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Adaptive characteristics of plants in the conditions of technogenic pollution

Nursulu Akhtaeva[1], Elmira Boribay[2], Akmaral Nurmakhanova[1], Bekzat Tynybekov[1], Zhanar Moldagazyyeva[2]

[1] Al-Farabi Kazakh National University, Department of Biodiversity and Bioresources, Al-Farabi Avenue 71, Almaty 050040, Kazakhstan
[2] Narxoz University, Department of Ecology, Almaty, Kazakhstan

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Abstract: The article deals with the problems of induction of the anatomical and morphological structure of plants of different life forms under the conditions of a long-term chronic action of ionising radiation on the territory of the Northern nuclear power plant. Currently, the study and assessment of the radioecological situation on the territory of the former Semipalatinsk nuclear test site, taking into account the ecological state of natural plant and animal populations, is of particular importance. The study of the reaction of living organisms, be it plants or animals, to different doses of chronic ionising radiation makes it possible to assess and diagnose the state of environmental quality, and these organisms themselves can serve as bioindicators of pollution. On the territory of the Semipalatinsk test site, at the experimental site "Balapan", 3 sections with meadow type of soil were studied: polluted section no. 1 – the north-western shore of Lake Chagan, polluted section no. 2 – the north-eastern shore of Lake Chagan, and control section no. 3. For structural analysis, the study recorded the vegetative organs of plant species with an increased radiation background. It was found that when the *EDR* (exposure dose rate) of gamma radiation increases and the plant growth is stimulated. In the conditions of radioactive contamination, with an increase in the activity of alpha, beta and gamma radiation, plants response and changes occur in the internal structure of their vegetative organs. Such adaptive features arise under the influence of a complex of environmental factors, including radiation pollution.

Keywords: anatomical structure, contaminated areas, mesophyll, soil, technogenic radionuclides

INTRODUCTION

For many decades, Kazakhstan has developed a predominantly raw material system of nature management with huge man-made loads on the environment. Environmental protection is one of the most important tasks in any state's development [Belozubova, Zubkova 2021]. Environmental problems are aggravated by the complex radiation environment. Its complexity in the territory of the Republic of Kazakhstan is attributable to the following reasons: activity of the former nuclear power plant, nuclear explosions carried out to solve economic problems, the functioning of enterprises of the nuclear industrial complex, extraction and processing of polymetallic ores of oil and gas with increased radioactivity, and natural anomalies of radionuclides in environmental objects [Baideldynov *et al.* 2019; Lukashenko 2010; Menzel 2018; Zhantasov *et al.* 2022]. The test sites in Kazakhstan occupy the first place in the world in terms of the total power of nuclear explosions. The total radiation dose will serve as an additional source of radiation for many generations in the future period of about 6000 years [Boribay 2015].

Currently, taking into account the ecological state of natural plant and animal populations, the study and assessment of the radioecological situation on the territory of the former Semipalatinsk nuclear test site is of particular importance. The study of the reaction of living organisms to different doses of chronic ionising radiation makes it possible to assess and diagnose the state of environmental quality, and these organisms themselves can serve as bioindicators of pollution [Chaplygin *et al.* 2021; Hinrichsen *et al.* 2018; Perevolotskii, Perevolotskaya 2020; Skalny *et al.* 2019]. It is plant communities that are the main link through which the radioactive products of nuclear explosions and all kinds of pollutants pass into the bodies of animals and humans [KALENSKA *et al.* 2021; VINOGRADOVA, GLUKHOV 2021; TYLISZCZAK *et al.* 2019]. Research on the external and internal structures of plants is one of the important stages of the ecological program, as they reveal features of the interaction between plants and the natural and altered anthropogenic environment.

Characteristics of radioactive contamination of soil and vegetation apply to the experimental site "Balapan". The site was exposed to a large number of tests and research work. Between 1965 and 1989, 108 underground nuclear tests were conducted at the "Balapan" site. The most intensive tests were carried out relatively recently in 1979 and 1984. After the landfill was closed, 13 wells prepared for testing remained at the "Balapan" site [MENZEL 2018]. Since 1996, the specialists of the Institute of Radiation Safety and Ecology of the National Nuclear Center of the Republic of Kazakhstan (city of Kurchatov) have surveyed the wells. During the survey of 103 wells, areas with an exposure dose of 0.1–8.0 $\mu R \cdot h^{-1}$ were identified, and the area of contamination did not exceed 0.2 km^2. The main reason for the contamination of this area was the early release of nuclear explosion products to the surface of the earth. When conducting tests in wells at the "Balapan" site, there were four cases of abnormal radiation. These included wells no. 1007, 1204, 1069, and 1301. Their testing revealed significant contamination of the wellhead areas. The largest contamination of the area occurred after the explosion in well no. 1301 [BORIBAY 2015]. The radiation level in the area after the accident was more than 10 $R \cdot h^{-1}$, and in 1999 the radiation level was in the range of 0.02–0.9 $\mu R \cdot h^{-1}$. The length of the radioactive trace with an *EDR* of 33 $\mu R \cdot h^{-1}$ is approximately 1 km.

MATERIALS AND METHODS

The material for the research was collected during the field work on the territory of the Semipalatinsk (50°07'N 78°43'E) test site. The "Balapan" site consists of 3 sections. The sections with meadow type of soil were studied: polluted section no. 1 on the north-western shore of Lake Chagan, polluted section no. 2 on the north-eastern shore of Lake Chagan, and control section no. 3. Samples taken from the study sites included: perennial herbaceous (*Stipa capillata* L.), *Agropyron cristatum* L. Gaertn., *Festuca sulcata* Hack., *Galium verum* L., *Artemisia sieversiana* Willd.), semi-shrub (*Artemisia marschalliana* Spreng.), shrubs (*Ephedra distachya* L., *Spiraea hypericifolia* L.). The plants were collected in a herbarium, and their structural analysis focused on aboveground and underground vegetative organs of the species studied originated from "polluted areas" with an increased radiation background. Fixation was carried out in 70% alcohol according to the Strasburger–Flemming method (alcohol, glycerin, water, 1:1:1).

Anatomical preparations were prepared manually and using a microtome with a TOS-2 freezing device. Sections were enclosed in glycerin and balsam in accordance with the generally accepted methods of BARYKINA *et al.* [2004]. The thickness of anatomical sections was 10–15 $\mu R \cdot h^{-1}$. More than 5.000 permanent and temporary drugs were prepared. For quantitative analysis, the morphometric parameters were measured using the MOV-1-15 eyepiece micrometer (with a lens × 9, magnification × 10.7). The micrographs were taken using an MBI-6 microscope (magnification × 63).

Plant samples for gamma-spectrometric and radiochemical analyses were taken after a ground-based survey of 2 × 3 m in each of the registered sites. The cut vegetation was placed in a bag, the weight of one bag was not less than 1.0–1.5 kg. Soil sampling was carried out in accordance with instructions and guidelines for assessing radiation in the contaminated area [MUSSINA *et al.* 2018]. Morpho-anatomical features of *Rosa iliensis* Chrshan were described according to generally accepted classifications [AIDOSOVA *et al.* 2019; AKHMETOVA *et al.* 2015; ATABAYEVA *et al.* 2016; BORIBAY *et al.* 2018; 2021; SEILKHAN *et al.* 2019]. Measurements of exposure doses were carried out in accordance with instructions and guidelines for assessing radiation in the contaminated area, and these were verified by graduated "Sintex" dosimeters, PDR-77, DRG-01T, SRP-88 and SRP-68-01, at a height of 1 m and 3–4 cm above the earth's surface, with the measuring devices located parallel to it. The density of surface contamination with alpha and beta particles was measured using KRA-1 M-410 and KRB-1 U916 devices. Gamma-spectrometric analysis was carried out at the Institute of Radiation Safety and Ecology of the National Nuclear Center of the Republic of Kazakhstan, city of Kurchatov (Kaz. Radïacïyalıq qawipsizdik jäne ékologïya ïnstïtwtı). Statistical processing of morphometric indicators was carried out using the "Statistica 6.0" software package. Intergroup differences were evaluated by the nonparametric criterion Mann–Whitney U-test. For pairwise connected groups, the nonparametric Wilcoxon test was applied.

RESULTS AND DISCUSSION

As a result of the radioecological survey of the site, the mosaic nature of the radioactive contamination was established. The degree of contamination does not exceed the standard level. The exception is the area of Lake Chagan (Tab. 1).

Table 1. The degree of contamination of the studied areas or field radiometry

Section	Alpha	Beta	Gamma	
			h = 3 cm	h = 1 cm
	parts·min·cm^{-2}		$\mu R \cdot h^{-1}$	
1	<1	775	18.50	26.40
2	<1	300	2.58	1.69
3	<1	<10	0.13	0.11

Explanations: sections no. 1, 2 – polluted sections, section no. 3 – control section.
Source: own study.

On the site, the dominant soil is zonal, light chestnut, often saline, and saline. They are common on slopes of closed depressions and on the sides of the Shagan River valley. The vegetation cover at the "Balapan" site is represented by desolate sagebrush-turf-and-mud steppes (*Stipa sareptana* Beck, *Festuca valesiaca* Gaud., *Artemisia sublessingiana* Krasch. ex Poljakov, etc.). A ground survey conducted by military specialists in 1990 showed that the main radiation contamination at the "Balapan" site concentrated in the dumps of soil for *EDR* during a nuclear explosion and the creation of the lake, as well as in the epicentral zones of individual vertical combat wells, where the main cause of contamination was the early release of explosion products to the surface. The areas of contamination of the epicentral zones are small, up to 0.2 km^2, and the maximum value of the *EDR* does not exceed 5 μR·h^{-1}. At a distance of 200 m from the epicenter of underground nuclear explosions, the *EDR* value drops to background values at almost all contaminated sites.

In the epicentral part, environmental samples were taken at places of the maximum *EDR* value in order to identify the isotopic composition. According to spectrometric data and radiometric measurements of the samples, the maximum content of ^{137}Cs in the soil, in water and in plants was 1.7·10^6, 10.2 and 10^4 Bq·kg^{-1}, respectively. The total activity of alpha-emitting nuclides was 9.4·10^4 Bq·kg^{-1} in the soil, 12.5 Bq·dm^{-3} in water and 0.45·10^5 Bq·kg^{-1} in plants. In addition, traces of ^{60}Co, ^{152}Eu, and ^{106}Ru were identified in the soil samples. To study the migration of artificial radionuclides in the soil plant system, light-brown soils, often of disturbed structure and covered with man-made soil or construction debris, were tested at the "Balapan" experimental site. These radiation-contaminated areas are test wellhead sites. Zonal species were selected for radiation analysis: *Stipa capillata* L., *Artemisia marschaliana* Spreng., *Festuca valesiaca* Gaud. The transfer and accumulation coefficients of caesium radionuclide are as follows: *Stipa capillata* L. – from 0.4 to 6.3 (N), 200–1000 (N); *Artemisia marschaliana* Spreng. – 0.1–4.7 (N), 22–750 (N); volosnets – 0.14–2.29 (N); *Festuca valesiaca* Gaud. – 0.1–16.5 (N).

- **Morphological structure of dominant plant species**

Stipa capillata L. – belongs to the family of *Poaceae* L., a dense-core perennial forage plant that grows in the steppes, deserts, and rocky slopes of the mountains of Kazakhstan. In the control areas, the stems are thin, glabrous up to 35.11 ±1.66 cm high, whereas they reach 62.96 ±0.31 cm in the contaminated areas (Fig. 1). The average length of leaves in the control areas is 22.07 and 24.25 cm in the polluted areas (Fig. 2). The leaves are narrowly linear, usually with strongly wrapped edges. The sheaths of the lower leaves are longer than the internodes, the length of the tongue of the upper stem leaf is 10–20 mm. The inflorescence is a single-maned panicle. Spikelets are mono-flowered. The length of the spikelet scales is 2.5–4.5 cm. The lower flower scales at the top end with an awn, the length of which is 12–18 mm, sinuous, rough, turning into a flexible and often pinnate part.

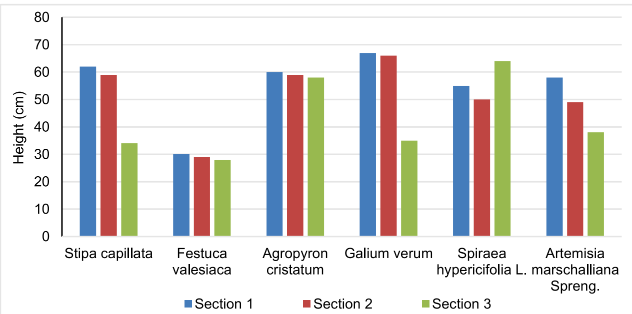

Fig. 1. Height of the studied plants of the experimental site "Balapan"; sections as in Tab. 1; source: own study

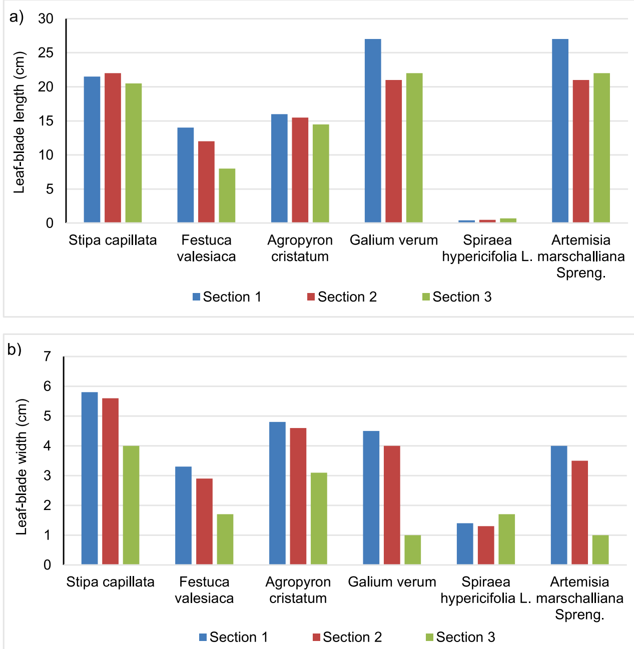

Fig. 2. The length (a) and the width (b) of the leaves of perennial herbaceous plants in the conditions of radioactive contamination of the experimental site "Balapan"; sections as in Tab. 1; source: own study

Festuca valesiaca Gaud. – a perennial, herbaceous plant. The stems are straight, the turf is dense, and the leaves are filiform, folded, with deep longitudinal grooves on the sides, reaching the inflorescence. The average height of the shoots in the control area is 27.29 ±1.01 cm, and 29.98 ±0.96 cm in the polluted area (Fig. 1). The average length of the leaf blade in the control area is 10.96 cm, and in the polluted area it is 15.64 cm (section 1), 13.97 cm (section 2) – Figure 2. The inflorescence is a panicle. The spikelets are 5–7-flowered, the lower flower scales are rough at the top, with a short awn.

Agropyron cristatum (L.) Gaertn. – a perennial herbaceous forage plant, forms turf; the stem under the ear is usually slightly pubescent, less often glabrous; the sheaths of the lower leaves are densely hairy, less often glabrous; the ligule is very short; the leaves are narrowly linear, rolled or flat with rolled edges, glabrous below, smooth, more or less hairy above; the ear is very dense, comb-like, oblong-ovate, barely upward narrowed with a finely pubescent axis; hairs are gray-green or violet-coloured, closely pressed together, 3–10-flowered, hairy. The average height of plants from the polluted section no. 1 (north-west of Lake Chagan) is 60.59 ±16 cm, and in the control 57.68 ±0.61 cm (Fig. 1). The leaf blade of plants in sections 1 and 2 is increased in comparison with the control. In plants at section 1, the leaf length is 18.06 cm, in plants at section 2 it is 17.4 cm, whereas in the control it is 14.7 cm (Fig. 2).

Galium verum L. is a perennial herbaceous plant, the stems are one or more, tetrahedral, straight, simple or short-branched. With an increase in the *EDR* of gamma radiation in *Galium verum* L. the height of the plants from the contaminated sections (1 and 2) increases in comparison with the control: 66.59, 64.79 and 35.68 cm, respectively (Fig. 1). At the same time, the length of the leaf blade increases.

Spiraea hypericifolia L. – shrubby plant up to 150 cm tall, with brown twig-like branches, bearing numerous, sometimes rare, sessile umbels of flowers. Specimens of *S. hypericifolia* L. in the north-western (section 1) and north-eastern parts (section 2) of Lake Chagan, the plants of the background (control) section 3 are stunted in comparison with the plants of the background (control) section 3. Their height is 55.1, 49.5, and 64.7 cm in the control. The leaves are short pubescent, oblong elliptical in shape, with a sharp tip. The length of the leaf blades does not change. However, there is some twisting of the leaf blade inwards and early yellowing of the leaves.

Ephedra distachya L. – a low-growing shrub, 10–25 cm in height, with a creeping rhizome, a shortened branched stem and spreading, usually curved, sinuous or twisted branches at the top. The plant is widely distributed on plains of steppe and desert zones, on stony and gravelly slopes and plumes of steppe mountains and hills. In previous studies, *Ephedra distachya* L. it was proposed as an express indicator of radioactive contamination, because among the studied species, this species turned out to be the most radiosensitive and reacted to radioactive contamination by changing the shape of the bush and spiral twisting of the shoots. In the studies at the "Balapan" sites, the height of plants from 1, 2 sections (at high EDRS of gamma radiation) decreased in comparison with the control: 7.6 cm, 5.6 cm, and, respectively, and in the control it was 9.9 cm (Fig. 1). The plants of the polluted areas are stunted, mostly creeping on the ground, with strongly twisted shoots.

Artemisia campestris subsp. campestris – semi-shrub. The whole plant is glabrous, green, or grayish-green with short, white, semi-striated hairs; at the base, the ascending fruiting stems, usually ribbed, brown or slightly reddish, deciduous and branched; the leaves of the barren shoots and the lower stalks are long-stem, oblong-ovate or broadly ovate in outline, dark green, glabrous or grayish with semi-striated, white hairs, twice or less often thrice pinnate; dissected, the terminal leaf lobes are filiform or narrowly linear, at the tip of the cartilaginous pointed. When studying the morphological structure of this type of wormwood under conditions of an increased background of beta and gamma radiation, it was found that ionising radiation acts as a stimulating factor. In plants from sections 1 and 2, where the *EDR* of gamma radiation reached 1.46–2.64 $mS \cdot v \cdot h^{-1}$. Their height reached 57.31 cm, 49.22 cm, and in control section 3 – 36.13 cm. In the polluted areas, active plant growth was noted, and there were specimens with a branching type that was not characteristic of this plant, with crowded shoots, and with a changed growth direction. There was an increase in the length of the leaf blades (2.84 cm – polluted 1 section, 1.98 cm – control 3 section). The width of the leaves remained unchanged.

- **Anatomical structure of dominant plant species**

The accumulation of radionuclides in plant tissues is related to their availability, its content in the water and soil cover of the region. Tables 2–4 present data on the accumulation of radionuclides in the basal soil, and in the aboveground and underground parts of the feather grass in the studied areas. There are significant differences in the content of radionuclides in

Table 2. Accumulation of technogenic radionuclides in the root layer of soil

Section	Content of gamma-emitting radionuclides ($Bq \cdot kg^{-1}$)							
	^{40}K	^{232}Th	^{238}U	^{241}Am	^{137}Cs	^{60}Co	^{152}Eu	^{154}Eu
1	436 ±35	34 ±6	28 ±4	1702 ±85	14359 ±574	5745 ±230	9684 ±387	7500 ±300
2	210 ±41	20 ±4	30 ±5	210 ±25	3890 ±272	979 ±39	1570 ±94	640 ±64
3	548 ±50	21 ±3	19 ±2	–	24 ±4	–	–	–

Source: own study.

Table 3. Accumulation of technogenic radionuclides in the aboveground part of plants

Section	Content of gamma-emitting radionuclides ($Bq \cdot kg^{-1}$)							
	^{40}K	^{232}Th	^{238}U	^{241}Am	^{137}Cs	^{60}Co	^{152}Eu	^{154}Eu
1	192 ±45	3 ±1	4 ±2	–	74 ±9	–	–	–
2	148 ±27	<2	3 ±1	–	64 ±7	–	–	–
3	141 ±33	<2	3 ±1	–	<3	–	–	–

Source: own study.

Table 4. Accumulation of technogenic radionuclides in the underground part of plants

Section	Content of gamma-emitting radionuclides ($Bq \cdot kg^{-1}$)							
	^{40}K	^{232}Th	^{238}U	^{241}Am	^{137}Cs	^{60}Co	^{152}Eu	^{154}Eu
1	310 ±78	7 ±3	10 ±3	69 ±21	1860 ±130	311 ±28	408 ±33	170 ±24
2	120 ±55	4 ±2	8 ±4	37 ±13	1350 ±108	154 ±14	253 ±50	63 ±12
3	110 ±25	6 ±2	5 ±2	–	18 ±4	–	–	–

Source: own study.

the aboveground and underground mass. Data analysis shows that in the conditions of pollution (north-west section no. 1 and north-east of Lake Chagan section no. 2 ^{238}U, ^{137}Cs, ^{232}Th accumulate mostly in the basal soil in comparison with the control area (Tab. 2). Moreover, ^{241}Am, ^{60}Co, ^{152}Eu, ^{154}Eu are not found in the root soil in the control area, whereas they are found in significant quantities in the contaminated areas.

In the polluted areas, specific activity of natural radionuclide ^{40}K in aboveground and underground masses of *Stipa capillata* L. is increased, although in the root soil of the plant it is reduced if compared to the control. A high concentration of transuranic radionuclide ^{241}Am (1702 ±85 Bq·kg^{-1}) was found in the root soil of plants in the north-western part of Lake Chagan section no. 1, while in the north-eastern part its concentration was 210 ±25 Bq·kg^{-1}. The activity of transuranic radionuclide in the above-ground mass of plants was not observed.

However, in the underground mass of plants from the contaminated site, it was 69 ±21 Bq·kg^{-1} (Tab. 4). Despite the high concentration of transuranic radionuclide in the root soil of plants, it did not accumulate in the aboveground mass. The gamma-emitting ^{137}Cs accumulated mainly in the aboveground part of the studied plant (Tab. 3). The underground part of the plants also contained large amounts of ^{137}Cs (1860 Bq·kg^{-1} and only 18 Bq·kg^{-1} – under control). There was also accumulation of ^{40}K, ^{232}Th, ^{238}U, ^{137}Cs, ^{241}Am, ^{60}Co, ^{152}Eu, ^{154}Eu (Tab. 4). Thus, a greater accumulation of technogenic radionuclides occured in the root and underground parts of plants. However, changes in the internal structure of plants occurred not only in the underground, but also in the aboveground parts of the studied plants.

Stipa capillata L. The epidermal layer of the plant stem in the contaminated area is thickened in comparison with the control ($8.76 \cdot 10^{-6}$ m, $5.83 \cdot 10^{-6}$ m). The thickness of the sclerenchymal ring of the contaminated area is greater than that of the control area (38.84 μR, 33.06 μR). A distinctive feature is also an increase in the diameter of xylem vessels, a decrease in the number of conducting bundles in the plant stem of the contaminated area. In the internal structure of the stem *Stipa capillata* L. under the influence of increased background radiation (*EDR* gamma radiation 18.5–2.58 mS·v·h^{-1}), the thickness of the epidermal cells and the thickness of the sclerenchymal layer increase and the number of conducting beams increases as well: the thickness of the epidermis in the contaminated area is 8.11 μR, in the control area – 5.83 μR, the thickness of the sclerenchymal layer of plants in the 1st section – 38.01 μR, in plants in the 2nd area – 38.84, in the control area – 33.06 μR. Conducting bundles became 5–6 more in plants of the sections 1 and 2 in comparison with the section 3.

In the leaves of *Stipa capillata* L. under conditions of high gamma radiation, structural changes occur in the direction of increasing parameters. Thus, in plants in sections 1 and 2, the thickness of the upper and lower epidermis, the thickness of the mesophyll, and the area of the conducting bundles increase. In leaves, the thickness of cell walls of the upper and lower epidermis of plants from the contaminated area is 6.9 ±1.4 μR and 7.4 ±1.58 μR, respectively, in the plants from the control area – almost 2 times less – 4.75 ±3.5 μR and 4.87 ±2.07 μR. The thickness of mesophyll increases in the contaminated area (56.71 ±1.52 μR) and in the control area (41.04 ±1.23 μR), and the conducting bundles of the sheet of the contaminated area are more enlarged compared to the control area ($21.64 \cdot 10^{-3}$ ±1.001 mm^2 and $18.20 \cdot 10^{-3}$ ±0.022 mm^2).

Festuca valesiaca Gaud. While comparing cross sections of plant stems at different sites, the following can be noted: at *Festuca valesiaca* Gaud. when the *EDR* of gamma radiation is equal to 31.47 mS·v·h^{-1} in the 1st site and 1.29 mS·v·h^{-1} in the 2nd site, the thickness of the epidermis and the thickness of the sclerenchymal layer increase (11.8 μR and 10.2 μR, 61.4 μR and 58.6 μR, respectively) in comparison with the control site (9.51 μR, 54.8 μR). The number of conducting beams has not changed. The diameter of the xylem vessels has increased. The area of the conducting beams increases slightly.

All indicators of the leaves of *Festuca valesiaca* Gaud. In conditions of a high radiation background, it is much higher than the indicators of the 3-control section. Moreover, the lower epidermis is much thicker than the upper one in polluted area no. 1. The thickness of the upper epidermis is 13.5 μR, and the lower one is 18.25 μR. The thickness of mesophyll and the area of the conducting beams have increased compared to the control. There are significant differences in the content of radionuclides in the aboveground and underground masses of the plants studied. The analysis of the data shows that under the conditions of contamination in the basal soil, the accumulation of large amounts of technogenic radionuclides ^{241}Am, ^{137}Cs, ^{60}Co, ^{152}Eu, ^{154}Eu are observed. Moreover, in samples of the basal soil of the control area, except for ^{137}Cs, the remaining technogenic radionuclides were not found. There is a correlation between the ^{137}Cs content in soils and roots.

In the polluted sites 1 and 2, the content of ^{137}Cs in roots increases in line with its content in soil. The specific activity of natural radionuclide ^{40}K in the contaminated areas has increased. The specific activity of natural radionuclides ^{238}U, ^{232}Th at the control and contaminated sites remains the same. A high concentration of transuranic radionuclide ^{241}Am (5385 ±162 Bq·kg^{-1}) was found in the root soil at site no. 1, and its concentration in site no. 2 was 227 ±11 Bq·kg^{-1}. The activity of transuranic radionuclide in the aboveground mass of plants is not observed. However, in the underground masses of plants from polluted areas, it is 98 and 39 Bq·kg^{-1}, respectively in section 1 and 2. Despite the high concentration of transuranic radio-nuclide in the root soil of plants, it is not concentrated in the aboveground mass. In the aboveground part of the plants, in polluted sections 1 and 2, an insignificant specific activity of gamma-emitting ^{137}Cs is observed. The underground parts of plants contain large amounts of ^{137}Cs – 2010 and 910 Bq·kg^{-1} in sections 1 and 2 respectively, and only 18 Bq·kg^{-1} in the control, and there is also an accumulation of natural radionuclides (^{40}K, ^{232}Th, ^{238}U) and technogenic radionuclides (^{241}Am, ^{60}Co, ^{152}Eu, ^{154}Eu) – Table 2. Thus, a greater accumulation of technogenic radionuclides occurs in the root soil and underground parts of plants. Therefore, the high specific activity of technogenic radionuclides in areas 1 and 2 at the experimental "Balapan" site led to a change in the internal structure of the plant.

Agropyron cristatum (L.) Gaertn. For the study, plants were collected only from two sites: 1 – the northwestern shore of Lake Chagan and 3 – the control one. Under conditions of high values of gamma radiation at an *EDR* of 23 mS·v·h^{-1}, *Agropyron cristatum* (L.) Gaertn. slightly increases the thickness of the epidermis. The thickness of the sclerenchymal layer of the plants at site no. 1 is 64.8 μR, which is 12 μR more than that of the plants at site no. 3. The number of conducting beams, the diameters of xylem elements, and the area of conducting beams in areas with an increased background radiation are increased.

Quite interesting changes have occurred in the structure of leaf blades. In the leaves of *Agropyron cristatum* (L.) Gaertn., the thickness of the upper and lower epidermis significantly decreases in the contaminated site (1). In the contaminated area, the thickness of the upper epidermis is 9.8 μR, the lower – 10.5 μR, and in the control area, 13.9 μR and 17.3 μR, respectively. However, the thickness of the mesophyll and the area of the conducting beams increased with increasing radiation levels.

According to the data from the gamma-spectrometric analysis, the contamination with natural radionuclide ^{40}K is uniform, both at polluted sections 1 and 2, and at the control site. According to the results of the analyses, in the root soil of plants at site no. 1, there is an increased concentration of technogenic radionuclides of ^{137}C, ^{60}Co, as well as ^{154}Eu, and ^{155}Eu. Despite the high activity of technogenic radionuclides in the root soil of plants in sites 1 and 2, the accumulation in the aboveground and underground parts of plants is low. Thus, in the aboveground and underground parts of *Agropyron cristatum* (L.) Gaertn., the specific activity of technogenic radionuclides is not high.

Galium verum L. collected at the experimental "Balapan" site also shows similar changes. In plant stems from the contaminated area, the thickness of the epidermis increases by 29.91 ±2.35 μR, the thickness of the parenchymal layer and the thickness of the phloem also increase. In the leaves of plants with the *EDR* of 1.69 mS·v·h^{-1}, the thickness of the palisade and spongy mesophyll, and the area of the conducting bundles increase as well. Thus, in the conditions of radioactive contamination, with an increase in the *EDR* of gamma radiation, plants respond and changes occur in their internal structure: thickness of the epidermis, thickness of the sclerenchymal layer, diameters of the xylem vessels and the area of the conducting beams increase. All these are adaptive features that have apparently arisen under the influence of a complex of environmental factors, including radiation pollution. Research to some extent confirms the literature data. Morphological and structural changes are found in *Stipa capillata* L., *Festuca valesiaca* Gaud., *Agropyron cristatum* L., Gaertn. collected from contaminated and control sites. With an increase in the *EDR* of gamma radiation, the internal structure of the stem increases: thickness of the epidermis, thickness of the sclerenchymal ring, diameters of the xylem elements, and the area of the conducting beams.

Spiraea hypericifolia L. According to quantitative indicators, changes in the internal structure of the stem of *Spiraea hypericifolia* L. were recorded in different sites of the polygon. In the stem of *Spiraea hypericifolia* L., the thickness of the periderm at site no. 2 (north-east of Lake Chagan) was 109.16 μR, while in the control site the thickness of the periderm of the stem was 93.65 μR. The same increase in indicators for plants from the contaminated and control areas occur as regards the thickness of the radial beam, number of rows of cells in the radial beam, and the number of xylem vessels between radial rays. Thus, the thickness of the radial beam in plants at section no. 2 was 71.69 μR, and in the control (section no. 3) 36.26 μR. The area of conducting beams in the contaminated area and control area were $6.05·10^{-3}$ mm^2 and $4.47·10^{-3}$ mm^2, respectively. When comparing the anatomical structure of plants in natural phytocenoses, changes in quantitative indicators in the internal structure of the leaf of *Spiraea hypericifolia* L. were revealed. There was an increase in the thickness of the palisade mesophyll and the area of conducting bundles depending on the growth conditions. In the leaf tissue on the north-eastern shore of Lake Chagan, the thickness of the palisade mesophyll was 58.51 ±1.21 / 58.02 ±1.02 μR, in the more polluted area of the well 61.22 ±1.53 / 60.99 ±2.17, on the clean section of the well 55.38 ±2.42 / 56.25 ±0.75 μR, and on the control 45.39 ±1.55/46.01 ±0.02 μR.

An increase in the area of conducting bundles of plant leaves from polluted areas was 51.87 ±2.87, whereas in the control 40.43 ±1.16. The number of rows of the palisade mesophyll was not changed. According to the gamma-ray spectrometric analysis, the following radionuclides were detected in the aboveground parts of plants from the north-eastern shore of Lake Chagan: ^{40}K, ^{232}Th, ^{238}U, ^{60}Co. Many long-lived radionuclides were recorded in the soil from the plant samples: ^{40}K, ^{232}Th, ^{238}U, ^{60}Co, ^{241}Am, ^{137}Cs, ^{152}Eu, ^{154}Eu. In the underground mass of *Spiraea hypericifolia* L. the following radionuclides were detected: ^{40}K, ^{232}Th, ^{238}U, ^{60}Co, ^{137}Cs, ^{152}Eu, ^{154}Eu. The data show that ^{40}K, ^{232}Th, ^{238}U, ^{60}Co, ^{241}Am, ^{137}Cs, ^{152}Eu, ^{154}Eu increased concentrations in the soil and underground parts of plants. A comparative analysis of the content of radionuclides in various parts of plants (aboveground and underground) showed that the specific activity of technogenic radionuclides in the underground part was higher than in the aboveground part. In the latter the greater specific activity was only ^{40}K. The low specific activity of ^{232}Th, ^{238}U in the aboveground and underground parts of plants should be noted. Despite the fact that ^{241}Am, ^{137}Cs, ^{152}Eu, ^{154}Eu dominated among other radionuclides in the surface layers of the soil on the north-eastern shore of Lake Chagan, *Spiraea hypericifolia* L. did not accumulate them in the aboveground mass of plants. In the underground mass of *Spiraea hypericifolia* L., ^{40}K (161 ±52 Bq·kg^{-1}), respectively in plot 1 and 2, and ^{137}Cs (164 ±13 Bq·kg^{-1}), respectively in plot 1 and 2, were distinguished by increased specific activity.

As in the samples from the north-eastern shore of Lake Chagan, the gamma-ray spectrometric analysis showed that gamma-emitting radionuclides were recorded in samples from the contaminated site. ^{40}K, ^{232}Th, ^{238}U, ^{60}Co, ^{241}Am, ^{137}Cs were found in soil samples from the contaminated site, and ^{40}K, ^{232}Th, ^{238}U, ^{137}Cs were found on the "clean" site. Comparative analysis of the specific activity of radionuclides in aboveground and underground parts of *Spiraea hypericifolia* L. It also showed that the underground mass of the plant accumulated radionuclides in larger quantities than the aboveground mass. The increased specific activity of ^{137}Cs from the sites was shown in soil samples from the contaminated well 1301 – 13836 ±553 Bq·kg^{-1}, respectively in plot 1 and 2, when in the control area it was 11 ±2 Bq·kg^{-1}, respectively in plot 1 and 2.

In the samples of soil, aboveground and underground mass of plants taken from the polluted and clean section of the well 1301, radionuclides were not found. The data from gamma-spectrometric and radiochemical analyses of the content of radionuclides in the aboveground and underground parts of *Spiraea hypericifolia* L., as well as in the soil at the sites of plant selection with different equivalent dose rates of gamma radiation indicated that in the area of the north-eastern shore of Lake Chagan and in the more polluted area of well 1301, the specific activity of radionuclides was high, which was reflected in the anatomical structure of the plant, e.g. leaves showed an increase in the area of conducting beams and the thickness of the palisade parenchyma, whereas in the stem, an increase in the thickness of the periderm, thickness of the radial rays, and area of the xylem vessels, and in the root, an increase in the thickness of the periderm, thickness of the radial ray, and the area of the xylem vessels. The aboveground part of *Spiraea hypericifolia* L. did not differ much in the intensity of the accumulation of radionuclides, the accumulation of radionuclides occured in the underground mass.

Ephedra distachya L. The stem consisted of a primary cortex covered by the epidermis, a central cylinder. Epidermal cells with unevenly thickened walls were elongated parallel to the stem. The cuticle was folded. In the contaminated area, the thickness of the primary stem bark was 167.445 ±3.766 μR, whereas in the control area 165.42 ±6.88 μR. The cells of the parenchyma were somewhat larger than epidermal cells and chlorophyll-bearing. In the parenchyma, sclerenchyma was found under the epidermis in the form of separate sections. It also accompanied the phloem of the conducting bundle. The number of sclerenchymal sites in the contaminated area was 30.5 ±0.5, and in the control area it was 28.33 ±0.38. In the cells of the parenchyma, calcium oxalate crystals were also found. Conducting bundles of various sizes, open, collateral, were arranged evenly around the circumference of the stem. Large conducting beams alternated with smaller ones. The number of conducting beams in both sections was the same. The interleaf cambium was well developed. The core was composed of parenchymal cells. The peripheral part of it, adjacent to the conducting tissue, was characterised by small cell sizes. The secretory system of the stem was represented by receptacles located in the bark and core. This gives reason to believe that in the polluted area, as a result of chronic exposure to ephedra, adaptive systems were induced and a new type with increased morphometric parameters was for *EDR*.

CONCLUSIONS

Authors have studied the anatomical and morphological structure of different plants under the conditions of long-term chronic action of ionising radiation on the territory of the Semipalatinsk test site. Studies found that when the *EDR* of gamma radiation increased, plant growth was stimulated, and the height of stems, as well as the length and width of leaf blades increased (*Stipa capillata* L., *Agropyron cristatum* (L.) Gaertn., *Festuca sulcata* Hack., *Galium verum* L.), and the flowering phase occurred earlier (*Galium verum* L.). With an increase in the *EDR* of gamma radiation to 360 mS·v·h^{-1} (*Artemisia sieversiana* Willd., *Ephedra distachya* L.), on the contrary, there was a decrease or inhibition of growth, the shape of the stem changed, as well as the type of leaf arrangement.

Thus, under conditions of radioactive contamination, with an increase in the activity of alpha, beta and gamma radiation, plants responded with changes in their internal structure. Moreover, in herbaceous perennials, changes were more noticeable in aboveground organs, and in shrubs and semi-shrubs in their underground ones. All these were adaptive features that apparently developed under the influence of a complex of environmental factors, including radiation pollution.

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