JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2024, 25(11), 306–316
https://doi.org/10.12911/22998993/193408
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.09.05
Accepted: 2024.09.23
Published: 2024.10.01

Accumulation of Macronutrients and Trace Elements in Leaves and Stems of *Reynoutria japonica* and *Reynoutria sachalinensis*

Agnieszka Edyta Parzych[1*], Zbigniew Sobisz[2]

[1] Institute of Geography, Department of Environmental Chemistry and Toxicology, Pomeranian University in Słupsk, ul. Arciszewskiego 22b, 76-200 Słupsk, Poland

[2] Department of Botany and Nature Protection, Institute of Biology, Pomeranian University in Słupsk, 22b ul. Arciszewskiego, 76-200 Słupsk, Poland

* Corresponding author's e-mail: agnieszka.parzych@upsl.edu.pl

ABSTRACT

Knotweeds, *Reynoutria japonica* (RJ) and *R. sachalinensis* (RS) are invasive species that strongly interfere with the soil environment and disrupt the biogeochemical cycles of many chemical elements. This paper analyses the content of C, N, P, K, Na, Mg, Ca, Al, Fe, Mn, Zn, Ni, Cu, Cd, Cr and Pb in the above-ground biomass of RJ and RS and in the soil (0–15 cm) in order to assess the accumulation properties of knotweed. Studies conducted in northern Poland showed statistically significant ($p<0.05$) differences in the content of Na in the soil of the studied knotweed. The elemental composition of the leaves and stems showed a good supply of macronutrients and increased concentrations of some trace elements. The leaves of RJ and RS were shown to be good bioaccumulators of N, K, Na, Mg, Ca, P, Mn, Zn, Ni, Cu and Cd, and the stems of N, K, Na, Ca, Ni, Cd, Cr and Pb. Based on the values of bioconcentration factors (BCF), the similarity between the studied knotweeds concerning Mn, Cu and Cr in the leaf/soil relation and Al, Fe, Cu, Cd, Cr and Pb in the stem/soil relation was demonstrated. The highest mobility from stems to leaves expressed by the translocation factor (TF) was exhibited by Mn and Mg, and the lowest by Cr. Despite the low content in the soil, RJ and RS leaves and stems accumulated significant amounts of trace elements, which indicates their phytoextractive properties.

Keywords: invasive species, soil pollution index, bioconcentration factor, translocation factor, phytoextraction, principal component analysis.

INTRODUCTION

Saline and contaminated with heavy metals urban areas hinder the functioning of native plant species. This creates an opportunity for invasive species [Tokarska-Guzik et al., 2006], to enter as they are characterized by high tolerance to anthropogenic factors and quickly adapt to changing environmental conditions [Rahmanov et al., 2019]. As a result of effective competition, local species are displaced from the environment by invasive species [Vichotová and Šerá, 2008].

Reynoutria japonica (RJ) and *R. sachalinensis* (RS) are considered invasive species in most countries of the central part of the European Union. Both species prefer heavily transformed anthropogenic habitats [Mandák et al., 2004]. In the urban areas, they inhabit ruderal places (roadsides, rubble, landfills, parks, cemeteries), as well as suburban meadows and river valleys [Tokarska-Guzik et al., 2006]. They are often found in areas with high levels of heavy metals in the soil [Hulina and Dumija 1999], (e.g. roadsides of communication routes, post-industrial areas) and with a high content of sulphur compounds. They perform well on soils with varying pH [Rahmanov et al., 2019]. They tolerate well high temperatures, drought, salinity and periodic water discharges. Due to the abundant production of biomass, these species enrich the soil annually with organic matter, modify the pH and other physicochemical properties of the soil [Dassonville et al., 2007; Rahmanov et al., 2014, 2019; Stefanowicz et al. 2018], transforming it for their own benefit [Lavoie 2017]. Strong interference of knotweed in the soil environment disrupts the biogeochemical cycles of elements [Ehrenfeld 2003]. Due to the rapid spread and awareness of the threat to native species, the interest of scientists taking actions to develop effective methods of removing knotweeds from the environment has significantly increased [Murrell et al., 2011; Michelot-Antalik et al., 2016]. Research is also carried out on the use of their biomass as a component of compost [Cvejič et al., 2021] and an additive supporting soil reclamation processes [Bradley et al., 2010].

Current knowledge about the accumulation properties of knotweed is not sufficient, which is why research has been undertaken to explain them. The aim of the study was: (1) to characterize and compare the accumulation properties of leaves and stems of *R. japonica* and *R. sachalinensis* in relation to macronutrients and trace elements, (2) to determine and compare the physicochemical properties of soil from the knotweeds' rhizosphere (3) and to determine the factor loads typical of RJ and RS accumulation properties.

MATERIALS AND METHODS

Study area

The research was conducted in northern Poland, in 16 localities, which according to physical and geographical regionalization [Solon et al., 2018] are located within three mesoregions: the Słupsk Plain (Kobylnica, Masłowice, Możdżanowo, Postomino, Reblino, Słupsk, Widzino, Włynkówko), the Koszalin Coast (Duninowo, Gąbino, Ustka) and the Damnica Upland (Damnica, Głobino, Jezierzyce, Objazda, Osieki Słupskie). According to the division of ATPOL code numbers, knotweed stations fit into BA and CA squares. The researched *R. japonica* and *R. sachalinensis* were located in parks and gardens (8), roadsides (3), cemeteries (3), railway embankments (2), wastelands and meadows (2) and others (2), (Table 1).

The area covered by the research is influenced by weather conditions shaped by the vicinity of the Baltic Sea. It features characteristic delay of the seasons and a relatively heavy and variable cloud cover. The average annual rainfall remains

Table 1. Location and use of the land of *R. japonica* and *R. sachalinensis*

Location	Geographical coordinates	ATPOL squares	Use of the land
R. japonica			
Damnica	17.2730, 54.5017	CA 6197	Manor park
Duninowo	16.8220, 54.5410	BA 6848	Manor park
Gąbino	17.0967, 54.6007	CA 5087	Manor park
Głobino	17.1003, 54.4418	CA 7056	Roadside
Jezierzyce	17.1103, 54.4956	CA 6097	Manor park
Masłowice	16.6148, 54.4725	BA 7715	Closed gravel pit
Postomino	16.7192, 54.4985	BA 6882	Municipal cemetery
Reblino	16.9146, 54.4296	BA 7964	Railway embankment
Słupsk	17.0408, 54.4700	CA 7022	Municipal cemetery Kaszubska St.
Widzino	16.9613, 54.4245	BA 7977	Meadow by the Kamieniec river
R. sachalinensis			
Damnica	17.2730, 54.5017	CA 6197	Roadside
Kobylnica	16.9948, 54.4406	BA 7959	Rural park Nad Śluzą St.
Możdżanowo	16.7835, 54.5003	BA 6886	Closed amber mine
Objazda	17.0486, 54.6032	CA 5073	Roadside
Osieki Słupskie	17.0900, 54.6053	CA 5076	Manor park
Reblino	16.9119, 54.4284	BA 7974	Manor park
Słupsk	16.9995, 54.4744	CA 7022	Allotment garden 3 Maja St.
Ustka	16.8688, 54.5720	BA 6901	Railway siding
Widzino	17.0021, 54.4327	CA 7060	Protestant cemetery
Włynkówko	16.9937, 54.5072	BA 6989	Wasteland

at 600 mm and the average annual air temperature is +7°C. Southwest and west winds prevail [Kirschenstein and Baranowski, 2008].

Sampling and physicochemical analyses of soil

The research was carried out in summer (in July). In order to implement the research assumptions, 10 sites of *R. japonica* and 10 sites of *R. sachalinensis* located in 16 localities were selected (Table 1). Under the crowns of knotweed, at each site, 6 soil samples were taken separately from a depth of 0–15 cm, and then combined into one mixed sample, representative for a given site. In total, 10 soil samples from the RJ and RS rhizospheres were used for physicochemical research. In the laboratory, the samples were dried at 65 °C, ground in a mortar, sieved through a sieve (1 mm). In the soil samples, the pH in an aqueous solution in a weight ratio of 1:2.5 was determined using the potentiometric method (pH-metr CPI 551, Elmetron) and the content of organic matter with the incandescent loss method in a muffle furnace (FCF 7SP, Czylok), at a temperature of 550 °C. The content of C and N was determined on the CHNS analyzer (Flash Smart, ThermoScientific), using methionine as the standard and reference material (Certificate number analysis – 291468, ThermoScientific). In order to determine the content of metallic elements and phosphorus, soil samples weighing 0.5 g were digested in a mixture of 65% HNO_3 and 30% H_2O_2 in a microwave oven at 200 °C (ETHOS EASY, Milestone connect), and then filtered and made up with deionized water to a volume of 25 ml. In the obtained solutions, the P content was determined by using the spectrophotometric method with ammonium molybdate (UV-VIS, Hitachi U-5100), and the K, Na, Mg, Ca, Al, Fe, Mn, Zn, Ni, Cu, Cd, Cr and Pb content was determined using the inductively coupled plasma optical emission spectrometer (Agilent, 5100 ICP-OES). Fluka standards (1g/1000 ml) were used to calibrate the apparatus. The analyses were performed in three repetitions.

Sampling and chemical analyses of the plant samples

The leaves and shoots of knotweed were sampled in accordance with the methodology described by MacNaeidhe [1995] from 10 sites of *R. japonica* and 10 sites of *R. sachalinensis.* After drying at 65 °C, the plant samples were homogenized in a laboratory grinder (IKA A11, basic). In solid samples, the content of C and N (CHNS Elementary Analyzer, Flash Smart, ThermoScientific) was determined. In the remaining tests of plant material, the same laboratory techniques were used as in the case of soil. In liquid samples, after digestion (0.5 g) of leaves and (0.5g) of stems in a mixture of 65% HNO_3 and 30% H_2O_2 and making up the solutions to a volume of 50 ml, the P content was determined by using the molybdate method (UV-VIS, Hitachi U-5100, Japan), and the content of metallic elements (K, Na, Mg, Ca, Al, Fe, Mn, Zn, Ni, Cu, Cd, Cr, Pb) by the inductively coupled plasma optical emission spectrometer (Agilent, 5100 ICP-OES).

Data analysis

The normality of the database distribution regarding the physicochemical properties of soil and chemical composition of leaves and stems of *R. japonica* and *R. sachalinensis* was investigated using the Shapiro Wilk test. A soil pollution index (SPI) was calculated for 20 sites (10 from rhizosphere of RJ and 10 from rhizosphere of RS) according to the equation (1) [Diatta et al., 2003]. The calculations used the limited values of trace elements published in the Regulation of the Minister of the Environment [2016]: Zn (300 mg·kg^{-1}), Cu (100 mg·kg^{-1}), Ni (100 mg·kg^{-1}), Cd (2 mg·kg^{-1}), Cr (150 mg·kg^{-1}) and Pb (100 mg·kg^{-1}).

$$SPI = \left(\frac{1}{n}\right) \sum_{i=1}^{n} 100\ \frac{VS}{LS} \tag{1}$$

where: n – number of elements determined, VS – element content in the soil, mg·kg^{-1}, LS – permissible content of the element in the soil, mg·kg^{-1}

The degree of soil contamination was interpreted based on the ranges of SPI values contained in Table 2. The physicochemical properties of the soil and the content of the analysed elements in the leaves and stems of RJ and RS were compared using the non-parametric Kruskal-Wallis test at $p<0.05$. The mutual relations between the content of macronutrients and trace elements in leaves, stems and soil are presented in the form of bioconcentration factors (BCF), (2):

$$BCF = \frac{C_{leaves\ (stems)}}{C_{soil}} \tag{2}$$

where: $C_{leaves\ (stems)}$, $C_{leaves(shoots)}$ – element content in leaves (stems), mg·kg^{-1}, C_{soil} – element content in soil, mg·kg^{-1}

Table 2. Soil pollution index (SPI) values and their interpretation

SPI	Degree of contamination
< 1	Low contamination
1 ≤ SPI < 3	The moderate contamination
3 ≤ SPI ≤ 6	High contamination
SPI > 6	Severe contamination of soil

The transport efficiency of a given nutrient from the stems to the leaves is expressed in the form of a translocation factor (TF):

$$TF = \frac{C_{leaves}}{C_{stems}} \quad (3)$$

Factor analysis (FA) with principal component analysis (PCA) was used to develop the test results in order to reduce the number of variables and find close relationships between the analysed parameters. The PCA results were obtained using a standardized varimax rotation algorithm. The applied rotation simplified the structures of the isolated factors, facilitating their interpretation. Two independent factors (FC1, FC2) explaining, respectively, 62% and 69% of the variability of the analysed macronutrients and trace elements in the leaves and stems of RJ and RS, were separated. Factor loads with values higher than 0.7 were used for interpretation. The mutual distribution of factor loads FC1 vs FC2 is presented in the form of categorized scatter plots, for each species separately. Calculations and figures were made using the Statistica program, version 13.3.

RESULTS

Physicochemical properties of soil

The soil samples from the RJ rhizosphere showed an acidic reaction (pH = 4.40–6.55), and in the case of MS, an acidic and neutral reaction (pH = 4.15–7.10). They were characterized by a low content of organic matter, from 2.42 to 9.52% in soil samples under RJ and from 2.85 to 10.36% in the RS rhizosphere, respectively, (Table 3). The content of macronutrients and trace elements in the soil varied both between the sites and the knotweed species. This is evidenced by the values of coefficients of variation from 7% (Cd) to 58% (Zn) in the RJ rhizosphere and from 4% (Cd) to 47% (Mg, Zn) in the case of RS. The soil under the RJ was richer in magnesium, aluminium, iron, manganese, nickel, copper and lead, and in the RS rhizosphere in nitrogen, potassium, sodium, calcium, phosphorus, zinc and chromium. The content of macronutrients and trace elements in the soil decreased according to the scheme: in the rhizosphere of *R. japonica*: Fe>N>Al>Ca>Mg>P>Na>K>Mn>Zn>Ni>Cu>Pb>Cr>Cd and Fe>N>Ca>Al>Na>Mg>P>K>Mn>Zn>Ni>Cu>Pb>Cr>Cd in the rhizosphere of *R. sachalinensis.* Statistically significant differences ($p<0.05$) between the physicochemical properties of the soil in the RJ and RS rhizospheres were demonstrated in the case of Na. The quality of the analysed soil due to the content of trace elements was assessed based on the average value of the SPI index, which remained at the level from 1.988 at RJ sites to 1.986 in the case of RS (Table 3).

Chemical composition of knotweeds tissues

The content of nutrients in RJ and RS leaves and shoots varied depending on the species (Tab. 4), the sampling site and the physicochemical properties of the soil (Table 3), and especially on the mobility and bioavailability of macronutrients and trace elements. The elemental composition of the examined above-ground biomass indicates a good supply of macronutrients to the leaves and stems and an increased content of trace elements. In the RJ leaves, the share of the analysed elements varied according to the decreasing series: C>Ca>N>K>Mg>Na>P>Al>Mn>Fe>Zn>Ni>Cu>Pb>Cr>Cd, and in the RS leaves: C>Ca>N>K>Mg>Na>P>Fe>Al>Mn>Zn>Ni>Cu>Pb>Cr>Cd w RS. In the stems, the content of macronutrients and trace elements varied according to the scheme: C>Ca>N>K>Mg>Na>P>Fe>Al>Zn>Ni>Cu>Pb>Cr>Cd in RJ and

C>Ca>K>N>Na>P>Mg>Fe>Zn>Al>Ni>Cu>Cr>Pb>Cd in the case of RS (Table 4). Among the analyzed components, the greatest variation expressed by the coefficient of variation (cv) characterized Mn (90%) and Al (79%) in RJ and Na (85%) and Ca (80%) in the case of MS. Most of the analyzed elements were accumulated in greater quantities in the leaves than in the stems, with the exception of Cr and Pb. Statistically significant differences regarding the accumulated elements in the biomass of the tested knotweeds were shown in the case of Na and Al (in leaves) and N, Ca and Pb (in stems) (Table 4).

Using bioconcentration factors (BCF), the accumulation capacity of leaves and stems of RJ and RS was characterized in relation to the analyzed

Table 3. Physicochemical properties of soil from rhizosphere of RJ and RS (mean ± sd (cv)) with Kruskal-Wallis (K-W) test results and soil pollution index (SPI)

Parameter		*R. japonica* (*n*=30)	*R. sachalinensis* (*n*=30)	K-W	
		mean ± sd (cv)		H	p
pH		5.81* ± 0.7 (12)	6.14* ± 0.8 (13)	1.1208	0.289
OM, %		6.04 ± 1.9 (31)	6.90 ± 2.4 (35)	1.1200	0.289
N, %		0.09 ± 0.01 (11)	0.11 ± 0.01 (9)	1.0121	0.332
K	$mg \cdot kg^{-1}$	870.3 ± 349 (40)	941.0 ± 375.8 (40)	0.0862	0.772
Na		3862.1 ± 1253 (32)	4853.6 ± 696.8 (14)	4.7803	**0.042**
Mg		4038.2 ± 1821 (45)	3523.4 ± 1653.5 (47)	0.3926	0.539
Ca		6569.6 ± 3593 (55)	8617.2 ± 2934.0 (34)	1.4772	0.239
P		2497.5 ± 706 (28)	2745.2 ± 705.9 (26)	0.6151	0.443
Al		6710.1 ± 1834 (27)	6347.4 ± 2465.7 (39)	0.1082	0.746
Fe		48072.8 ± 12709 (26)	45218.6 ±13858.8 (31)	0.1696	0.685
Mn		544.9 ± 231 (42)	368.2 ± 159.2 (43)	3.9586	0.062
Zn		308.3 ± 179 (58)	341.1 ± 160.8 (47)	0.1484	0.705
Ni		32.3 ± 9 (28)	25.1 ± 5.0 (20)	0.1101	0.744
Cu		25.7 ± 8 (31)	22.4 ± 6.1 (27)	0.3512	0.561
Cd		0.6 ± 0.0 (7)	0.6 ± 0.0 (4)	0.3188	0.579
Cr		4.8 ± 0.7 (15)	5.1 ± 0.9 (18)	0.6484	0.431
Pb		5.9 ± 0.9 (15)	5.6 ± 0.8 (14)	0.3417	0.566
SPI		1.988	1.986	–	–

Note: *pH = -log[H^+], OM – organic matter, sd – standard deviation, cv – coefficient of variation (%), bold values – statistically significant, SPI values calculated based on Zn, Ni, Cu, Cd, Cr and Pb content in soil.

nutrients (Table 5). The highest BCF values related to the macronutrients N, K, Ca, Mg and Na, while the smallest to the trace elements of Fe and Al. The calculated BCF values showed similarity of the studied species in the case of Mn, Cu and Cr in the leaves/soil relationship and Al, Fe, Cu, Cd, Cr and Pb in the stems/soil relationship. The greatest mobility from stems to leaves expressed by the translocation factor (TF) was demonstrated by Mn (11.63 and 13.01) and Mg (7.87 and 9.25) in RJ and RS, respectively. The smallest mobility characterised chromium, with TF values of 0.82 for RJ and 0.98 for RS.

Principal component analysis

Using the principal component analysis (PCA) method, two main components characterizing the chemical composition of the soil, leaves and stems of knotweed, explaining in total from 62% (RJ) to 69% (RS*)* of the chemical composition variance, were distinguished, (Table 6). In the case of *R. japonica*, the first factors (*FC1*), explained 47% of the variance and grouped N, K, Mg, Ca, P, Al, Fe, Mn, Zn and Cu, characterized by high, positive values of factor loads. The second factor (*FC2*) explained 15% of the variation and was formed by directly proportionally correlated Cr and Pb. These elements were characterized by high, positive values of factor loads. In the case of *R. sachalinensis*, the first factor (*FC1*) explained 53% of the variance and grouped K, Na, Mg, Ca, Al, Fe, Mn, Zn and Cu, also characterized by high, positive values of factor loads. Unlike RJ, this factor was created with the participation of Na. The second factor (*FC2*) explained 16% of the variation and was formed by Pb, having a high, negative factor load value (Table 6). The mutual relations between factor loads *FC1* and *FC2* for the tested knotweed are presented in the form of categorized scatter diagrams (Figure 1).

DISCUSSION

Physicochemical properties of soil

R. japonica and *R. sachalinensis* from 16 localities in northern Poland, occurred on soils with different pH (4.15–7.10), which is confirmed by the research results of other authors [Rahmanov et al., 2019]. A similar pH range of soil samples

Table 4. Elements content (mg·kg^{-1}) in leaves and stems of knotweeds

Parameter	Tissue type	*R. japonica*	*R. sachalinensis*
		mean ± sd (cv, %)	
C	leaves	426258.0 ± 4475 (3)[a]	430060.0 ± 5379 (1)[a]
	stems	422109.0 ± 12357 (3)[a]	425626.0 ± 6825 (2)[a]
N	leaves	31113.5 ± 3810 (12)[a]	29649.0 ± 4684 (16)[a]
	stems	16782.0 ± 1688 (10)[a]	9317.0 ± 1150 (12)[b]
K	leaves	16678.3 ± 3295 (20)[a]	22949.7 ± 15419 (67)[a]
	stems	14248.7 ± 3940 (28)[a]	13127.1 ± 3272 (25)[a]
Na	leaves	9576.6 ± 749 (8)[a]	12543.1 ± 690 (85)[b]
	stems	9865.9 ± 2953 (30)[a]	8850.6 ± 655 (7)[a]
Mg	leaves	10720.1 ± 3922 (37)[a]	13027.8 ± 8454 (65)[a]
	stems	1360.7 ± 471 (35)[a]	1408.8 ± 338 (24)[a]
Ca	leaves	35322.9 ± 8218 (23)[a]	41987.0 ± 33599 (80)[b]
	stems	17552.8 ± 3074 (18)[a]	21794.5 ± 3879 (18)[b]
P	leaves	2624.5 ± 555 (21)[a]	2768.2 ± 483 (18)[a]
	stems	2072.7 ± 641 (31)[a]	1881.6 ± 595 (32)[a]
Al	leaves	1335.9 ± 754 (79)[a]	561.7 ± 263 (65)[b]
	stems	171.5 ± 90 (52)[a]	131.5 ± 93 (71)[a]
Fe	leaves	580.0 ± 229 (40)[a]	649.6 ± 379 (59)[a]
	stems	245.4 ± 47 (19)[a]	225.0 ± 31 (14)[a]
Mn	leaves	651.5 ± 502 (88)[a]	535.9 ± 395 (74)[a]
	stems	56.0 ± 48 (90)[a]	41.2 ± 17 (41)[a]
Zn	leaves	277.3 ± 87 (32)[a]	383.9 ± 250 (65)[a]
	stems	155.3 ± 56 (36)[a]	163.0 ± 89 (54)[a]
Ni	leaves	39.2 ± 12 (30)[a]	34.1 ± 13 (37)[a]
	stems	39.7 ± 19 (48)[a]	32.2 ± 15 (46)[a]
Cu	leaves	21.8 ± 3 (16)[a]	24.1 ± 16 (67)[a]
	stems	15.8 ± 5 (33)[a]	13.6 ± 3 (22)[a]
Cd	leaves	1.0 ± 0.1 (8)[a]	0.9 ± 0.2 (25)[a]
	stems	1.0 ± 0.0 (4)[a]	0.9 ± 0.3 (36)[a]
Cr	leaves	4.1 ± 0.1 (2)[a]	4.5 ± 0.2 (3)[a]
	stems	5.0 ± 0.9 (18)[a]	4.6 ± 0.1 (2)[a]
Pb	leaves	5.9 ± 0.7 (12)[a]	4.8 ± 1.5 (32)[a]
	stems	6.0 ± 0.4 (7)[a]	3.9 ± 0.6 (16)[b]

Note: the same letter in superscript means no significant difference according to the Kruskal-Wallis test, sd – standard deviation, cv – coefficient of variation (%).

in the RJ rhizosphere was demonstrated by Rahmanov et al. [2014] and Barney et al. [2006], (4.0–7.7 and 4.5–7.4, respectively). The highest pH values of soil samples were recorded in the city of Słupsk and its immediate vicinity, which is the result of dust-fall, coming mainly from the combustion of hard coal and road traffic. The neutral reaction of the surface soil layer in Słupsk was also demonstrated in other studies [Parzych and Jonczak, 2014]. The varied content of the analyzed nutrients in soil samples resulted mainly from the location of the test sites (Table 1, 2). Statistically significant differences concerned sodium (Na). Most of the RS sites were located closer to the Baltic Sea and were under its stronger influence than in the case of RJ. Sodium is part of NaCl, which is the main component of marine aerosols [Lewandowska and Falkowska, 2013]. The marine aerosol of the Baltic Sea forms by the release of sodium chloride molecules and other minerals from seawater as a result of its crashing on the shore, the friction of the wind on the surface of the water and the floating of water molecules in the evaporation process. The impact of marine

Table 5. Bioconcentration factors (BCF) and translocation factors (TF) values in leaves and stems of knotweeds

Elements	*R. japonica*			*R. sachalinensis*		
	BCF		TF	BCF		TF
	leaves/soil	stems/soil	leaves/stems	leaves/soil	stems /soil	leaves/stems
N	34.79 ± 12.2	18.65± 9.5	1.86	26.95 ± 15.3	8.47± 11.4	3.18
K	22.08 ± 9.0	18.01± 5.3	1.17	39.43 ± 36.6	31.23±41.8	1.75
Na	2.77 ± 1.0	2.72 ± 0.8	0.97	2.67 ± 2.4	2.07 ± 0.7	1.42
Mg	3.16 ± 1.7	0.39 ± 0.2	7.87	4.18 ± 2.7	0.48 ± 0.3	9.25
Ca	7.27 ± 4.5	3.53 ± 2.1	2.01	6.37 ± 5.7	2.67 ± 1.8	1.93
P	1.15 ± 0.5	0.90 ± 0.4	1.27	1.36 ± 1.1	0.83 ± 0.4	1.47
Al	0.20 ± 0.2	0.03 ± 0.0	7.79	0.10 ± 0.1	0.03 ± 0.0	4.27
Fe	0.01 ± 0.0	0.01 ± 0.0	2.36	0.02 ± 0.0	0.01 ± 0.0	2.89
Mn	1.57 ± 2.4	0.12 ± 0.1	11.63	1.52 ± 1.2	0.20 ± 0.2	13.01
Zn	1.18 ± 0.8	0.64 ± 0.4	1.78	1.34 ± 1.1	0.56 ± 0.2	2.36
Ni	1.27 ± 0.3	1.36 ± 1.0	0.99	1.45 ± 0.8	1.50 ± 0.8	1.06
Cu	1.14 ± 0.6	0.78 ± 0.4	1.38	1.09 ± 0.6	0.82 ± 0.6	1.77
Cd	1.66 ± 0.2	1.72 ± 0.1	1.00	1.52 ± 0.4	1.74 ± 0.1	1.00
Cr	1.00 ± 0.2	1.06 ± 0.2	0.82	0.92 ± 0.1	1.01 ± 0.2	0.98
Pb	1.01 ± 0.2	1.04 ± 0.2	0.98	0.88 ± 0.4	1.10 ± 0.2	1.23

Table 6. Factor loading obtained from the PCA method after normalized varimax rotation on the basis of the macro- and trace elements in soil and knotweeds tissues

Elements	*R. japonica*		*R. sachalinensis*	
	FC 1 Nutrients	FC 2 Toxic elements	FC 1 Nutrients	FC 2 Toxic elements
N	**0.89**	-0.16	0.61	-0.47
K	**0.70**	-0.16	**0.90**	0.28
Na	0.00	0.41	**0.79**	0.36
Mg	**0.91**	-0.06	**0.97**	0.04
Ca	**0.84**	-0.14	**0.91**	0.30
P	**0.75**	-0.23	0.67	-0.15
Al	**0.85**	-0.02	**0.85**	-0,09
Fe	**0.86**	0.03	**0.90**	-0.05
Mn	**0.75**	0.09	**0.80**	-0.15
Zn	**0.90**	-0.15	**0.89**	0.13
Ni	0.02	0.63	-0.00	-0.62
Cu	**0.81**	0.27	**0.91**	0.30
Cd	-0.22	0.64	0.33	0.55
Cr	-0.03	**0.74**	-0.07	-0.58
Pb	-0.04	**0.70**	0.12	**-0.81**
Eigen values	6.90	2.24	7.95	2.35
Explained variance [%]	0.47	0.15	0.53	0.16
	62%		69%	

Note: factor loading >0.7 are in bold.

aerosols was also observed in studies on the content of macro- and micronutrients in lichen thalli collected in the vicinity of the Baltic Sea [Parzych et al., 2016]. The results of the analysis of soil samples from the RJ and RS rhizospheres expressed in the form of the SPI index indicate its moderate contamination (Table 2, 3), which results from low industrial and economic activity

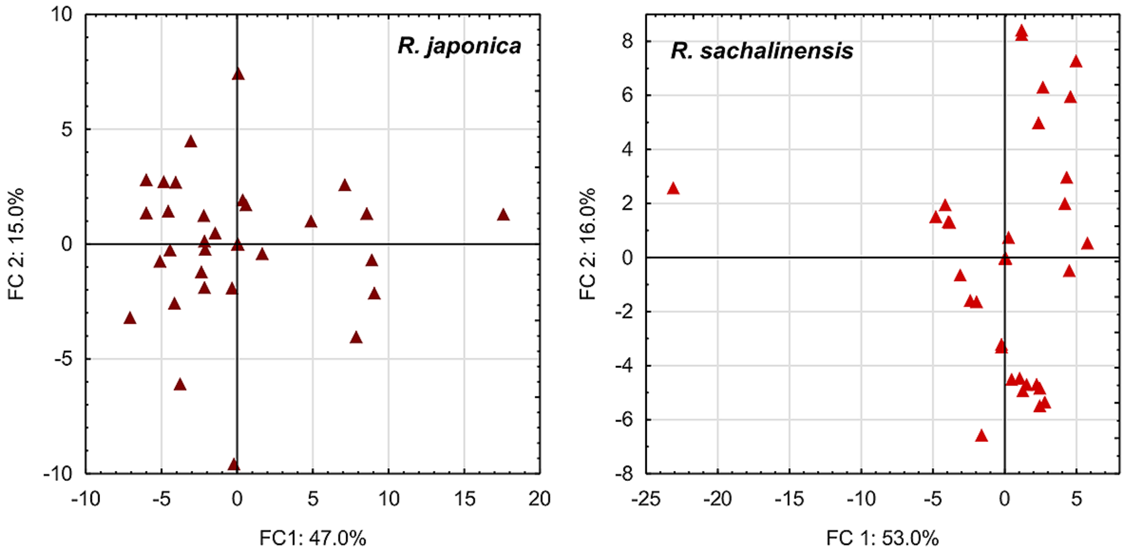

Figure. 1. Projection of variables onto the factor plane (*FC1* vs *FC2*)

in the area covered by the research. The SPI index is used in international research to assess the quality of soil, because it is based on the analysis of the content of many toxic metals [Diatta et al., 2003, Mihali et al., 2017, Zaakour et al., 2023]. Much higher content of trace elements in the RJ rhizosphere in southern Poland was demonstrated by Rahmanov et al. [2014, 2019].

Chemical composition of knotweeds tissues

Scientific research indicates that plants uptake nutrients from the surrounding environment in a selective way [Wierzbicka, 2015]. The amount of macronutrients and trace elements taken is strictly dependent on the physiological demand of a given species and variable during the growing season [Parzych et al., 2018]. The content, bioavailability and mobility of nutrients in the soil play an important role in plant nutrition. The bioavailability of many components depends on soil pH [Kabata-Pendias and Pendias, 1999]. Most macronutrients, i.e. nitrogen, phosphorus, potassium, sodium, magnesium and calcium, are present in forms bioavailable to plants at soil pH from 6.0 to 8.0 (8.5). On the other hand, the assimilation of trace elements increases with higher soil acidity. The largest amounts of Cu, Ni, Zn, Mn and Fe, as well as toxic elements, i.e. Cd, Cr or Pb are taken by plants at pH 4.0–5.5, and Mn also at pH~8 [Kabata-Pendias and Pendias, 1999]. According to Ostrowska and Porębska [2002] the results we obtained indicate a very good supply of macronutrients to RJ and RS leaves and stems. Lower Mg and Ca contents in RJ leaves were obtained by Dassonville et al. [2007], Sołtysiak et al. [2011] and Rahmanov et al. [2014]. The conducted research showed an increased content of some trace elements (Zn>100 $mg·kg^{-1}$, Mn>500 $mg·kg^{-1}$, Ni>10 $mg·kg^{-1}$, Cr>2 $mg·kg^{-1}$, [Kabata-Pendias and Pendias, 1999]) in the leaves in relation to other plant species as well as Zn, Ni and Cr in the stems of RJ and RS. However, no signs of toxicity were observed on the leaves or stems of knotweed, which indicates significant tolerance of RJ and RS to toxic metals accumulated in above-ground biomass. Similar Zn and Ni contents in RJ leaves were obtained by Lerch et al. [2022].

In the case of the analyzed knotweeds, statistically significant differences in the content of Na and Al in the leaves were demonstrated. The relatively close location of the RS test sites in relation to the Baltic Sea [Lewandowska and Falkowska, 2013] was related to the increased content of Na in the soil and leaves of the RS compared to the RJ sites located slightly further from the Baltic coastline. At the same time, the lower pH of soil samples in the RJ rhizosphere affected greater mobility and contributed to twice the Al content in RJ leaves, compared to RS. The solubility of aluminium compounds, and thus their bioavailability to plants, is greatest at pH<4.7 and pH>8. In soils with a pH in the range of 6–8, aluminium occurs in the form of poorly soluble compounds, not participating in biochemical cycles [Widłak, 2011]. According to Norouzi et al. [2015] and Shi et al. [2017], plants with abundant aboveground biomass effectively filter the air, trapping dust and absorbing some ingredients through the leaves. The uptake of such elements as Fe, Mn, Cu or Zn, in small quantities, stimulates the course of metabolic processes, while taken in excessive amounts can be harmful to both plants and animals.

It was assumed that if the values of bioconcentration factors (BCF) are greater than 1, then plants are good bioaccumulators of such components [Parihar et al., 2021]. Accordingly, it should be assumed that RJ and RS leaves are good bioaccumulators of N, K, Na, Mg, Ca, P, Mn, Zn, Ni, Cu and Cd. A slightly different situation applies to the stems of the tested knotweed, in which BCF>1 was demonstrated in the case of N, K, Na, Ca, Ni, Cd, Cr and Pb (Tab. 5), which is reflected in the research of Vidican et al. [2023]. Our research results indicate that despite moderate soil contamination with trace elements (Table 3), significant amounts of these elements were accumulated in both leaves and stems of RJ and RS, which confirms the phytoextractive properties of the tested knotweeds in relation to these components. This information is important due to the utilization of their biomass. High values of the bioconcentration factor (BCF>1) for macronutrients indicate that RJ and RS biomass may be an important additive, enriching compost. However, BCF values show variability during the growing season [Parzych et al. 2017]. This is related to the pH-dependent bioavailability of nutrients from soil and groundwater [Kabata-Pendias and Pendias, 1999, Parzych, 2011]. The proximity of urban agglomerations and the associated alkalinization of soils usually limits the uptake of nutrients by plants, and thus reduces BCF values. In the case of increased content of trace elements in leaves and stems, the ecotoxicological impact of biomass should be assessed before its further use. Similar BCF values for Zn and Cd in knotweed shoots were shown by Michalet et al. [2017] and Parihar et al. [2021]. TF values >1 indicate that N, K, Mg, Ca, P, Al, Fe, Mn, Zn and Cu are transported from the stems to the leaves of RJ, and in the case of RS it applies also to Na and Pb.

The main components extracted with PCA explained 62% to 69% of the variance in the chemical composition of RJ and RS leaves and stems. FC1 factors concerned the accumulation of nutrients, and FC2 the accumulation of toxic elements. The participation of Na in the creation of FC1 of R. sachalinensis, unlike R. japonica, resulted from the stronger impact of marine aerosol [Lewandowska and Falkowska, 2013] on research sites located in close proximity to the Baltic Sea. FC2 factors were formed by toxic metals (Cr and Pb and Pb, respectively). The sequence of identified factors emphasizes the dominant function of macro- and micronutrients in the formation of the chemical composition of aboveground biomass of plants [Ostrowska and Porębska, 2002]. A significant dispersion of points (Figure 1) in both species of knotweed is the result of the influence of local factors on the accumulation properties of RJ and RS. The lower pH of the soil in the RJ rhizosphere, compared to the RS sites, favoured greater accumulation of Cr and Pb, which is reflected in the components of the FC2 factor.

CONCLUSIONS

Studies conducted in northern Poland showed that RJ and RS occurred on both acidic and inert soils (4.15–7.10). Statistically significant ($p<0.05$) differences in the content of Na in soil samples in their rhizosphere were demonstrated. The leaves and stems showed a good supply of macronutrients and increased concentrations of some trace elements. The leaves of RJ and RS were shown to be good bioaccumulators of N, K, Na, Mg, Ca, P, Mn, Zn, Ni, Cu and Cd, and the stems of N, K, Na, Ca, Ni, Cd, Cr and Pb. The main components created by nutrients and toxic metals, respectively, were isolated using the PCA method. Based on the values of bioconcentration indicators, the similarity of the studied knotweed species regarding Mn, Cu and Cr in the leaves/soil relation and Al, Fe, Cu, Cd, Cr and Pb in the stems/soil relation was demonstrated. Among the analyzed components, Mn and Mg showed the highest and Cr the lowest mobility from stems to leaves, expressed by the translocation factor. The research shows that despite moderate soil contamination, RJ and RS leaves and stems accumulated significant amounts of trace elements, which indicates their phytoextractive properties. In the case of increased content of toxic metals in the leaves and stems of knotweed and the desire to use their biomass as a component of compost or an additive enriching soil reclamation processes, the risk of using biomass should first be assessed from an ecotoxicological point of view.

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