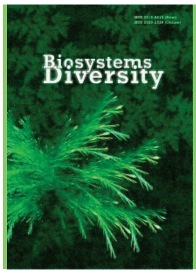

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Peculiarities of the distribution of assimilates in the organs of *Schisandra chinensis* plants under different soil and climatic conditions

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Peculiarities of accumulation of nutrients in the leaves of *Schisandra chinensis* (Turcz.) Baill. and rhizosphere soil under the conditions of its continuous monoculture have been studied. Comparative analysis of the distribution of nutrients in the leaves of plants under different soil and climatic conditions revealed significant differences. It was found that plants grown on podzolic chernozem of Kolomyia State Forest Fund (Otyniia, Ukraine) were characterized by more intensive absorption of such nutrients as Ca, Si, P, Cu, Zn and Mg. The content of P, K, S, Mn was much higher in the foliar tissues of *S. chinensis* plants cultivated on the territory of the M. Gryshko National Botanical Garden (Kyiv, Ukraine) in the conditions of dark grey forest soil. The high ability of plants to accumulate and release Mg into the rhizosphere soil was revealed, which is fully consistent with the selective ability of plants to release mineral elements into the soil environment in accordance with their ecomorphotypes. At the same time, the amount of Ca in the rhizosphere soil decreased significantly at the end of the vegetative period, which could be explained, on the one hand, by the intensive influx of Ca into plant tissues and, on the other hand, by participation in chemical balancing processes to reduce manganese and nitrogen mobility in the soil. Barrier-free accumulation of Fe, Ca, Mg, Al elements in *S. chinensis* leaves was revealed, which should be taken into account when developing plant cultivation technology. The studies of allelopathy activity of vegetative and generative organs of plants and rhizosphere soil have shown that phenolic substances accumulate in small amounts in the soil under *S. chinensis*, which is a prerequisite for successful cultivation of this fruit vine in the Forest-Steppe zone of Ukraine under conditions of continuous long-term cultivation. The largest amount of phenolic substances was in the upper soil horizons, which gradually decreased with depth, which is consistent with the course of redox processes for the studied soil profiles. The pool of free amino acids of *S. chinensis* plants growing in different soil and climatic conditions was analyzed, the concentration of amino acids in the leaves was the most indicative. Evaluation of the quantitative and qualitative distribution of free amino acids in plant tissues serves as a diagnostic sign of plant sensitivity to soil and climatic conditions.

Keywords: fruit vine; nutrients; rhizosphere soil; assimilates; phenolic substances; amino acids; allelopathic activity.

Introduction

The expansion of the cultivated fruit plant species in orchards and increasing the biodiversity of the orchard phytocenosis is possible through the introduction of new and uncommon plant species, which include, in particular, *Schisandra chinensis* (Tucrz.) Baillon – a valuable medicinal, fruit and ornamental plant. Schisandra's fruit is a source of biologically active compounds – vitamins C, E, P (Chun et al., 2014), saponins, flavonoids (Szopa et al., 2017), organic acids, lignans (Opletal et al., 2004; Tian et al., 2005; Gnabre et al., 2010; Ekiert et al., 2013), pectins (Lin et al., 2020), aromatic substances (Zheng et al., 2004), which have adaptogenic, tonic (Pannosian, 2003), immunostimulatory (Szopa et al., 2016), antioxidative (Lu & Dao, 2009; Ma et al., 2012), anti-inflammatory, regenerative and antitumour effects (Cheng et al., 2013; Nowak et al., 2019; Park & Lee, 2021).

Flowers, shoots, leaves and rhizomes of plants in addition to fruits also have medicinal properties. The biological activity of *S. chinensis* and its stimulating effect on the human body are mainly due to the presence of lignans, which are dominated by schisandrin, γ-schisandrin, schisandrol, contained in all organs of the plant (Ekiert et al., 2013; Thandavarayan et al., 2015). *S. chinensis* belongs to plant adaptogens with pronounced tonic properties. Therefore, Chinese and Tibetian healers have used plants as a tonic for physical fatigue and asthenia from ancient times (as early as the V century AD) (Adams et al., 2018). Preparations from the medicinal raw materials of *S. chinensis* restore efficiency, cure fatigue, increase the acuity of night vision, stimulate tissue regeneration, stimulate the central nervous and cardiovascular systems (Thandavarayan et al., 2015), respiration, and have antitumour-promoting, and anti-HIV (human immunodeficiency virus) effects (Lu & Dao, 2009). In China since the XVI century this plants has belonged to the first category of drugs recommended for restoration of vitality. According to modern research, the biologically active compounds of *S. chinensis* have anticancer, antimicrobial action, improve the functioning of the pancreas, stimulate insulin secretion, and prevent complications in diabetic diseases (Panossian, 2008; Venkanna et al., 2014; Lv et al., 2015; Nowak et al., 2019), as well as showing hepatoprotective effects (Pu et al., 2012) and antiviral activity (Li & Peng, 2013).

Due to the growing demand for medicinal raw material of *S. chinensis*, it is worth noting its introduction into horticultural practice outside its natural range. Long-term research on the growth and development of *S. chinensis* in the M. Gryshko National Botanical Garden of NAS of Ukraine (NBG, Kyiv) indicates its successful introduction, and, accordingly, the prospect of creating commercial plantings, which will provide an opportunity to obtain valuable raw materials for the pharmaceutical, food and perfume industries (Skrypchenko & Slyusar, 2020). The chemical composition and biological activity of plant extracts of *S. chinensis* depend on the place of plant growth, namely humidity, light, soil type, geographical location, temperature, and other factors (Liu et al., 2013; Wang et al., 2018). Therefore, it is important to develop scientific grounding for the introduction of *S. chinensis* in horticulture and the development of technology for its cultivation in different soil and climatic conditions, in which priority must be given to the study of plant nutrition, and its impact on the soil ecosystem. The issue of soil fatigue remains important because due to the continuous release of excretions by plants of various organic compounds into the soil around the roots, a zone of biochemically active substances is formed, which may negatively or, conversely, positively affect the surrounding plants (Zaimenko et al., 2020). Long-term cultivation of *S. chinensis* as monoculture is accompanied by the accumulation of phytotoxic phenolic allelochemicals in the rhizosphere soil leading to allelopathic soil fatigue (Osipova & Moroz, 2001; Li, et al., 2010; Skrypchenko et al., 2020).

It is known that the normal growth and development of plants require a balanced supply of mineral nutrients. Their availability to plants directly affects the processes of respiration and photosynthesis, and supplies the resistance to diseases, pests, and abiotic stressors. The formation of the elemental composition of plants is influenced by two factors: (i) genetic, determining certain species requirements to macro- and micronutrients amount in the soil; (ii) ecological – the more elements contained in the soil, the more plants absorb them (Ilin & Syiso, 2015). However, sometimes a plant has the ability to accumulate certain nutrients, which are present in the soil in insignificant amounts, and, conversely, not to accumulate nutrients present in the soil in high amounts. Commonly, in different soils mineral nutrients are almost never present in soil in such quantities and in such a balanced ratio that would be optimal for the growth and development of certain plant species (Zaimenko, 2008), each species has formed certain genetically fixed requirements for different chemical nutrients in the process of evolution (Alloway, 2010; Ilin & Syiso, 2015; Khramova et al., 2019). Biological selectivity in their absorption and accumulation, first of all, determines the elemental composition of plants, which is considered an important systematic feature. The mechanism of entry of chemical elements into plants, including toxic, heavy metals, and radionuclides, is explained by the system of barrier-free accumulation (Yan et al., 2020).

Since the concentration of macro- and micronutrients in plant tissues is the most reliable indicator of the chemical state of plants, which provides for the control of a large number of other factors, we studied the distribution of biogenic elements in the leaves of the fruit vine. Given the above, the objective of the study is to analyze the distribution of macro- and micronutrients in the system "soil–plant" under conditions of continuous long-term cultivation of *S. chinensis* under various soil and climatic conditions.

Materials and methods

The experimental work was performed in 2016–2019 in the Fruit Plant Acclimatization Department of the NBG (Kyiv, dark grey forest soil) and Otyniia Forestry of the Kolomyia State Forest Fund (named as KSFF) (Ivano-Frankivsk region, Otyniia, podzolic chernozem). The object of the study was *S. chinensis* plants (c. 'Sadovyi-1'), which grew in one place for more than 40 years. Plant leaves were used, which were dried to air-dry state and crushed for analysis. Leaf samples were taken at the beginning of the growing season and during fruit ripening. Simultaneously with the sampling of leaves, soil samples were taken at a depth of 0–20, 20–40, 40–60 cm in accordance with DSTU 17.4.02-84. Phenolic compounds were isolated from the soil by ion exchange (desorption) using the ion exchanger KU-2-8 (H^+) as a model of the root system with soluble and absorptive capacity for mobile organic compounds. Soil acidity was measured using a HANNA Instruments HI 2211 pH / OPR Metter, Vienna, Austria.

The total content of mineral elements in plant leaves and root soil was analyzed using an optical emission spectrometer with inductively coupled plasma iCAP 7200 Duo ("Thermo Fisher Scientific", 2017) on the basis of the test center SE "Ivano-Frankivsk Standardmetrologiya" according to the method (Masson et al., 2010). Monoelement and multi-element standard solutions were used to calculate the concentration of mineral nutrients in the experimental sample, on the basis of which calibration graphs were constructed. Biological accumulation coefficients (BAC) of plants were calculated to determine the intensity of absorption of macro- and micronutrients by plants as the ratio of the content of the element in the dry mass of leaves to its content in the soil (Lovkova et al., 1989). Qualitative and quantitative composition of free amino acids was determined by Stein and Moore in the modification of Volochay & Kovalev (2012) and evaluated by HPLC using Agilent 1100 chromatograph ("Agilen Technologies", USA, 2008). The content of photosynthetic pigments in leaves was evaluated by the method (Wellburn, 1994) on an ICAP 6300 DUO spectrophotometer. Dimethyl sulfoxide (DMSO) was used to extract the pigments. A sample of 200 mg was poured into 5 mL of DMSO, kept in a thermostat for 12 hours. The measurement was carried out on a Specord 200 spectrophotometer (Analitic Jena, 2003) at a wavelength of 480 nm for carotenoids, 665 and 649 nm for chlorophyll-*a* and chlorophyll-*b*, respectively.

The experiments were repeated five times for each variant. The obtained data were processed by generally accepted methods of variation statistics. The data in the tables are presented as x ± SD (mean value ± standard deviation). The reliability of the difference between experimental variants was evaluated using ANOVA. Differences between the samples were considered statistically significant at $P < 0.05$, $P < 0.01$ and $P < 0.001$.

Results

A comparative analysis of the distribution of macro- and microelements in different plant organs was performed at the first stage of the research. According to the results of the study, the elemental composition of fruits, leaves, and seeds of *S. chinensis* plants is represented by a complex of macro- and microelements, the main of which are potassium, calcium, phosphorus, iron, manganese, copper, zinc. Accumulation and distribution of macro- and microelements in the tissues of various plant organs are uneven (Table 1).

Table 1
The content of macro- and microelements in organs of plants *S. chinensis* (NBG), mg/g of dry weight (DW) (x ± SD, n = 5)

Element	Leaves	Fruits	Seeds
Ca	30.209 ± 0.370^a	16.851 ± 0.459^b	11.133 ± 0.392^c
K	28.972 ± 0.348^a	45.591 ± 0.389^b	31.510 ± 0.469^c
P	3.474 ± 0.056^a	4.034 ± 0.066^b	10.553 ± 0.137^c
Mg	2.099 ± 0.336^a	ND^b	2.454 ± 0.489^c
Al	1.358 ± 0.133^a	1.522 ± 0.136^a	0.512 ± 0.174^b
Si	1.293 ± 0.061^a	1.018 ± 0.051^a	0.673 ± 0.078^b
S	1.285 ± 0.031^a	1.838 ± 0.027^b	4.990 ± 0.063^c
Fe	0.689 ± 0.016^a	0.549 ± 0.024^b	0.554 ± 0.021^b
Mn	0.232 ± 0.011^a	0.947 ± 0.039^b	1.341 ± 0.039^c
Cu	0.048 ± 0.003^a	0.039 ± 0.005^b	0.093 ± 0.006^c
Zn	0.036 ± 0.002^a	0.096 ± 0.006^b	0.133 ± 0.007^c

Note: different letters of upper indices ^{a}, ^{b}, ^{c} in the Table indicate values that significantly differ one from another within the row as a result of comparison using the Tukey test ($P < 0.05$) taking into account Bonferroni correction; ND – not detected.

Fruits are characterized by higher concentrations of potassium; seeds have the highest content of calcium, phosphorus, sulfur, manganese, copper, and zinc. Leaf tissues are characterised by high levels of silicon, calcium, and iron. Comparative analysis of the elemental composition of leaves, fruits, and seeds of *S. chinensis* showed insignificant fluctuations in the concentration of iron in plant organs. Since Ca is a constitutional element, is part of pectin, improves the synthesis of chlorophyll, and K is involved in the opening and closing of stomata, and is concentrated in young and biochemically active tissues, the physiological role of these macronutrients determines their predominant content in plant leaves and fruits. As for iron, this element accumulates in almost equal amounts in fruits and seeds, and in the leaves. Approximately the same distribution of Al, Si, S, and P is found in the fruits and leaves of plants.

A balanced supply of plants with macro- and microelements influences positively the numerous metabolic processes and plays a key role in the formation of yield and fruit quality. A comparative analysis of their content in the leaves and soil under *S. chinensis* plants in conditions of longer cultivation in different soil and climatic conditions (dark grey forest soil (NBG) and chernozem podzolic (KSFF) was carried out to assess the balance in the distribution of mineral nutrients. An analysis of rhizosphere soil samples revealed higher concentrations of main macro- and micronutrients in podzolic chernozem, except for Si and Cu (Table 2).

The studied mineral nutrients could be placed in the following descending order according to their amount in the rhizosphere soil: Si > Al > K > Fe > Ca > Mg > P > S > Mn > Cu > Zn (for soil collected from plots of NBG) and Si > Al > K > Fe > Ca > Mg > P > Mn > S > Zn > Cu (for soil selected from plots of KSFF). Analysis of the distribution of mineral nutrients in *S. chinensis* leaves showed that the descending order of their distribution in plants cultivated at NBG was as follows: Ca > K > P > Mg > Al > Si > S > Fe > Mn > Cu > Zn. However, for plants cultivated at KSFF the pattern of mineral nutrients distribution was somewhat different: Ca > K > Si > Mg > Al > Fe > P > S > Mn > Zn > Cu.

Comparative analysis of the distribution of nutrients in the leaves of plants under different soil and climatic conditions revealed significant differences. The content of Ca, Si and Fe in the leaves of plants growing on chernozem was found to be higher than in those cultivated on dark grey forest soil. The content of P, K, S, Mn is much higher in the leaf tissues of NBG plants. Barrier-free accumulation of chemical elements Fe, Ca, Mg, Al in the leaves, the content of which is proportional to their concentration in the soil, was revealed. The higher the content of these elements in the soil, the higher their accumulation in the leaves of plants.

Table 2
The content of macro- and microelements in the leaves and rhizosphere soil layer of *S. chinensis* (x ± SD, n = 5)

Element	Leaves, mg/g of DW		Soil, mg/g of DW		Coefficient of biological accumulation	
	NBG	KSFF	NBG	KSFF	NBG	KSFF
Ca	30.209 ± 0.370	38.289 ± 0.261***	0.813 ± 0.021	1.148 ± 0.033***	37.469 ± 3.393	33.249 ± 4.021
K	28.972 ± 0.348	21.852 ± 0.231***	3.133 ± 0.063	3.822 ± 0.062***	9.365 ± 1.023	5.554 ± 0.616***
P	3.474 ± 0.056	1.522 ± 0.043***	0.162 ± 0.013	0.253 ± 0.011***	21.099 ± 2.054	6.011 ± 0.593***
Mg	2.099 ± 0.336	2.311 ± 0.093	0.592 ± 0.006	0.792 ± 0.071***	3.481 ± 0.293	2.804 ± 0.301**
Al	1.358 ± 0.133	1.762 ± 0.129**	4.131 ± 0.039	5.459 ± 0.491***	0.345 ± 0.021	0.334 ± 0.029
Si	1.293 ± 0.061	3.241 ± 0.082***	38.493 ± 0.063	34.908 ± 0.062***	0.031 ± 0.003	0.089 ± 0.011***
S	1.285 ± 0.031	1.333 ± 0.031*	0.051 ± 0.002	0.091 ± 0.003***	25.155 ± 3.924	14.475 ± 1.213***
Fe	0.689 ± 0.016	1.563 ± 0.032***	1.681 ± 0.006	3.679 ± 0.012***	0.419 ± 0.036	0.421 ± 0.033
Mn	0.232 ± 0.011	0.071 ± 0.012***	0.051 ± 0.002	0.111 ± 0.002***	4.456 ± 0.387	0.613 ± 0.067***
Cu	0.048 ± 0.003	0.058 ± 0.004**	0.002 ± 0.000	0.005 ± 0.001***	24.245 ± 2.619	11.599 ± 0.871***
Zn	0.036 ± 0.002	0.065 ± 0.004***	0.008 ± 0.001	0.019 ± 0.004***	4.595 ± 0.434	3.531 ± 0.289**

Notes: the data were statistically significant as compared with the measurements in NBG and KSFF (** – significant for P < 0.01; *** – significant for P < 0.001).

At the same time, a barrier accumulation of K, S, Si elements was detected, as evidenced by significant differences in the distribution of mineral nutrients in plant leaves under different growth conditions. The concentration of Si and Ca in the foliage tissues of *S. chinensis* plants under the conditions of chernozem in KSFF is higher than in the leaves of plants growing on dark grey forest soil (NBG). The content of P in the leaves of *S. chinensis* plants collected at NBG is more than two times higher than in the leaves collected in KSFF, where its concentration in the soil is 1.5 times higher compared to the soil conditions of NBG. It was found that at a sufficiently high concentration of Si in the soil of the experimental plots, this element accumulates in plant tissues in small quantities.

It should be noted that a higher content of Si was found in the leaves of *S. chinensis*,which were collected in KSFF (2.3 times), where its concentration in the soil is much lower as compared to the soil of NBG. The increase of the Si concentration in plant tissues occurs simultaneously with a decrease in the supply of Mn to the leaves. At the same time, three times higher concentration of Mn in *S. chinensis* leaves, collected in NBG against the background of much lower content of this element in the soil, was found in comparison with samples taken in KSFF. Since Mn is involved in the processes of reducing transpiration and increasing the water-regulating capacity of plants, it can be assumed that insufficient moisture supply of plants under cultivation in the drier conditionsof NBG is the cause of accumulation in the tissues of the leaves of this micronutrient.

The integral criterion for assessing the selective absorption of nutrients is the coefficient of biological accumulation. Conditions under which CBA < 1 indicate a low level of absorption of a certain element with the plant (Lovkova, 1989). Based on the results of the calculation of biological accumulation coefficients (Table 2), it was established that *S. chinensis* plants are characterized by a high level of absorption of elements Ca, S, Cu, P, K, Zn and Mg under growth conditions in different soil and climatic conditions. It is worth noting that, regardless of the difference in the absolute values of the biological accumulation coefficients, their sequence of placement in descending order remains the same for plants growing both on black soil and on dark grey forest soils. The exception is the element Mn, whose CBA reaches 4.46 under NBG conditions, which indicates a high level of absorption of the element, while for KSFF soil and climatic conditions it was only 0.62. As noted above, this may be due to the drier conditions of the NBG. At the same time, the calculated coefficients of biological accumulation in our studies prove that *S. chinensis* plants are characterized by a low level of absorption relative to the elements Fe, Al and Si. The last element (Si) at a fairly high concentration in the soil of the experimental plots accumulates in plants in very small quantities.

Analysis of the distribution of Ca, Mn and Mg over of the profile of dark grey forest soil under *S. chinensis* plants during the two growing seasons proves the validity of the assumption of the selective ability of plants to release mineral elements into the soil environment according to their ecomorphotype (Table 3). It is known that lianas are characterized in comparison with other plants by a higher ability to accumulate magnesium in tissues and release it into the rhizosphere soil. This is evidenced by the results of the analysis of the distribution of magnesium in the soil profile under *S. chinensis* plants.

Table 3
Distribution of Ca, Mn, Mg in the rhizosphere soil of *S. chinensis* (mg/g of DW, x ± SD, n = 5)

Horizons of soil profiles, cm	Ca		Mn		Mg	
	spring	autumn	spring	autumn	spring	autumn
0-20	41.8 ± 4.2	34.0 ± 3.5*	0.24 ± 0.02	0.27 ± 0.03	0.71 ± 0,07	2.44 ± 0.24***
20-40	42.9 ± 3.9	38.1 ± 4.8	0.21 ± 0.01	0.25 ± 0.02*	0.73 ± 0.07	2.52 ± 0.24***
40-60	40.0 ± 3.3	30.9 ± 0.4***	0.21 ± 0.02	0.22 ± 0.03	1.62 ± 0.16	3.96 ± 0.35***

Note: the data of comparison by elements were statistically significant as compared with the spring measurement in the same horizon within the row (* – significant for P < 0.05; *** – significant for P < 0.001).

The opposite relationship is observed for another element – calcium - its amount decreases significantly at the end of the vegetative period, which is explained, on the one hand, by the intensive supply of Ca to plant tissues, and on the other hand, participation in chemical balancing processes to reduce Mn and NH4+ mobility in the soil. In particular, the ability of *S. chinensis* to release Mn ions into the soil environment, which can be very toxic to plants under conditions of high soil acidity and low iron supply, has been established.

Also noteworthy are the data on the distribution of ammonia nitrogen in the soil (Fig. 1). These revealed a significant decrease in the concentration of NH4+ in the autumn, which is associated with increased mobility of Ca^{2+}. It is known that as a result of unbalanced nutrition, plants show signs of violation of the water regime, photosynthesis, respiration, enzyme activity, carbohydrate and protein metabolism. This, in particular, is indicated by the data obtained during the comparative analysis of the distribution of free amino acids in the leaves of *S. chinensis* when growing plants in different soil and climatic conditions (Fig. 2).

It was found that the qualitative composition of amino acids of the studied objects is identical. However, the quantitative content of amino acids in the leaves of plants that grew in different soil and climatic conditions differ. The results showed some differences in amino acid composition, in particular, plant tissues grown in Ivano-Frankivsk region had higher contents of arginine, lysine, alanine, valine, proline, glutamic acid and lower phenylalanine, histidine, tyrosine, asparagine than in plants that grew in NBG.

This difference is explained both by features in the distribution of macro- and micronutrients in the vegetative organs of plants, and their response to growing conditions, as the qualitative and quantitative composition of free amino acids depends on the relationship between carbon, phosphorus and nitrogen metabolism. This is confirmed by the results of assessing the content of photosynthetic pigments in the leaves of which biosynthesis was activated in plants from Otyniia under conditions of insufficient supply of phosphorus, nitrogen and potassium, as well as a slight water deficit (Table 4).

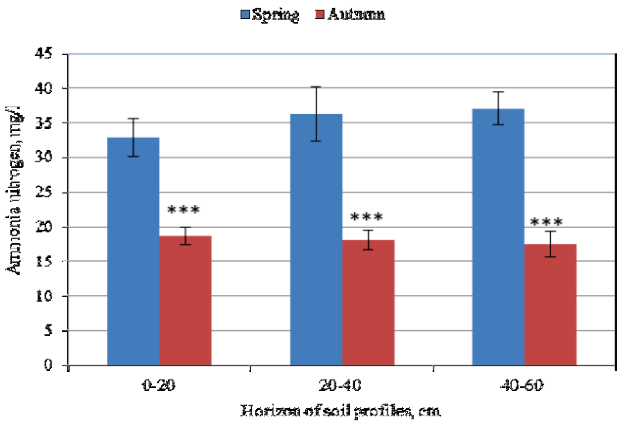

Fig. 1. Distribution of ammonia nitrogen along the horizons of the soil profiles under perennials of *S. chinensis* plants (x ± SD, n = 5): *** – the data were statistically significant as compared with the spring measurement in the same horizon (P < 0.001)

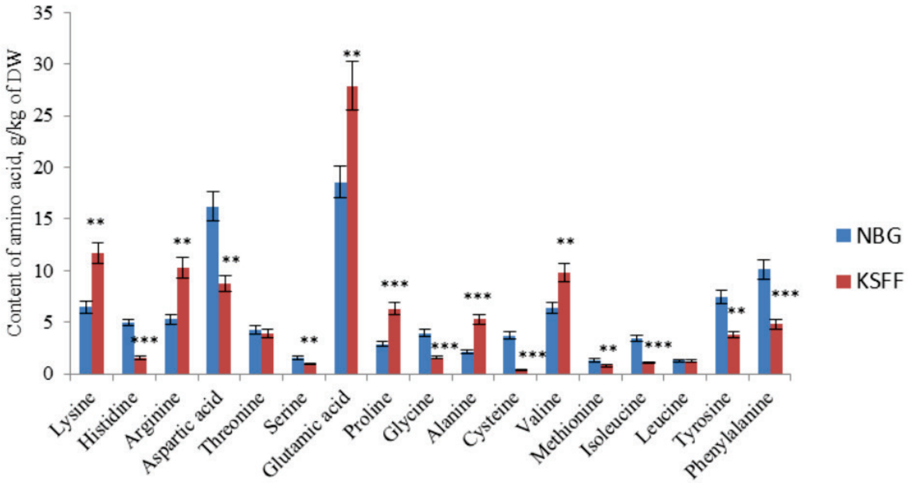

Fig. 2. Content of amino acids in *S. chinensis* leaves under different soil and climatic conditions (x ± SD, n = 3): the data were statistically significant as compared with the measurements in NBG and KSFF; ** – significant for P < 0.01; *** – significant for P < 0.001

Table 4
The content of photosynthetic pigments in *S.chinensis* leaves under different soil and climatic conditions (x ± SD, n = 5)

Place of growth	Chlorophyll, mg/g of raw weight (RW)			Carotenoids (*c*), mg/g of RW	*a* / *b*	(*a* + *b*) / *c*
	a	*b*	*a* + *b*			
NBG	4.51 ± 0.37	2.63 ± 0.24	7.14 ± 0.60	7.59 ± 0.81	1.71 ± 0.07	0.94 ± 0.05
KSFF	6.21 ± 0.89**	3.15 ± 0.29*	9.36 ± 1.18**	4.98 ± 0.46***	1.97 ± 0.10**	1.88 ± 0.07***

Notes: the KSFF (Kolomyia State Forest Fund) data were statistically significant as compared with the measurements in NBG (National Botanical Garden) within the column; * – significant for P < 0.05; ** – significant for P < 0.01; *** – significant for P < 0.001.

Analysis of the content of photosynthetic pigments in the leaves of Chinese magnolia vine plants proved a higher content of chlorophylls *a*, *b* and their sum in the leaves of *S. chinensis* selected in KSFF conditions compared to the samples selected in NBG while a higher content of carotenoids was observed in the leaves of plants in NBG conditions, which indicates an adaptive reaction of the pigment complex to destructive photooxidation due to stress factors. The ratio of chlorophyll *a* to chlorophyll *b* is considered to be an important characteristic of the photosynthetic activity of plants and their resistance to adverse factors. This ratio was equal to 1.97 in KSFF samples and 1.71 in NBG samples. At the same time, the ratio (*a* + *b*) / *c*, which is also an indicator of plant resistance to adverse factors, is twice as large for KSFF leaves as compared to NBG leaves. Characteristic of perennials is the formation of their own allelopathic field, which includes phytoactive substances contained in precipitation and litter or leached from the leaves by rain. The root system of plants during the growing season also releases biologically active compounds into the rhizosphere soil, which may affect the surrounding species of plants, creating a certain allelopathic potential in the phytocenosis environment.

The phenomenon of soil fatigue is observed, which is caused by the accumulation of toxins and phytopathogenic microorganisms, a decrease in the intensity of mineralization processes and the content of available nutrients, which is manifested in the suppression of the growth and development of follower plants and a decrease in the productivity of young plants, which cannot be overcome with the help of fertilizers, plant protection agents, irrigation and other agricultural techniques (Moroz, 1990). An important role in the process of soil depletion in orchards is played by allelochemicals of phenolic nature, which may act on the whole plant both directly, by disrupting basic physiological processes, and indirectly, through changes in microbiota composition and physicochemical properties of soil.

The results of studies of the accumulation features of phenolic substances in the soil under *S. chinensis* showed that their concentration during the growing season ranges from 37.1 ± 1.9 to 92.3 ± 5.2 mg/kg. It was found that the content of phenolic substances increases at the end of the growing season and decreases during dormancy. Over the next year, the pattern of seasonal accumulation of phenolic substances is maintained. The highest amount of phenolic substances was in the upper soil horizons, which gradually decreased with depth horizons. This is consistent with the course of redox processes for the studied soil profiles (Fig. 3).

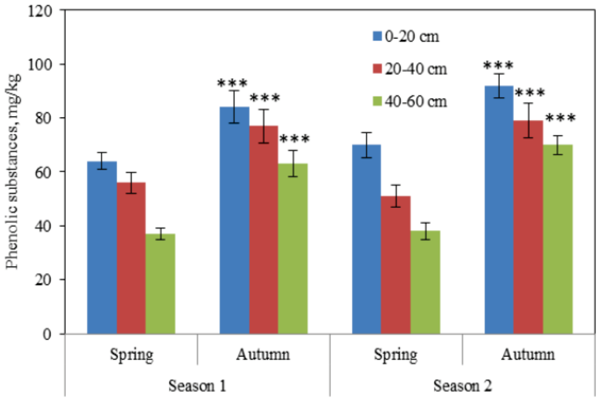

Fig. 3. The content of phenolic substances on the horizons of the soil profile under long-term cultivation in monoculture of *S. chinensis* (x ± SD, n = 5): *** – the data were statistically significant as compared with the spring measurement in the same horizon P < 0.001

The analysis of the obtained results showed that phenolic compounds accumulate in small quantities in the rhizosphere soil of *S. chinensis*, and their content undergoes constant changes, reaching a maximum in autumn and significantly decreasing in spring, due to leaching by atmospheric precipitation, partial decomposition by microorganisms and binding by the humus complex. This indicates the ability of the rhizosphere soil not only to accumulate allelopathically active substances, but also to neutralize them, which is a prerequisite for the successful cultivation of magnolia vine plants in monoculture.

Discussion

The study of metabolic changes under the influence of various factors of abiotic nature provides the maximum information about the metabolism of substances in the plant organism, makes it possible to establish the dependence of the physiological properties of plants on environmental conditions and to characterize their corresponding reactions to a number of exogenous and endogenous factors, as well as to develop the physiological bases of optimization of cultivation (Hall, 2011; Obata & Fernie, 2012; Li et al. 2017).

Analysis of changes in the quantitative and qualitative composition of free amino acids makes it possible to establish the dependence of physiological properties of plants on environmental conditions and characterize their corresponding responses to a number of exogenous and endogenous factors, as well as to develop physiological bases for optimizing *S. chinensis* cultivation. In addition, the study of amino acid composition allows the analysis of the ability of plants to self-sustain, identify ways to adapt to climate change and increase adaptability due to improved cultivation technology. Amino acids are synthesized in leaves from inorganic N and photosynthates (Yao et al., 2020).

The established fact of the increase of the content of arginine and lysine in *S. chinensis* in Ivano-Frankivsk region testifies to the insufficient phosphate supply of plants. A decrease in the concentration of amino acids in the aromatic series also indicates a violation of phosphorus metabolism. The synthesis of phenylalanine, histidine, and tyrosine, which is associated with the formation of the benzene ring and the starting material for which are phosphorylated sugar compounds, is reduced by inhibiting the intensity of photosynthetic carbon dioxide absorption, but also by disrupting phosphate metabolism and plant energy.

The analysis of the quantitative and qualitative composition of free amino acids revealed an increase in the content of aspartic acid in the leaves of *S. chinensis* in NBG, indicating the aging of plants, and the decrease in its level in the leaves of *S. chinensis* from Otyniia indicates a violation of nitrogen metabolism. The decrease in aspartic acid content is caused by the suppression of amination and reamination reactions. With an insufficient nitrogen supply, a significant part of inorganic phosphorus accumulates in the vacuoles, resulting in a decrease in its entry into the cytoplasm and chloroplasts.

In turn, a decrease in the level of inorganic phosphorus in the cytoplasm causes an increase in the level of phosphoglyceric acid, and starch synthesis and limits photosynthesis. The increase in the content of glutamic acid in the leaves of plants that grew in the soil and climatic conditions of the Ivano-Frankivsk region indicates the activation of photosynthetic processes.

It is known that environmental stress leads to a change in the synthesis of bioactive molecules, a decrease of chlorophyll in the plant (Mukherjee et al., 2019), and an increase of the ratio of carotenoids to chlorophyll (Esteban et al., 2015). At the same time, accelerated biosynthesis of photosynthetic pigments in the leaves may be caused by insufficient phosphorus supply in the presence of minor water deficiency, accompanied by the binding of pigments in the protein-lipid complex. This is confirmed by the lower concentration of potassium in plant tissues. The increase in water deficiency is also indicated by the increase in the concentration of alanine, valine, and proline, which should be considered as an adaptive response of the plant organism associated with the neutralization of excess ammonia. The stressful situation for the development of *S. chinensis* plants in Ivano-Frankivsk region is evidenced by the increase in the concentration of silicon in the leaves.

It was found that the *S. chinensis* plants are characterized by a high level of absorption of elements Ca, S, Cu, P, K, Zn and Mg in different soil and climatic conditions, which may be a species-specific feature feature. At the same time, regardless of the difference in the absolute values of the biological accumulation coefficients, their sequence of placement in descending order remains the same for plants growing both on black soil and on dark grey forest soils. The obtained results are consistent with literature data and indicate that when adapting to changes in growth conditions, plants have developed specific biochemical mechanisms for absorbing nutrients in conditions of their lack in soils, and can also limit the absorption of a certain element at its high concentrations in the substrate (Kabata-Pendias, 2005). It is also possible to assume that the deterioration of chlorophyll biosynthesis is caused by disruption of calcium transport and accumulation of this element in leaf tissues. It should be noted that the quantitative analysis of chemical elements is also a reliable criterion for assessing the imbalance in species of various ecomorphotypes, in particular, the Ca : Mg ratio is much higher in woody vines (Zaimenko et al., 2020a).

Phenolic compounds are considered one of the most important classes of allelochemicals due to their wide distribution in the plant world and versatile effects on key physiological and biochemical processes, such as respiration, photosynthesis and growth of plants (Li et al., 2010). The leaves and roots of *S. chinensis* are characterized by a high content of phenolic compounds (Mocan et al., 2014), which can enter the root environment through precipitation leaching, rotting of plant remains or as part of root secretions and exhibit an allelopathic effect, cause phytotoxicity of the rhizosphere soil. This was investigated in a previous study of the allelopathic potential of magnolia vine plants, which showed that water extracts from different plant organs were characterized by different contents of water-soluble allelopathically active compounds and had both stimulating or inhibiting effects on the growth of test plants depending on the concentration and growing phase of *S. chinensis* plants (Skrypchenko et al., 2020). The study of the rhizosphere soil of *S. chinensis* over two years showed a significant accumulation of phenolic substances during the vegetation period and a decrease in their amount during the dormancy period, which indicates the prospects of its cultivation in the form of monoplants.

Conclusions

The ability of *S. chinensis* plants to accumulate micro- and macroelements depends on soil-climatic conditions of growth, and first of all, on the biogeochemical cycle of elements in the "soil-plant" system. Barrier-free accumulation of elements Fe, Ca, Mg, Al in *S. chinensis* leaves was revealed, which must be taken into account when developing plant growing technology.

It was found that the coefficients of biological accumulation of the main biogenic elements for *S. chinensis* plants growing in different soil and climatic conditions differ in absolute values, but their sequence of placement in descending order remains the same and is a species-specific feature. The highest values of the coefficient of biological accumulation are characteristic for Ca, the lowest are character for Fe, Al and Si. The selective ability of *S. chinensis* plants to accumulate in tissues and release magnesium and manganese ions into the surrounding soil is revealed.

The insignificant accumulation of phenolic substances in the rhizosphere soil of perennial *S. chinensis* plantations indicates the prospects of magnolia vine growing in monoplantings.

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