JEE ISSN: 2288-1220
https://doi.org/10.5141/jee.25.023
Journal of Ecology and Environment (2025) 49:14

RESEARCH

Influence of anthropogenic pollution on ecological and morphological characteristics of the narrow-headed vole (*Stenocranius gregalis* Pallas, 1779) in steppe ecosystems of the Pavlodar Pre-Irtysh region

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ARTICLE INFO
Received March 31, 2025
Revised May 20, 2025
Accepted June 13, 2025
Published on July 2, 2025

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Background: The article presents the results of a comprehensive study of the impact of industrial pollution on narrow-headed vole (*Stenocranius gregalis* Pall., 1779) in steppe ecosystems of Pavlodar Pre-Irtysh. Studies were conducted in different zones of industrial pollution, including impact, buffer and background zones near the aluminum production of Pavlodar city, as well as in the control area. Various ecological parameters including population size, its age and sex structure, morphological and cranial characteristics of animals, as well as fluorine content in bone tissue were evaluated.
Results: The results showed that aluminum production emissions have a significant effect on reducing the population size, morphological and cranial parameters of narrow-headed vole. It was found that fluorine accumulation near emission sources reaches the highest values and decreases with distance from the plants.
Conclusions: The obtained data confirm that the narrow-headed vole is a reliable bioindicator of industrial pollution, which makes this species a model species for ecological monitoring of anthropogenic impact on steppe ecosystems.

Keywords: accumulation, bioindicator, craniology, fluorine, industrial pollution, morphology, *Stenocranius gregalis*

Introduction

The territory of Pavlodar Pre-Irtysh is located within the boundaries of Pavlodar region in the extreme northeast of the Republic of Kazakhstan. It is located in the central part of the Eurasian continent in the zones of forest-steppe, steppe and semi-desert, along the middle course of the Irtysh River. Most of Pavlodar Pre-Irtysh is located in the Pre-Irtysh Plain (the whole north and northeast), which is the southern tip of the West Siberian Plain. The northeastern part of the study area borders the Baraba steppe, and the eastern and southeastern parts border the Kulunda steppe. Absolute heights of these steppes are 100–130 m. The surface of the territory of Pavlodar Pre-Irtysh has a general inclination from south to north, moreover, in the south the average altitude is 350 m, in the north - 100 m, and near the city of Pavlodar does not exceed 145–150 m. Geologically, the region belongs to the southern part of the West Siberian Plate, composed of sedimentary, magmatic and metamorphic genesis rocks, as well as to the northeastern part of the Kazakh hummocky terrain (Pavlodar Pre-Irtysh 2003).

To the present time, detailed studies have been conducted on the impact of harmful emissions of industrial production on the population of rodents and insectivores. These works address the issues of species composition and population dynamics of small mammals in the gradient of distance from industrial emissions of ferrous and nonferrous metal industry enterprises (Demina et al. 2011; Katayev 2014; Mukhacheva et al. 2010). Much attention has been paid to the impact of industrial pollution on morphological and physiological parameters of small mammals (Ivanter and Medvedev 2015; Lyubashevsky and Starichenko 2010; Shevliuk et al. 2013; Zemlyanoy et al. 2001), as well as on their cranial structure (Yalkovskaya et al. 2016). Many authors suggest using the bank vole, Northern Red-backed Vole and yellow-necked wood mouse as indicator species of local pollution (Al Sayegh Petkovšek et al. 2014).

In Central and North-Eastern Kazakhstan, toxicological studies on the accumulation of heavy metals in the internal organs of small mammals as a result of the activity of the Temirtau metallurgical plant and Pavlodar-Ekibastuz industrial complex have been carried out (Atalikova 2009; Shaimardanova 2010). Previously, within Pavlodar Pre-Irtysh, studies on the impact of aluminum production on the structure of small mammal communities, on their population characteristics, as well as on the accumulation of fluorine in the bone tissue of animals were conducted (Dupal et al. 2017; Sergazinova 2023; Sergazinova et al. 2017, 2018).

The ecological condition of steppe ecosystems under anthropogenic impact is an up-to-date problem of modern science. Of particular interest are the processes of transformation of such ecosystems under the influence of anthropogenic factors, including emissions of toxicants such as fluorine. These changes have a significant impact on biodiversity, community structure and adaptation mechanisms of species that play a key role in ecosystem functioning.

The narrow-headed vole (*Stenocranius gregalis*) is one of the typical representatives of steppe fauna, known for its high ecological plasticity and ability to respond sensitively to habitat changes. This species is an important object for research, as its abundance and the state of its populations can serve as an indicator of the ecological well-being of steppe ecosystems.

Existing studies are mainly devoted to the study of the ecology of the narrow-headed vole in natural conditions, including the issues of population dynamics, morphophysiological adaptations and distribution features (Balakhonov et al. 1997; Balakhonov and Stroh 1995; Danilov 2000; Dupal and Abramov 2010; Malkova et al. 2003; Prokopyev and Vinokurov 1986; Shvartz 1980). However, studies concerning the influence of anthropogenic factors, including fluorine pollution, on the ecological and morphological characteristics of this species are practically absent. This creates a gap in understanding the mechanisms of adaptation of the narrow-headed vole to the conditions formed by industrial impact and requires further study.

The purpose of this study is to analyze the influence of industrial pollution on ecological and morphological characteristics of narrow-headed vole in different zones of industrial load of Pavlodar Pre-Irtysh.

Materials and Methods

Field studies were conducted on 12 sample plots in similar biotopes located in three zones of anthropogenic load. The zones were allocated on the basis of literature data (Mukhacheva 2005), taking into account the degree of transformation of ecosystems under the influence of emissions of aluminum production enterprises (JSC «Aluminum of Kazakhstan» and JSC «Kazakhstan electrolysis plant») (Fig. 1).

Allocation of zones and placement of sites:

1. *Impact zone:* covers the territory at a distance of up to 0.5–3 km from the sources of pollution. Five sample plots were selected here:
- mixed grass-wormwood steppes (I1, I2);
- mixed grass-feather grass-wormwood steppes (I3, I4);
- mixed grass-fescue grass steppe (I5).

2. *Buffer zone*: located at a distance of 3–5 km from pollution sources. It includes three areas:
- fescue grass-wormwood steppe (B6);
- wormwood-feather grass steppe (B7);
- mixed grass-fescue grass steppe (B8).

3. *Background zone*: 20–25 km away from pollution sources. It includes four sites:
- fescue grass-wormwood steppes (F9, F10);
- wormwood steppes (F11, F12).

The conditionally non-polluted Karasuksky site (Kk) was selected as a control area. It is located 200 km away from Pavlodar, in the northeastern direction, in the vicinity of the village of Troitskoye (Russian Federation, Novosibirsk region).

The studies were conducted on the territory of the Karasuksky research station of the Institute of Systematics and Ecology of Animals SB RAS. The site is represented by the following biotopes: an area of cereals-mixed grass vegetation on the lake shore, fescue grass-cereals-mixed grass steppe, a small area of feather grass-fescue grass steppe along a forest belt, and an area of arable field overgrown with cereals-mixed grass vegetation. In addition, to study interpopulation morphological variability, we also used data from the Biysky control plot (BC), located in the southern forest-steppe subzone in the vicinity of Biysk (Al-

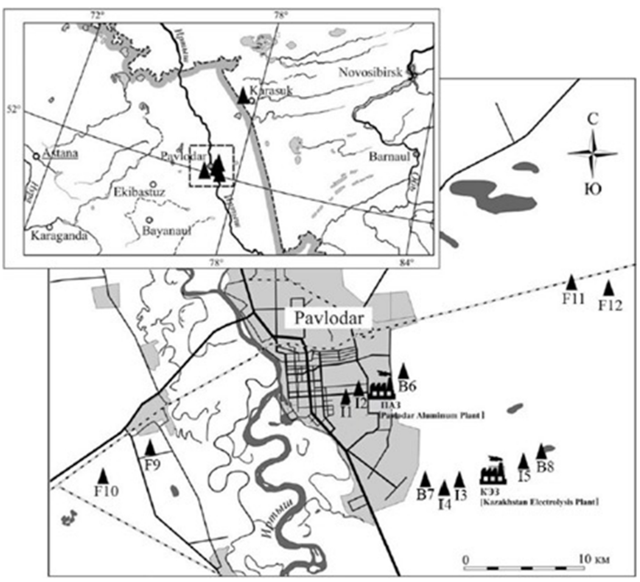

Fig. 1 Study area and small mammal capture sites.

tai region, Russian Federation). This plot included two open biotopes: meadows with copses and pasture meadows.

To capture and count small mammals, the method of pitfall traps was used, which provides the most massive and representative material (Naumov 1955). Five plastic cones, 45–50 cm high and 25 cm in diameter, were dug into the bottom of the pitfall trap, 50 m long and 10 m deep, with a distance of 10 m between them and 5 m behind the outermost cones. Ordinary 5-liter plastic containers with cut bottoms were used as cones. Pitfall traps were checked daily in the early morning. Trapping was conducted throughout the snow-free period, from May through September 2016–2017 and from May through June 2018, for 10–20 days in each month. A total of 10292 c/d were operated in the anthropogenic pressure zone during the study period. 76 individuals of narrow-headed vole were captured. Data on the Karasuksky control plot were taken from the materials provided by T. Dupal (119 individuals) (Dupal 2010). For the Biysky control plot, the volume of material studied amounted to 129 individuals.

Animal catches per 100 cone per day were taken as the unit of record. The dominance structure of each community was assessed using the dominance index, which represents the proportion of species in the community. When estimating the abundance of small mammals, point characteristics were used (Kuzyakin 1962):

- numerous 10 or more;
- common 1.0–9.9;
- rare 0.1–0.9;
- very rare - less than 0.1 animals (per 100 c/d).

Dominance was assessed on the following scale:

- dominants - 10% and more;
- co-dominants - 5–9%;
- secondary - less than 5% of captures.

The age of animals was determined by a complex of traits, taking into account body size and weight, the state of the reproductive system, craniological signs, the degree of erasure of teeth and hair cover (Dunayeva 1955). According to these indicators, three age groups were distinguished: overwintered (Sen), sexually mature juveniles (Ad), and immature juveniles (Subad).

The following exterior parameters were used in the study of interpopulation morphological variability: body weight, body length, tail and foot length. When analyzing cranial variability of the narrow-headed vole, 8 traits were used: total skull length; condylobasal skull length; cheekbone width; interorbital width; upper diastema length; upper dentition length; cerebral width; and skull height. Skull measurements were taken with a trammel to the nearest 0.01 mm. For each trait, mean values and mean error, coefficient of variation, reliability of differences were calculated (Lakin 1990). All calculations were performed in the package of statistical data analysis STATISTICA 12.0.

One of the specific emissions of aluminum production is fluorine. Determination of fluorine content in bone tissue of animals was carried out in the laboratory of soil biogeochemistry of the Institute of Soil Science and Agrochemistry SB RAS. Fluorine content was determined by potentiometric method using ion-selective electrodes (Khazemova et al. 1983; Methods of measuring..., 2012). Samples of the analyzed material were combined according to the age of the animals and the capture area, i.e., the zones of industrial load and the control area. Sexually mature and non-sexually mature juveniles were combined into one group due to the small number of each of them.

Determination of species affiliation of captured animals was carried out according to the identification guide (Gromov and Yerbayeva 1995).

Results

The narrow-headed vole (*Stenocranius gregalis* Pall., 1779) belongs to the Kazakh-European faunistic complex (Vinogradov 2012). Based on similar ecological features typical of steppe animal species, Kucheruk (2006) attributes it to mountain-tundra-steppe forms with a steppe center of origin. The range of the species covers the tundra zone from the European North and western Pre-Ural area in the west to the Anadyr region in the east. In the south, the range covers forest-steppe and steppe parts of Siberia, Kazakhstan, Central Asia, Northern and Central Mongolia, and northwestern China (Gromov and Yerbayeva 1995). In Pavlodar Pre-Irtysh it is a common species, but it is most abundant in places with moist soil and lush herbage. It most readily inhabits moist meadows, steppes, areas of dense grass and shrubs, as well as forest outliers (Solomatin 2007).

Numbers and sex-age structure of the narrow-headed vole population under industrial impact. In the areas of industrial load the narrow-headed vole was most often recorded in the fescue grass-wormwood steppe with elements of woody vegetation within the buffer area of the Pavlodar aluminum plant (B6) (3.0 individuals per 100 c/d). Its abundance is slightly less in western background areas (F9, F10) (1.9). Its abundance is much lower in the buffer area of Kazakhstan electrolysis plant (B7) (0.6), and minimum abundance is characteristic for all impact zones, as well as for the eastern background area (F11) (0.1–0.3). When averaging the abundance values of the narrow-headed vole across the impact areas, a sharp decrease in its abundance was observed from the control area to the industrial load zone (Fig. 2). Within the industrial load zone, the lowest abundance of the Narrow-headed Vole was recorded in the impact sites (0.1), while in the buffer and background sites its abundance was 10 and more times higher (1.0–1.2). Thus, in the zone of industrial production of aluminum production in Pavlodar, the average abundance of narrow-headed vole is significantly lower than in the control area (0.8 and 7.8, respectively). Pavlodar averaged index of narrow-headed vole abundance is significantly lower than in the control area (0.8 and 7.8, respectively). This indicates a high degree of impact of aluminum production on the environment.

In the population of the narrow-headed vole in the vicinity of Pavlodar city the predominance of males over females was revealed (59 and 41%). Their ratio varies among different age groups. Thus, in overwintering animals and sexually mature juveniles the shares of males and females are almost equal (50 and 48%, respectively), and among immature juveniles males significantly prevail over females (67.5 and 32.5%).

The dynamics of age composition by months corresponds to traditional ideas about the ecology of small mammals. The proportion of overwintering adult animals was very low throughout the year, so in May, July and August, their total share in captures amounted to only 6% (n = 4). In May and June, the population of the narrow-headed vole was dominated by juveniles (94%, n = 34), among which sexually mature and immature animals accounted for 50% each (n = 16). By mid-summer, the proportion of immature juveniles increased sharply, with a total proportion of 70% (n = 16), and participation of sexually mature juveniles did not exceed 26% (n = 6). The main population of the narrow-headed vole in late summer and in the fall is formed by immature juveniles (58%), among which males dominate (65%).

Depending on the distance from industrial emission sources, the change of age composition in the population of the narrow-headed vole occurs as follows (Fig. 3).

The proportion of overwintering animals is very low everywhere, and they were not recorded at all in the impact and background areas. At the border with the aluminum smelters («Aluminum of Kazakhstan» JSC and «Kazakhstan Electrolysis Plant» JSC), due to very low numbers of animals, the narrow-headed vole population is dominated by young sexually mature animals (ad), while the proportion of immature voles (sad) is insignificant. Significant predominance of immature juveniles over all other age groups starts from the buffer zone, where they account for 56%. Their proportion slightly increases in the background areas (61%) and reaches maximum values in the control area (70%). The ratio of sexually mature young animals (ad) in these plots varies from 26% in the control area to 39% in the background plots.

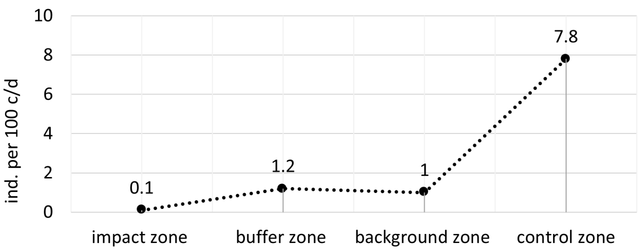

Fig. 2 Dynamics of the relative abundance of narrow-headed vole in the gradient of industrial impact of aluminum production in Pavlodar, individuals per 100 cone per days (c/d).

Fluorine content in bone tissue of narrow-headed vole

As a result of the activity of the enterprises «Aluminum of Kazakhstan» JSC and «Kazakhstan Electrolysis Plant» JSC in the soils of Pavlodar city and its vicinities, areas of fluorine concentration with maximum indicators exceeding background values 492–847 times and maximum permissible concentrations (MPC) from 1.5 to 8.4 times were formed (Makarina 2015). The content of fluorine in soils increases with the proximity to the plants. The highest values of fluorine content are observed in the impact zones of both plants (14.5–15.3 mg/kg) and in the buffer zone of the electrolysis plant (12 mg/kg), which exceeds the MPC norm and background values in remote areas (6.3 mg/kg) (Sergazinova et al. 2018). Through the soil, fluorine contaminates primarily many plants, and its concentration depends on species affiliation and on external conditions, with fluorine accumulation occurring mainly in the vegetative mass. Accumulation of fluorine in plants in polluted areas has a significant impact on mammals, primarily herbivores and granivorous. Fluorine ions can interact with any tissue of a living organism and accumulate in bones, teeth, hair and nails (Savchenkov and Nikolayeva 2011).

The study of fluorine content in bone tissue of the narrow-headed vole (*Stenocranius gregalis*) revealed significant differences between the control area and the anthropogenically impacted areas. In background areas the fluorine content doubled (144.8 mg/kg) compared to the control area, and in buffer and impact areas by another 2.5 and 3 times (209 and 175 mg/kg, respectively). On the example of individual age groups, this trend takes the following form (Fig. 4). In overwintering individuals inhabiting the control plot, fluorine concentration was 22.3 mg/kg,

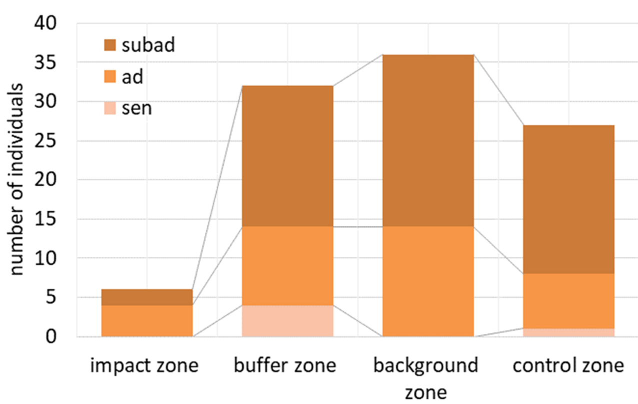

Fig. 3 Change in the age composition of the narrow-headed vole population in the gradient of remoteness from pollution sources.

whereas in the buffer zone this indicator almost tripled to 63.2 mg/kg. Among juveniles in the control area the fluorine content in bones is 48.8 mg/kg, approximately three times this indicator increases in the background and buffer plots (144.8 and 146.1 mg/kg) and reaches the maximum value in the impact zone (175.4 mg/kg). Thus, on the example of narrow-headed vole, the tendency of linear increase of fluorine content in bone tissue with the proximity to emission sources is clearly visible.

It should be noted that on the downwind side from the sources of industrial pollution, the fluorine content in bone tissue, as a rule, is higher than on the windward side. Thus, in downwind background areas the fluorine content values (255 mg/kg) were almost twice as high as those of the animals caught in background areas located on the windward side (133 mg/kg). The same was noted for the buffer zone of the aluminum plant located on the downwind side (B6), where the maximum values of fluorine content (831.5 mg/kg) were recorded. This regularity was previously shown by us on the example of other species: Southern Birch Mouse (*Sicista subtilis*), steppe lemming (*Lagurus lagurus*) and Siberian (Striped) Desert Hamster (*Phodopus sungorus*) (Sergazinova et al. 2017, 2018).

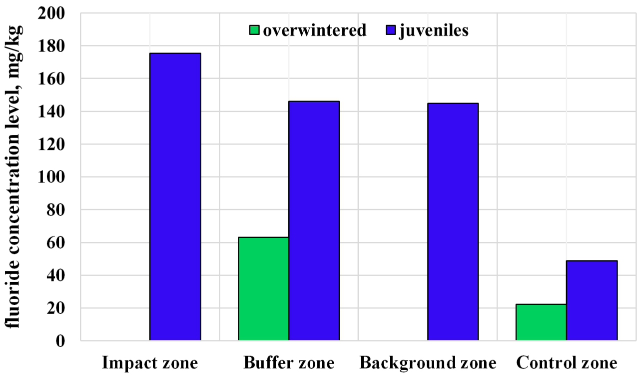

Fig. 4 Concentration of fluorine in bones of narrow-headed vole on the control territory and in the zones of industrial load (mg/kg of ash).

Interpopulation morphological and cranial variability of the narrow-headed vole of industrial and control territories

Analysis of exterior traits (mass, body length, foot and tail length) of the narrow-headed vole from the anthropogenic load zones and control areas showed the following. Overwintered females (sen) from the areas of industrial load have significantly lower weight ($p < 0.01$) than animals from the control Karasuksky site. However, overwintering males in the zone of anthropogenic load have a higher body weight than in the control areas. Probably, these data are not reliable, as due to insufficient sampling it is not possible to draw a consistent conclusion. The sexually mature juveniles (ad) from the areas of industrial load have lower weight, reliably, both in females ($p < 0.001$) and males ($p < 0.001$). Unsexually mature juveniles (sad) have no significant differences in weight (Fig. 5).

The body length of overwintering (sen) females of narrow-headed voles from the industrial areas is significantly less ($p < 0.001$) than that of voles from control areas (Karasuksky and Biysky). Sexually mature (ad) and unsexually mature (sad) juveniles also had significantly smaller body lengths of both females ($p < 0.001$) and males ($p < 0.05$) than animals from control sites (Fig. 6).

Overwintered (sen) females from control sites (Karasuksky and Biysky) have reliably greater tail length ($p < 0.001$) than animals from industrial load zones. The same is true for sexually mature juveniles (ad) from the Karasuksky control site, the tail length of which is significantly greater for both females ($p < 0.001$) and males ($p < 0.05$) than for

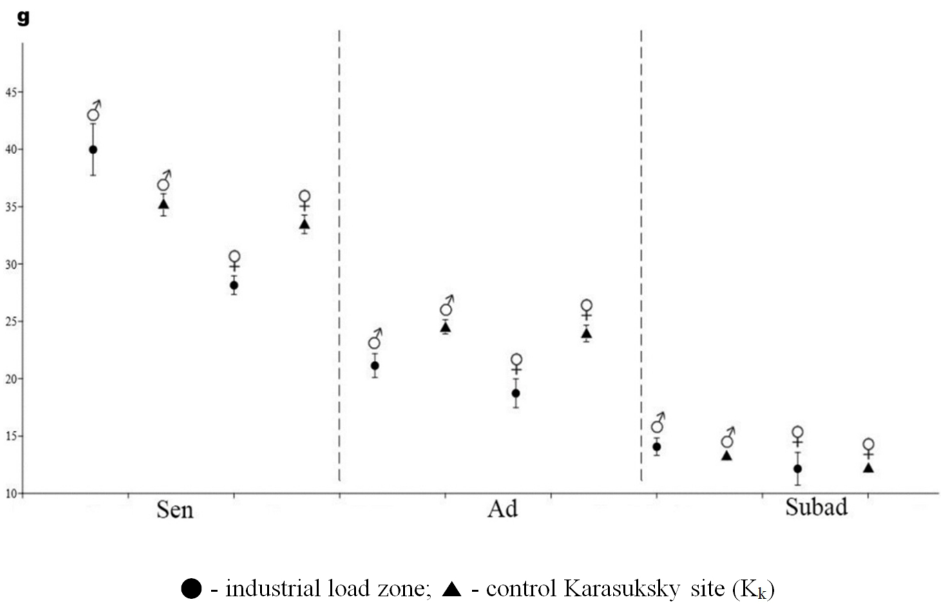

Fig. 5 Variability of body weight of narrow-headed voles captured in the industrial and control areas.

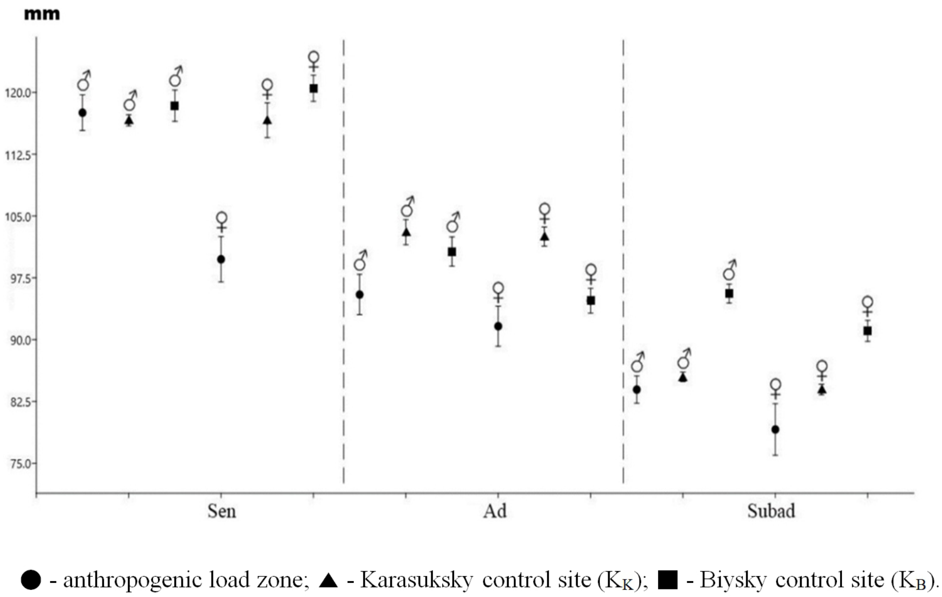

Fig. 6 Variability of body length of narrow-headed voles captured in the industrial and control areas.

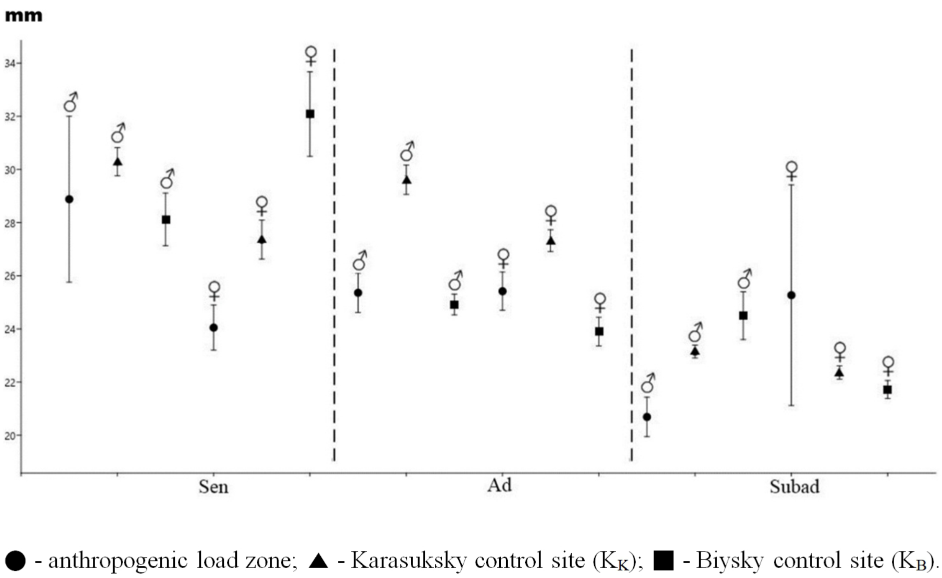

Fig. 7 Variability of tail length of narrow-headed voles captured in the industrial and control areas.

their counterparts from the industrial area. This tendency is also specific for males of immature (sad) juveniles, whose tail length from both control sites is significantly greater ($p < 0.01$) than in the industrial territory. At the same time, the slightly greater tail length of immature females from the industrial area is unreliable and is probably caused by low sampling (Fig. 7).

The revealed tendency of reduction of the foot length dimensional indices in animals from the areas of industrial load, as compared to animals from control territories, is characteristic of all age groups (Fig. 8). However, a significant decrease in these values is characteristic only for overwintering (sen) females ($p < 0.01$), sexually mature (ad) young females ($p < 0.01$), as well as for immature (sad) young males and females ($p < 0.001$).

The revealed tendency of the narrow-headed vole morphological traits decrease in the anthropogenic territory was also noted when analyzing craniological variability. Young males and females from the control area are characterized by larger cranial size characteristics than young animals from industrial areas. At the same time, for the majority of exterior traits these differences are characterized by a high degree of reliability (Table 1). The same is generally applicable to adult voles, but due to the low sample of animals from the industrial area, these differences are not reliable. However, in general, the trend of increasing skull size in animals from the control area is maintained, and the reliability of differences is confirmed for such characteristics as skull height and width of the brain section.

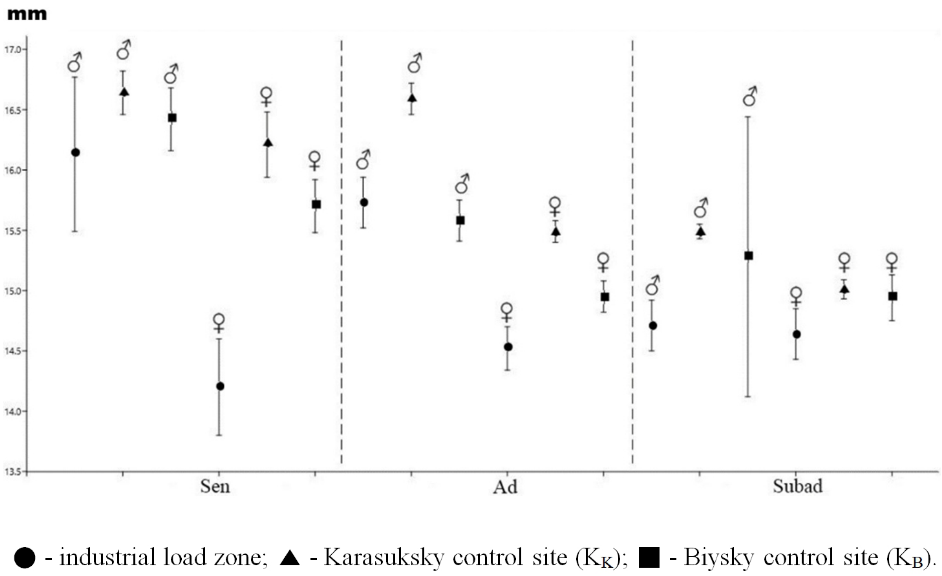

Fig. 8 Variability of foot length of narrow-headed voles captured in the industrial and control areas.

Table 1 Interpopulation cranial variability of narrow-headed vole of industrial and control areas

	Industrial area			Control (K_B)			t
	n	M ± m	CV	*n*	M ± m	CV	
Adult males							
Total skull length	2	25.28 ± 0.36	0.020	39	25.81 ± 0.21	0.051	0.6
Condylobasal length of skull	2	24.65 ± 0.24	0.014	39	25.31 ± 0.21	0.052	0.7
Cheekbone width	2	12.09 ± 0.02	0.002	39	12.56 ± 0.12	0.059	0.9
Interorbital width	2	2.77 ± 0.48	0.24	39	2.80 ± 0.03	0.065	0.2
Diastema	2	7.73 ± 0.14	0.026	39	7.89 ± 0.06	0.050	0.5
Upper dentition length	2	6.11 ± 0.14		39	5.77 ± 0.06	0.067	1.2
Cerebral width	2	9.47 ± 0.10	0.015	38	10.10 ± 0.05	0.032	2.7*
Skull height	2	8.59 ± 0.17	0.027	37	8.97 ± 0.05	0.033	1.8
Adult females							
Total skull length	2	24.50 ± 0.54	0.031	27	25.16 ± 0.24	0.049	0.7
Condylobasal length of skull	2	24.50 ± 0.78	0.045	27	24.55 ± 0.27	0.058	0.04
Cheekbone width	2	11.57 ± 0.49	0.060	27	12.11 ± 0.13	0.054	1.1
Interorbital width	2	2.78 ± 0.19	0.097	27	2.77 ± 0.03	0.065	0.04
Diastema	2	7.34 ± 0.14	0.026	27	7.64 ± 0.08	0.052	1.1
Upper dentition length	2	6.08 ± 0.09	0.021	27	5.77 ± 0.06	0.056	1.3
Cerebral width	2	8.86 ± 0.08	0.014	27	9.85 ± 0.09	0.047	3**
Skull height	2	7.86 ± 0.20	0.037	27	8.69 ± 0.06	0.035	3.7***
Young males							
Total skull length	36	22.60 ± 0.18	0.048	35	23.74 ± 0.17	0.041	4.6***
Condylobasal length of skull	36	22.31 ± 0.19	0.052	35	23.09 ± 0.18	0.046	2.9**
Cheekbone width	38	10.06 ± 0.14	0.085	35	10.82 ± 0.11	0.062	4.2***
Interorbital width	39	2.65 ± 0.03	0.075	35	2.85 ± 0.02	0.049	4.9***
Diastema	39	6.50 ± 0.07	0.067	35	7.07 ± 0.05	0.044	6.4***
Upper dentition length	39	5.52 ± 0.05	0.058	35	5.44 ± 0.05	0.051	1.2
Cerebral width	36	9.10 ± 0.07	0.046	34	9.58 ± 0.08	0.046	4.7***
Skull height	36	7.87 ± 0.05	0.039	35	8.70 ± 0.06	0.039	10.9***
Young females							
Total skull length	23	22.46 ± 0.29	0.063	28	23.21 ± 0.19	0.043	2.2*
Condylobasal length of skull	23	22.24 ± 0.29	0.063	28	22.63 ± 0.17	0.040	1.2
Cheekbone width	26	10.19 ± 0.16	0.078	28	10.53 ± 0.12	0.060	1.7
Interorbital width	27	2.69 ± 0.04	0.081	28	2.75 ± 0.04	0.070	1.08
Diastema	27	6.51 ± 0.11	0.089	28	6.86 ± 0.06	0.047	2.8**
Upper dentition length	27	5.33 ± 0.05	0.044	28	5.47 ± 0.05	0.050	2.03*
Cerebral width	23	9.14 ± 0.10	0.054	28	9.37 ± 0.07	0.041	1.8
Skull height	23	7.79 ± 0.11	0.069	28	8.51 ± 0.07	0.044	5.6***

n, number; M, average value; m, error of the arithmetic mean; CV, coefficient of variation.
t is the reliability criterion: $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Discussion

It is known that the effects of industrial pollution by toxicants and habitat transformation are among the significant external factors affecting the changes in animal metabolism. In such habitat conditions, animals undergo modification of metabolism processes, which is expressed in changes of some biochemical parameters of the organism, including their morphological structure. Decreases in average body length and weight can be observed (Katayev 1984; Lukyanova and Lukyanov 1998).

The comparative analysis of morphological exterior traits of the narrow-headed vole showed a decrease in body length, tail, foot, and weight in the industrial territories compared to the control territories. This indicates, first of all, a decrease in the quality and quantity of forage resources in the territories affected by industrial emissions. It may also be a consequence of intensification of metabolic processes necessary for neutralization and excretion of pollution ingredients and significant energy expenditures necessary for survival of voles (Mukhacheva 1996; Zemlianoy 2007). The analysis shows that the adaptation of voles to the harmful effects of aluminum production follows the path of intensification of vital activity processes that allow to compensate for the increased mortality of animals in the zones of industrial production (Lukyanova and Lukyanov 1998).

Anthropogenic impacts such as industrial pollution lead to significant morphological changes in rodents, including the narrow-headed vole (*Stenocranius gregalis*). In areas with high anthropogenic load, an increase in fluctuating asymmetry of cranial structures, especially in the lower jaw, is observed, indicating a disturbance in the stability of ontogenetic development (Yalkovskaya et al. 2016). Industrial emissions of heavy metals and sulfur dioxide disrupt metabolism, which leads to a decrease in body size in most rodents, but in some populations an increase is also possible due to the selection of stable individuals and reduced competition (Mukhacheva et al. 2010, 2022). Thus, changes in morphometric and craniometric indices of rodents can serve as indicators of the ecological state of the environment, reflecting the influence of both direct toxic effects and indirect environmental factors.

According to the data of the Southern Birch Mouse, steppe lemming and Siberian (Striped) Desert Hamster living in the same area of impact of aluminum production in the north-east of Kazakhstan, a similar trend of linear increase in the fluorine content in bone tissue with proximity to the sources of emissions was observed. The peak of fluorine concentration in these cases falls at the nearest distance from the plants (Sergazinova et al. 2017, 2018). At the same time, the average fluorine content in the bones of narrow-headed vole in all zones of anthropogenic load is 100.1 mg/kg, which is significantly lower than in the steppe lemming (296.2 mg/kg) and Siberian (Striped) Desert Hamster (349.1 mg/kg). One of the reasons for the relatively low fluorine content is that the narrow-headed vole was less frequently encountered in the impact zone of the plants, so the average values of fluorine accumulation in its bones were lower. Maximum high values of fluorine accumulation in bone tissue were registered in the Southern Birch Mouse (605.5 mg/kg). These differences in fluorine concentration are also due to the peculiarities of ecology and trophic specialization of species. The narrow-headed vole predominantly feeds on vegetative plant fodder, which limits fluorine intake into its organism. In contrast, the Southern Birch Mouse and Siberian (Striped) Desert Hamster have a wider dietary range, including insects and seeds, which can accumulate significant concentrations of fluorine. In insects, for example, fluorine can accumulate to critical levels. For example, at a distance of 1 km from an aluminum smelter, the fluorine content in the chitin cover of insects can be 17–35 times higher than in the control (Dewey 1973; Selikhovkin 2013). In addition, the intensity of migration and the ability to avoid contaminated sites also affect the level of toxicant accumulation. It is noteworthy that in narrow-headed voles living near a large aluminum smelter of the Sayan industrial complex, where fluoride pollution occurs for a long time, the fluorine content in narrow-headed vole bones reached 860–2,600 mg/kg (Prelovsky 2015). This indicates a high degree of bioaccumulation of the toxicant under long-term exposure to emissions and confirms that the level of environmental pollution determines the intensity of fluorine accumulation in the animal body.

Small mammals living near sources of fluorine emissions accumulate it in bone tissue in significantly higher concentrations compared to individuals from “clean” areas. According to literature data, depending on the natural zones of plant locations, fluorine concentration in the bones of animals near emission sources varies from 175 to 17,200 mg/kg, while in unpolluted territories - from 23 to 1,000 mg/kg. Different animal species differ in the level of fluorine accumulation, which is related to the peculiarities of nutrition, physiology and metabolism. Maximum fluorine concentrations were recorded in house mice (5,000–17,200 mg/kg), voles (832–11,000 mg/kg) and steppe lemming (1,140–3,400 mg/kg). The weasel, as a predator, accumulates fluorine in smaller amounts (860 mg/kg), which is associated with biomagnification at higher trophic levels. In addition, each species has specificity of response to different levels of fluorine. Thus, the Turkestan rat at the fluorine content level of 5,900 mg/kg shows signs of fluorosis, while the house mouse, even at high concentrations of fluorine in bones, does not show them. Seasonal and spatial regularities were also noted. In the fall, there is an increase in the concentration of fluorine in the organisms of animals, which is associated with its accumulation in vegetation. With increasing distance from the source of pollution, the fluorine content in animals decreases, while species diversity and total biomass of mammals increases (Dzhuraev 1993; Prelovsky 2015; Walton 1985).

The tendency of the narrow-headed vole population level decrease and fluorine accumulation increase in the bone tissue of animals as they approach the plants are consistent with the data on other industrial zones of aluminum production. Thus, as a result of long-term negative impact of aluminum smelters of Sayan industrial complex, Tajik aluminum smelter on ecosystems of South Minusinsk basin and Hisar valley there was a gradual accumulation of harmful substances in all their components and expansion of the total pollution zone. These accumulations manifested themselves in abnormally high concentrations of fluorine in animal organisms even at a considerable distance from the plants. Under such conditions, animal communities are characterized by simplification of the structure of species composition, reduction of total biomass and species diversity. Due to the high mobility of small mammals, local pollution can very strongly affect animals inhabiting an area hundreds of times larger than the area of the original pollution (Chibiryak 1996; Dzhuraev 1993; Prelovsky 2015). High concentrations of fluorine have a pronounced toxic effect on the organism of small mammals, leading to premature death, morphological disorders of teeth and negatively affecting the reproductive system and offspring (Boulton et al. 1994, 1995; Krasowska et al. 2004).

Further increase in the capacity of aluminum production in northeastern Kazakhstan is predicted to increase the industrial load on the surrounding ecosystems and increase fluorine concentrations in soils and in the bodies of animals and human beings.

Conclusions

The results of the study confirmed the significant impact of industrial pollution on the ecological and morphological characteristics of the narrow-headed vole (*Stenocranius gregalis*) in steppe ecosystems of Pavlodar Pre-Irtysh. Under conditions of anthropogenic impact, a decrease in the number of this species is observed, as well as pronounced morphological changes, including a decrease in body size, craniometric parameters and animal weight. It was found that fluorine content in the bone tissue of voles increases as they get closer to pollution sources, reaching maximum values in impact zones. The revealed patterns indicate high sensitivity of narrow-headed vole to fluoride pollution and confirm the appropriateness of its use as a bioindicator of steppe ecosystems. The obtained data can serve as a basis for further study of the mechanisms of adaptation of small mammals to anthropogenic stress. Further studies in this direction should be aimed at clarifying the impact of fluorine pollution on the physiological and reproductive parameters of the narrow-headed vole. Conducting comprehensive monitoring will make it possible to assess the level of ecological risk and develop recommendations to minimize the negative effects of industrial pollution on the biodiversity of steppe ecosystems.

Abbreviations
Not applicable.

Acknowledgements
Not applicable.

Authors' contributions
ZMS: led the research, conducted fieldwork, conducted the literature review, prepared the manuscript. AVM: conducted fieldwork, conducted literature review and prepared the manuscript. NTY: interpreted and analyzed the data, proofread the manuscript.

Funding
Not applicable.

Availability of data and materials
Not applicable.

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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