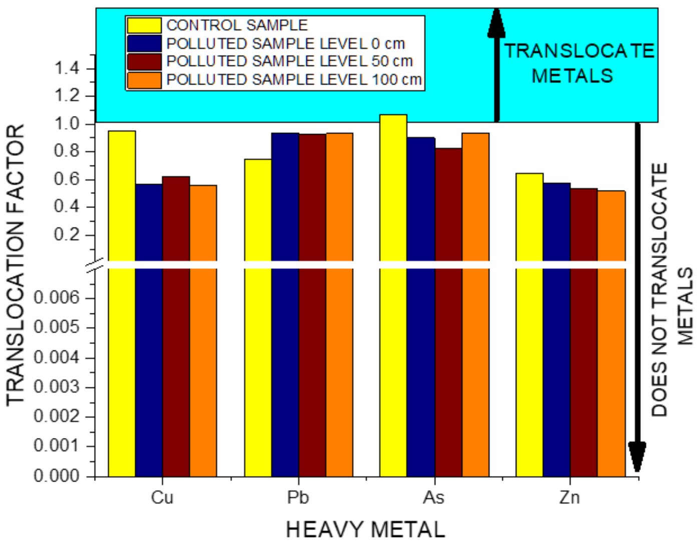

Figure 8. The translocation factor of metals in Phragmites Australis (common reed) plant species, control sample and polluted, for location of Siret River—downstream confluence Bistrita/Siret.

Enrichment coefficient (EF) values for soil, root, stem, leaves, and flowers of the plant species Phragmites Australis (common reed) for the Siret River—Bridge Holt region sampling point are shown in Figure 9. Maximum enrichment was observed in the flowers of the plant species Phragmites Australis (common reed) for the metals Cu (41—0 cm level) and Pb (11.263—0 cm level), and for Zn, the highest enrichment coefficient values were observed in the root of the plant species Phragmites Australis—common reed (34.5—0 cm level). In the case of the metal As, the enrichment coefficient values recorded were very low, below the value of one (0.199–0.601).

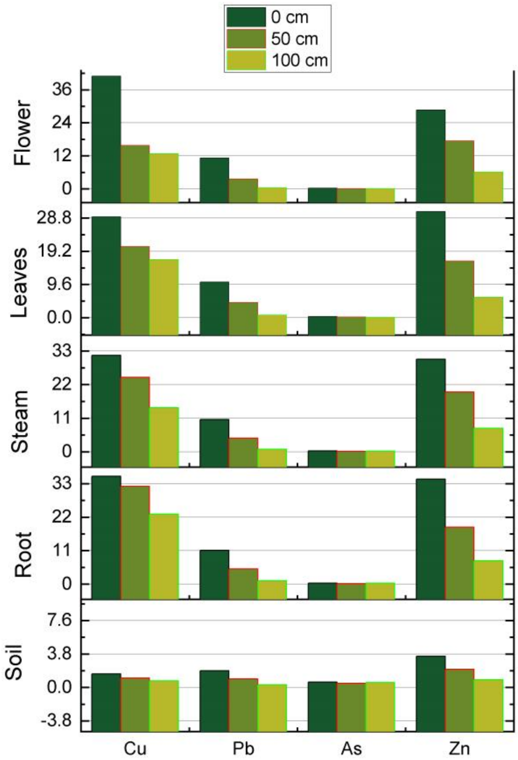

Figure 9. The enrichment coefficient of metals in Phragmites Australis (common reed) plant species for location of Siret River—Bridge Holt region.

In the case of the Siret River—UHE canal sampling point, the enrichment factor values (Figure 10) for soil were very low for all four metals analyzed (Cu, Pb, As, Zn), with values between 0.191 and 0.878.

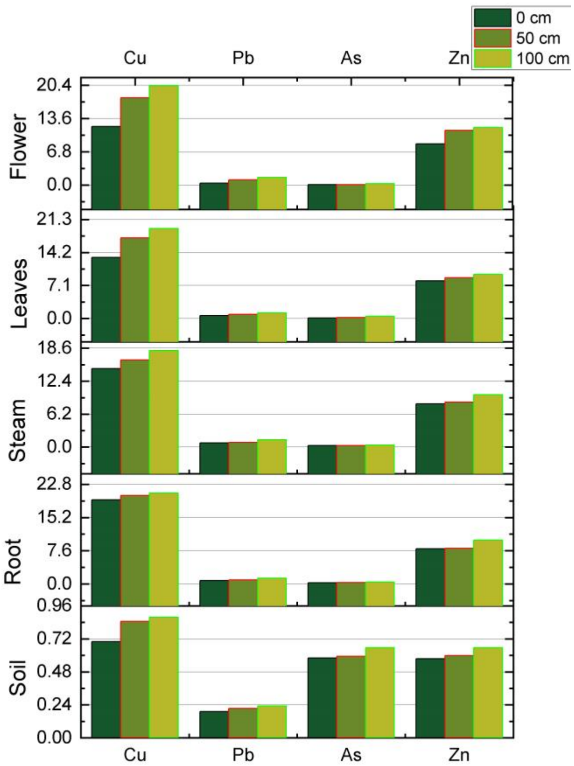

Figure 10. The enrichment coefficient of metals in Phragmites Australis (common reed) plant species, for location of Siret River—canal UHE.

In the case of the metal As, the enrichment coefficient values recorded for the sampling point Siret River—UHE canal were very low, below the value of one, both in soil and in all parts (root, stem, leaf, and flower) of the plant species Phragmites Australis—common reed (0.208–0.656).

For Pb metal, high enrichment coefficient values (sampling point Siret River—UHE canal) were recorded for the root of the plant species Phragmites Australis—common reed (1.336—100 cm level), stem (1.364—100 cm level), leaf (1.223—100 cm level), and flower (1.084—50 cm level and 1.557—100 cm level).

Zn enrichment factor values for the Siret River—UHE canal sampling point were very high for all parts of the plant species Phragmites Australis (common reed), with the highest value in the flower (11.788—100 cm level).

In the case of the Siret River—downstream confluence Bistrita/Siret sampling point, the enrichment factor values (Figure 11) for soil were very low for the metals Pb, As, and Zn, with values between 0.256 and 0.971. For the metal Cu, the enrichment factor values for soil were greater than one for the sampling levels 0 cm (1.029) and 50 cm (1.1) for the sampling point Siret River—downstream confluence Bistrita/Siret.

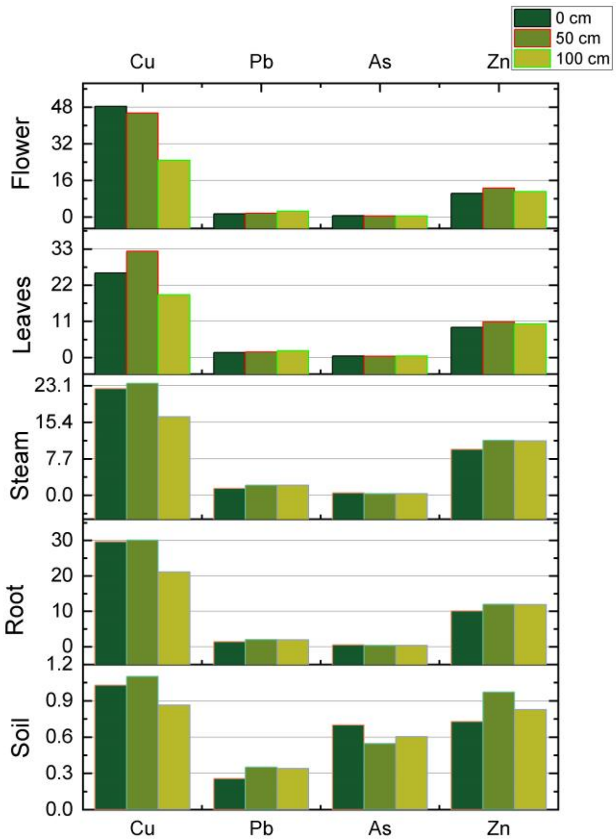

Figure 11. The enrichment coefficient of metals in Phragmites Australis (common reed) plant species for location of Siret River—downstream confluence Bistrita/Siret.

In the case of the metal As, the enrichment coefficient values recorded for the sampling point Siret River—downstream confluence Bistrita/Siret were very low, below the value of one both in the soil and in all parts (root, stem, leaf, and flower) of the plant species Phragmites Australis—common reed (0.334–0.575).

In the plant species Phragmites Australis (common reed) for the sampling point Siret River—downstream confluence Bistrita/Siret, the enrichment coefficient values recorded were very high for the metals Cu, Pb, and Zn, with the highest values being recorded for the metal Zn in the flower of the plant species Phragmites Australis—common reed (48.333—0 cm level).

5. Conclusions

This study shows the differences in accumulated/translocated heavy metals in Phragmites Australis (common reed) plant species at the slope maturity stage according to the three areas analyzed along the Siret River banks in the Siret hydrographic basin (Siret River—Bridge Holt region, Siret River—UHE canal, and Siret River—downstream confluence Bistrita/Siret).

The content of heavy metals in the soil at the three investigation sites varied significantly, indicating historical industrial pollution, especially for the metals Cu, Pb, and Zn, with the most polluted site being the Siret River—Bridge Holt region.

The transfer coefficient was quite variable depending on the concentration of the heavy metals analyzed and was generally higher from the sediment to the plant root, with the order of the average transfer coefficient values being Cu > Zn > Pb > As for all three areas analyzed.

The translocation of heavy metals from the root of the plant species Phragmites Australis (common reed) to the upper aerial part of the plant was of the form As > Pb > Zn > Cu.

The enrichment/accumulation factor of heavy metals varied greatly, showing a high accumulation of Cu, Pb, and Zn in the plant species Phragmites Australis (common reed), with the highest heavy metal enrichment recorded in the plant flower.

The values obtained for the three coefficients (transfer coefficient, translocation factor, and enrichment factor) indicate that the plant species Phragmites Australis (common reed) can be used in phytoremediation processes, i.e., for phytostabilization of heavy metals, phytoextraction (continuous or induced) of heavy metals from soil, and their rhizodegradation, for areas polluted with heavy metals (especially Cu, Pb, Zn, and As).

The theoretical studies and experimental results of this work can provide useful material for the optimization of soil remediation processes (very complex processes) and the optimization of phytoremediation of polluted soils.

In the future, it should be taken into account how many generations of plants have developed in the studied area; the other plants developed in the analyzed areas; the soil pH; organic matter in the soil; physical, chemical, and biological properties of the soil; meteorological factors, i.e., for a higher accuracy of the experimental data and for a clarification of all correlations that exist between soil pollution with heavy metals and the accumulation/bioaccumulation capacity of heavy metals in plants.

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