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PRODUCTIVITY ASSESSMENT OF VARIOUS PLANT COMMUNITIES AT URANIUM MINE SITES IN CENTRAL KAZAKHSTAN

**A. BUGUBAEVA[1,2], A. KUPRIJANOV[3], V. CHASHKOV[1*], S. KUANYSHBAEV[1], K. VALIEV[1], S. MAMIKHIN[6], A. SHCHEGLOV[6], A. NUGMANOV[6], A. BULAEV[4], G. SULTANGAZINA[1], K. KUNANBAYEV[5], O. CHERNYAVSKAYA[1], G. BAUBEKOVA[1], G. RUCHKINA[1],
O. SAFRONOVA[6], M. UXIKBAYEVA[1], and Y. SOKHAREV[7]**

[1]A. Baitursynov Kostanay Regional University NJSC, Kazakhstan
[2]Lomonosov Moscow State University, Russia
[3]Kuzbass Botanical Garden, Russian Federal State Research Center of Coal and Coal Chemistry SB RAS, Russia
[4]Research Center of Biotechnology, Russian Academy of Sciences, Russia
[5]Scientific and Production Center of Grain Farming named after A.I. Barayev LLP, Kazakhstan
[6]Laboratory of Agrochemical Analysis, Zarechnoye Agricultural Experimental Station LLP, Kazakhstan
[7]Municipal State Company "Kostanay Regional Pathoanatomical Bureau" of the Health Department of the Akimat of Kostanay Region, Kazakhstan
*Corresponding author's email: vadimnc@mail.ru
Email addresses of coauthors: alia-almaz@mail.ru, Kupr-42@yandex.ru, kuanyshbayev65@bk.ru, v-gulnar-abay@mail.ru, svmamikhin@mail.ru, a.i.shcheglov@soil.msu.ru, almabek@list.ru, bulaev.inmi@yandex.ru, gul_sultan@mail.ru, kai-82@mail.ru, chernyavskaya_ol@mail.ru, baubekova1973@mail.ru, all2007ra@mail.ru, olga_safronova73@mail.ru, u.muldir@mail.ru, tdutybq_1981@mail.ru

SUMMARY

Examining the overgrowth of dumps, techno-soils, and areas containing waste products of uranium mines is vital for understanding the dynamic features of vegetation cover in technogenic landscapes. The main aim of this study was to investigate variations in the plant species composition and their productivity in dumps and technological areas and the intensity of soil ionizing radiations under varying environmental conditions based on the Shantobe Uranium Deposit, Kazakhstan. The vegetation at the waste dumps and technogenic sites is in the early stages of syngenesis and is representative of pioneer and group-thicket communities. Adverse ecological conditions associated with intense sulfate salinization formation thrive at the technological sites. However, the floristic composition is illustrative of highly resistant species (*Calamagrostis epigejos* and *Phragmites australis*) and secondary species. Typically the formation of steppe zone plant communities of Kazakhstan does not occur in these sites. The productivity of the recultivated dump and banks of the former uranium mine is quite high at 120–150 g/m^2, which matches the meadow-ruderal communities of Northern Kazakhstan. However, the lowest productivity of 30–37 g/m^2 emerged in the non-recultivated and partially processed sulfuric acid heap leaching stacks containing uranium ore, which create exceedingly unfavorable conditions for the establishment of crop plants. Several plant species identified as self-seeding live in partially processed piles of sulfuric acid heap-leaching uranium ores

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with a sufficient level of resistance to survive in soil with high levels of sulfate-containing salts and ionizing radiation of 1200–1400 μR/hr. These facts can authenticate to consider the possibility of growing these plant species in the artificial grassing of uranium-containing dumps to create herbage.

Keywords: Shantobe Uranium Deposit, Kazakhstan, technogenic sites, uranium-bearing ores, sulfate-containing salt-resistant plant species, floristic composition, ionizing radiation, recultivated dump

Key findings: The presented study identified that several plant species have enough resistance to survive and grow well on sulfuric acid heap-leaching uranium ores and soils with high sulfate-containing salts and ionizing radiation (1200–1400 μR/hr). It confirms the possibility of using these plant species for artificial grassing in uranium-containing soils to create herbage.

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INTRODUCTION

In the middle of last century, when intensive studies on the features of overgrowth of dumps started, the uniformity at the initial stages of syngenesis on the dumps was repeatedly accentuated, i.e., settlement → accumulation of species → stabilization → para zonal community (Manakov *et al*., 2011). Zonal plant communities appeared to have not formed on the currently existing dumps. Despite the uniformity of processes of dump overgrowth, this process has zonal features due to environmental factors and usually the moisture distribution in the dumps (Kumar *et al*., 2020; Nugmanov *et al*., 2022a, b; Zhao *et al*., 2022).

The vegetation occurrence in dumps links with the soil formation process, with the rate of its incidence also defined by favorable and unfavorable environmental factors (Kupriianov *et al*., 2017; Gusev *et al*., 2022; Utebayev *et al*., 2022). The study of the overgrowth of dumps, techno-soils, and areas containing waste products of uranium mines is helpful and relevant both for understanding the dynamic features of vegetation cover in technogenic landscapes (Glazyrina *et al*., 2016; Bekezhanov *et al.*, 2020; Bugubaeva *et al*., 2022) and practical use of this information in the planning and development of re-cultivation of various plant species resilient to uranium-containing soils (Kupriianov and Manakov, 2016; Navasardova *et al.*, 2021).

There are virtually no studies on the overgrowth of the dumps and technogenic sites of uranium mines in this region, as well as, on the productivity data of various plant communities emerging on the dumps and technological sites. As part of the preliminary accumulation of information on this issue, the study team determined from June to July 2022, the occurrence of various plant species on the banks of a natural radioactive effluent accumulator reservoir at the Grachevsk Uranium Deposit in Kazakhstan (Bugubaeva *et al*., 2022). The recent research also aimed to identify plant species with resistance to high sulfate-containing salts and ionizing radiation sites observed in the sulfuric-acid heap and uranium ores. It will also allow exploration and the possible use of these plant species in the artificial grassing of uranium-containing dumps, tailings, and stacks, to create herbage (Kupriianov and Manakov, 2016; Glazyrina *et al*., 2016).

The presented study findings can help develop and apply technologies for the artificial overgrowth of reclaimed uranium deposit mine sites, including industrial waste dumps, liquid uranium waste storages, and technogenic sites with dumps of uranium-bearing ores. The study mainly aimed to investigate variations in the plant species composition and productivity in landfills and technological areas and the intensity of soil ionizing radiations under varying environmental conditions based on the Shantobe Uranium Deposit, Kazakhstan.

MATERIALS AND METHODS

The recent study ran from June to July 2022 at the mine sites of the Shantobe Village (Balkashinskoe) Uranium Deposit, located in the Northwestern part of the Akmola region, Kazakhstan (Figures 1 and 2). Under the regulatory requirements of the Republic of Kazakhstan and the resolutions of intergovernmental bodies (the International Atomic Energy Agency [IAEA] and the Commonwealth of Independent States), Kazakhstan organizes and performs re-cultivation activities of various resistant plant species at former uranium mine sites. The re-growing measures include restoring soil cover and the creation of a so-called re-cultivation layer, which provides favorable conditions for the plant's growth (Commission of the Commonwealth of Independent States, IAEA, and Parliament of the Republic of Kazakhstan, 2021). The former uranium mines located in the Shantobe Uranium Deposit, Kazakhstan facilities, operate the re-cultivation and conservation within the framework of the established requirements.

The uranium deposit areas locate within the Kokchetav Upland and the steppe zone of Kazakhstan. The main element of the region's relief is an undulating plain with isolated groups of hills scattered on the surface across the area. The climate is also acutely continental and arid, with warm summers and cold winters. It belongs to the West Siberian climatic region of the temperate zone. The average July air temperature in the territory is 18.5 °C–21.2 °C, and the average January air temperature is around 14.3 °C–16.5 °C. The average monthly air temperature reaches its highest value in July and the lowest in January (Baisholanov, 2017).

In the territory, there is a significant variation in average monthly temperatures in the warmest period of the year, gradually decreasing by winter. Likewise, in the region, the annual sum of total solar radiation (MQ) varies from 6100 to 6500 MJ/m^2 when the sky is clear and between 4600 and 5000 MJ/m^2 under moderately cloudy conditions. In this case, the Earth's surface received about 75% of the possible total radiation. The deposits' location is in a relatively humid and warm agroclimatic zone. The average precipitation for the warm season is 260–280 mm. The moisture coefficient K for the Balkashino station is 1.14, which is also consistent with optimal and stable moisture supply. The specified area mostly has sandy loam and dark chestnut soils (Baisholanov, 2017).

The studied territory is characteristically a steppe type of vegetation, and the common species are Silaum-Stipa steppes (*Silaum silaem* + *Stipa zalesskii*) (Kupriianov, 2020; Sultangazina *et al*., 2020). The inter-forest spaces are also with meadow steppes, characterized by the presence of *Eremogone koriniana* (Fischer ex Fenzl) Ikonn, with replacements of *E. longifolia* (Bieb.) Fenzl in steppe meadows. The basis of the herbage was turfgrasses (*Stipa rubens* P. Smirn., *Festuca valesiaca* Gaudin, *Helictotrichon desertorum* [Less.] Nevski, *Koeleria cristata* L. Pers.) and rhizomatous and loose-bunch grasses (*Calamagrostis epigejos* L. Roth., *Elytrigia repens* L. Nevski, *Phleum phleoides* L. H. Karst). An essential component of said herbage were meadow-steppe species, i.e., *Filipendula vulgaris* Moench., *Fragaria viridis* (Duchesne) Weston., *Astragalus onobrychis* L., *Oxytropis pilosa* L. DC., *Seseli libanotis* L. W.D.J. Koch, and *Medicago falcata* L. (Ruchin, 2014; Nugmanov *et al*., 2022a, b).

The conducted studies were on the following ecotopes, i.e., a recultivated dump, the shores of a flooded uranium mine decommissioned over 50 years ago, the surface of sulfuric-acid-leaching stacks of uranium ore, the banks of reservoirs formed from the accumulation of natural precipitations and remnants of waste solutions that had flowed from the stacks, and the shores with accumulated evaporation basins of liquid containing uranium waste. The study also determined the vegetation cover, floristic composition, and syngenesis stages (Kupriianov and Manakov, 2016; Kupriianov, 2020). For phytomass accounting, the above-ground parts received eight repetitions of mowing at the soil level on each ecotope, with laboratory processing also performed on the same day (Ruchin, 2014; Nugmanov *et al*., 2022a). Each fraction underwent the following

Figure 1. Shantobe uranium deposit on the map of the Republic of Kazakhstan.

Figure 2. The territory of the Shantobe (Balkashinskoe) deposit. 1: Shantobe village, 2: the territory of the old mine, decommissioned, and 3: the deposit mine, mothballed.

steps: wrapping in paper, drying in a cabinet of the TS-200 SPU type with forced ventilation at 50 °C up to a constant air-dry state, and then weighed and re-weighed on a scale of the VLKT-500 type with an accuracy of 0.1 g.

Assessing the intensity of residual ionizing radiation, including gamma-radiation, used an analyzer of ionizing radiation intensity with appropriate metrological characteristics and an accuracy class of a professional class type SBM-20 (SOEKS, Russia). During the assessment, the team followed the recommendations in the measurement and control methods of radioactive radiation factors and considered the work features in the field and expediency (Rosstandart, 2014). Statistical analysis (ANOVA) employed Microsoft Excel and AGROS 2.11. The said method also assessed and compared the differences among several groups of observations.

RESULTS

Decommissioned Shantobe deposit

The northern part of the Shantobe village has an area of the old decommissioned mine. Two recultivated objects of the Shantobe deposit, located on this territory, are cultivated industrial waste dumps and a flooded, exhausted open pit uranium mine (Figure 3).

Figure 3. The territory of the old mine of the Shantobe deposit, decommissioned. 1: Recultivated dump and 2: Flooded uranium mine.

Figure 4. General view of the recultivated dump.

Recultivated dump

The mining-technical stage of re-cultivation started in 2002–2006 and consisted in shaping the dump with a 15° slope and placing a 1-m layer of dark-chestnut soil. At present, the dump site is a hill about 60 m high. The dump was left to self-overgrow (Figure 4).

A group-thicket community of 28 species has formed at the dump. Among these, the species, i.e., *Artemisia absinthium* L., *A. austriaca* Jacq., and *Elytrigia repens,* have the most significant population and dominate the other species. The productivity of the phytocenosis was 122.8 ± 20.8 g/m^2 at the base of the slope, 120.4 ± 23.6 g/m^2 in the middle, and 142.4 ± 32.8 g/m^2 at the top. The ionizing radiation intensity was within 10–20 μR/hr (Table 1).

Shores of the flooded uranium mine

After open-pit mining, the uranium mine was flooded about 50 years ago (Figure 5). Meadow-steppe communities belonging to a complex phytocenosis have formed along the shores. An intensive anthropogenic load influenced the vegetation cover formations, as the quarry served for recreational purposes. The dump has 26 plant species populations,

Table 1. Productivity of vegetation cover of objects in the old Shantobe deposit mine, decommissioned.

Location	Character of plant communities	Coordinates	Intensity of ionizing radiation (μR/hr)	Productivity, (g/m^2) (n=8)
Recultivated dump, base of the slope	Group-thicket community	52. 46721° N, 68. 18835° E, 393 masl	15–20	122.8±20.8
Same, middle part of the slope	Group-thicket community	52. 46347° N, 68. 1875° E, 400 masl	15–20	120.4±23.6
Same, top	Group-thicket community	52. 46913° N, 68. 18655° E, 416 masl	10–15	142.4±32.8
Shores of the flooded uranium mine	Complex phytocenosis	52. 46505° N, 68. 18849° E, 374 masl	40–50	158.0±21.2

Figure 5. General view of the flooded uranium mine.

with the most abundant species comprising *Artemisia absinthium* L., *A. dracunculus* L., *Elytrigia repens* L., *Eryngium planum* L., and *Onobrychis arenaria* L. (Kit.) DC. Plant productivity reaches 158.0 ± 21.2 g/m^2, and the ionizing radiation intensity ranges from 40 to 45 μR/hr (Table 1).

Mothballed Shantobe mine

Recently mothballed uranium mine sites appear in Figure 6. These sites include stacks of direct surface uranium ore sulfuric acid leaching, ponds formed from precipitation, moisture runoff from the stacks, and evaporation basins serving as liquid waste accumulators.

Stack No. 1-2-3

The area with partially processed uranium ore stack undergoing surface sulfuric acid leaching has since mothballed in 2012. Soils on the surface were highly saline with sulfates due to the impact of technological solutions with sulfuric acid. Figure 7 also shows the white sulfate-containing areas. Vegetation cover is at the stage of pioneer community plants settle on micro-depression, the developed fine-grained plots, and their total projective coverage was less than 30%. The dump has 17 species; however, the most populous were *Artemisia absinthium* L., *Artemisia dracunculus* L., *Calamagrostis epigejos* L., and *Oberna schottiana* L. (Schur) Tzvelev. Their productivity amounts to 37.2 ± 10.5 g/m^2, while the ionizing radiation intensity was 400–600 μR/hr (Table 2).

Figure 6. The territory of the mothballed Shantobe deposit mine. Technological sections of the mine marked on a satellite map.

Figure 7. The top part of stack No.1-2-3 of heap sulfuric acid leaching.

Table 2. Productivity of the vegetation cover of the mothballed Shantobe deposit mine facilities.

Locations	Character of plant communities	Coordinates	Intensity of ionizing radiation (μR/hr)	Productivity, (g/m^2) (n=8)
Stack 1-2-3, top	Pioneer community	52. 44336° N, 68. 23865° E, 376 masl	400–600	37.2±10.5
Stack No. 6, top	Pioneer community	52. 44808° N, 68. 24228° E, 391 masl	1,200–1,400	30.7
Reservoir near stack No. 1-2-3	Group-thicket community	52. 44336° N, 68. 23865° E, 374 masl	350–450	116.0±24.8
Reservoir No. 2, severe sulfate salinization	Pioneer community	52. 44788° N, 68. 24239° E, 379 masl	350–450	79.6±11.8
Evaporation basin No. 5	Pioneer community	52. 45088° N, 68. 24964° E, 366 masl	60–70	95.6±21.2
Evaporation basin No. 1	Pioneer community	52. 45559° N, 68. 25622° E, 370 masl	80–90	31.6±7.0

Stack No. 6

A partially processed stack of uranium ore site subjected to surface sulfuric acid leaching has stood still since 2012. The soils were highly saline with sulfates due to exposure to process solutions containing sulfuric acid, with the sulfate-containing white areas shown in Figure 8. The vegetation cover illustrative of a pioneer community formed where the fine-grained soil has washed away has a projective coverage of less than 5%. A total of eight species emerged on the dump, including self-seeding birches (*Betula pendula* Roth.) and poplars (*Populus* × *sibirica* G. Kryl. et Grig. ex A. Skvort.) with 0.5–0.7 m in height. The most populous species were *Calamagrostis epigejos* L. and *Oberna schottiana* L*.* Overall, the productivity of the plants was 30.7 g/m^2, while the ionizing radiation intensity was 1200–1400 μR/hr (Table 2).

Uranium extraction stacks consisted of uraninite treated with sulfuric acid. As a result, these stacks were highly permeable, preventing plant settlement. Formation of plant communities, accumulating fine-grained deposits of nanorelief elements, has molded from water erosion. Even small areas of fine-grained deposits of 5–10 cm are well-washed and capable of retaining moisture.

Reservoir near stack No.1-2-3

The reservoir age was about 10–15 years, with a natural accumulator of precipitation and runoff from the adjacent uranium ore stack (Figure 9). Piles made up of pieces of partially processed uranium ore also showed in the foreground. The intensity of ionizing radiation highly exceeds the norm by about 10 times. A group-thicket community with projective coverage of about 70% developed along the shoreline; however, the overgrowth starts at the water's edge, and the floristic composition includes 10 species. Yet, the highest projective coverage resulted from *Calamagrostis epigejos* L. and *Phragmites australis* L. (Cav.) Trin. ex Steud. Plant productivity amounts to 116.0 ± 24.8 g/m^2, while the intensity of ionizing radiation on the shore reaches 350–450 μR/hr (Table 2).

Reservoir No.2

The reservoir was roughly 10–15 years old, representing a natural accumulator of precipitation and runoff from the adjacent uranium ore stack. Behind the reservoir in Figure 10, stacks of nearly untreated uranium ore appear. The intensity of ionizing radiation was well above the norm by a factor of about 10. Overgrowth occurs at least 1.5 m from the water's edge because of severe sulfate salinization. The pioneer community that has formed has a 50% projective coverage. The floristic composition includes 13 species, with the extensive covering shown by *Calamagrostis epigejos* L. and *Phragmites australis* L. Plant productivity was 79.6 ± 11.8 g/m^2, and the ionizing radiation intensity on the dump-shore-reservoir line was around 350–450 μR/hr (Table 2).

Evaporation basin No.5

Evaporation basin No. 5 remained unused since 2013 (Figure 11). Overgrowth starts at least 1.5 m from the water's edge, which might be due to severe sulfate salinization. A pioneer community formed has a 30% projective coverage. The floristic list includes 10 species, dominated by two species, i.e., *Calamagrostis epigejos* L. and *Phragmites australis* L. Productivity reach 95.6 ± 21.2 g/m^2, while the ionizing radiation intensity ranges from 60 to 70 μR/hr (Table 2).

Evaporation basin No.1

Evaporation basin No. 1 has also remained idle since 2013 (Figure 12). A pioneer community with a 3% projective coverage has formed. At a distance of 1–1.5 m from the water's edge, the single groups of species *Calamagrostis epigejos* L. and *Phragmites australis* L. individuals appeared; however, the higher rim was of birch sprouts (*Betula pendula* L.). Plant productivity was around 31.6 ± 7.0 g/m^2, with the intensity of ionizing radiation within 80–90 μR/hr (Table 2).

Figure 8. The top part of stack No. 6 of heap sulfuric acid leaching.

Figure 9. General view of the reservoir near stack No. 1-2-3.

Figure 10. General view of reservoir No. 2.

Figure 11. General view of evaporation basin No. 5.

Figure 12. General view of evaporation basin No. 1.

DISCUSSION

The vegetation cover of the dumps and technogenic sites of the Shantobe uranium mine is in the early stages of syngenesis, illustrative of pioneer and group-thicket communities. Adverse environmental conditions associated with severe sulfate salinization have formed at the technological sites. This fact gives reason to consider the possible use of these plant species in the artificial grassing of uranium-containing dumps, tailings, and stacks to create herbage. The overgrowth of the recultivated dump was well within the classical scheme of syngenesis and largely revoked the ionizing radiation (Parliament of the Republic of Kazakhstan, 2021). On degraded chernozems and solodized soils, the productivity also roughly corresponds to meadows (Ruchin, 2014; Nugmanov *et al*., 2022b).

Most studies on overgrowth of flooded mines were in the territory of depleted coal quarries. In vegetation cover during syngenesis, the typical change occurred to be: the pioneer stage, which lasts 2–3 years, a group-thicket community, and then a diffuse community. The sub-arid zone of Kazakhstan has the formation of dispersed communities on dumps occurring for 30 years at the beginning of the shoreline (Kupriianov *et al*., 2017; Bugubaeva *et al*., 2022). In this case, the rocky shores and the lack of a fine-grained part near the shore edge prevented the formation of supralittoral vegetation (Glazyrina *et al*., 2016; Nugmanov *et al*., 2022a, b). In reality, ruderal-meadow vegetation covered the banks of the quarry, typical of the Kokchetav floristic area (Kupriianov, 2020).

Overgrowth of water bodies usually starts from the water's edge. On the evaporation basins, profusion begins at least 1.5 meters from the water's edge, although the soils were extremely wet. The radioactivity level might not have caused that, but the degree of salinization (Vesselova *et al*., 2022). In the steppe zone of Kazakhstan, the solonchak and solonetz soils were commonly associated with *Artemisia pauciflora* L. and *Atriplex cana* L. dominating the other species. The typically appearing species on solonetz soils were *Atriplex verrucifera* Bieb., *Anabasis salsa* (C.A. Mey.) Benth. ex Volkens*, A. truncata* (Schrenk) Bunge*, Limonium gmelinii* (Willd.) Kuntze*,* and *Poa bulbosa* L. (Ruchin, 2014; Kupriianov, 2020; Nugmanov *et al*., 2022a, b). However, typical halophytes have not surfaced around the studied reservoirs.

CONCLUSIONS

The floristic makeup is of highly resistant species (*Calamagrostis epigejos* and *Phragmites australis*) and incidental species. The formation of halophilic complexes typical of the steppe zone of Kazakhstan does not occur. The productivity of the recultivated dump and the shores of the former uranium mine was quite high at 120–150 g/m^2, corresponding to the meadow-ruderal communities of Northern Kazakhstan. The lowest productivity is 30–37 g/m^2 on the non-recultivated partially processed sulfuric acid heap leaching stacks containing uranium ore. The study identified several plant species (self-seeding) that populate partially processed stacks of sulfuric acid heap-leaching uranium ores and have enough resistance to survive in soils with high levels of sulfate-containing salts and ionizing radiation of 1200–1400 μR/hr. The presented findings can serve to assess the conditions of uranium mine sites and design measures for the recultivation of industrial uranium-containing waste dumps and reservoirs. This study was limited to the mine sites of the Shantobe Uranium Deposit, located in the northwestern part of the Akmola region, Kazakhstan. In further research, it is necessary to study plant communities at uranium mine sites in other zones of Kazakhstan.

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