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*Article*

# Impact of traffic-generated emissions on the snow cover of agricultural landscapes in Karelia

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**Abstract.** The article reports the results of an assessment of the impact of traffic-generated emissions on the snow cover of agricultural landscapes in Karelia. The study was carried out in 2018 and 2019 in the region's most agriculturally favorable southern agroclimatic zone. The snowfall formed under road traffic impact exhibited medium or low dust pollution levels. The dust pollution load onto a drained agricultural landscape within 50 m off the road was 129.8–385.9 kg/(km$^2$×day), exceeding the background 8.3–25.0-fold. The integrated pollution index values for the snow cover (solid residue) of the agricultural landscapes were at medium and high levels. The insoluble residue of snow predominantly contained high concentrations of Mo, W, Ti, Al, K, Cu, Na, Mn, Ca, Mg, Fe, Ni, Cr, Cd, with concentration coefficients 1.5–74 times that of the background. Maximum permissible concentrations (MPC) were exceeded for Cd (up to 10-fold), Zn (9.4), Co (9.0), Mo (7.9), Cu (3.2), Ni (2.4), Sb (3.3), Fe (2.1). The integrated pollution index for snow in the liquid phase was generally below the threshold values, with the greatest impact found between 100 and 150 m off the road. The total man-made pollution load on the agricultural landscape declined with distance from the road and was classified as medium-level within 15 m off the road.

**Keywords:** snow, farmlands, pollution, macro- and micronutrients, road and vehicle complex, dust pollution load, middle taiga subzone

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*Научная статья*

# Влияние выбросов автотранспорта на снежный покров агроландшафтов в условиях Карелии

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**Аннотация**. В работе представлены результаты оценки влияния выбросов автотранспорта на снежный покров агроландшафтов Карелии. Исследование проведено в наиболее благоприятной для сельскохозяйственного производства южной агроклиматической зоне региона в период с 2018 по 2019 гг. Атмосферные осадки в виде снега, формирующиеся в условиях влияния автотранспорта, характеризовались средним и низким уровнем пылевого загрязнения. Выпадения пыли на территорию мелиорированного агроландшафта до 50 м от автотрассы составили 129.8–385.9 кг/(км$^2$×сут), что превышало фоновые значения в 8.3–25.0 раза. Коэффициенты суммарного загрязнения снежного покрова (по твердому остатку) на агроландшафтах демонстрировали средний и высокий уровни. В составе нерастворимого остатка снега в высоких концентрациях преобладали Mo, W, Ti, Al, K, Cu, Na, Mn, Ca, Mg, Fe, Ni, Cr, Cd; коэффициенты концентрации этих элементов относительно фона составляли от 1.5 до 74. Обнаружено превышение ПДК для Cd (до 10 раз), Zn (9.4), Co (9.0), Mo (7.9), Cu (3.2), Ni (2.4), Sb (3.3), Fe (2.1). Значения показателя суммарного загрязнения жидкой фазы снега в целом не достигали пороговых значений, при этом наиболее подверженной воздействию оказалась территория в 100 и 150 м от дороги. Общая техногенная нагрузка на агроландшафт с удалением от дороги снижалась и до 15 м от трассы определена как средняя.

**Ключевые слова:** снег, сельскохозяйственные угодья, загрязнение, макро- и микроэлементы, автодорожный комплекс, пылевая нагрузка, подзона средней тайги

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## Introduction

Mobile pollution sources, including motor vehicles, are among the chief factors for environmental deterioration. As opposed to stationary sources of dust pollution (industrial facilities, construction sites, etc.), motorized traffic is a non-point, areal source with harmful substances emitted at human breathing level (Nevmerzhitsky, 2017). While playing a governing role in the country's economic growth and social development (Absolyamova, 2021), the road and vehicle sector is at the same time a major polluter of air, soil, natural waters, plants, etc. (Baensch-Baltruschat et al., 2020). In Russia, pollutant emissions from the road and vehicle infrastructure in general account for 50 to 80% of total emissions amounts (Egorova et al., 2014), and according to some estimates the contribution of motor vehicles to the total emissions is 70-90% (Nevmerzhitsky, 2017).

The main components of the pollution related to motor vehicle use are exhaust gases, evaporated oil products, dust, tire-, break-shoe-, clutch-disc-, asphalt- and concrete wear products, etc. (Egorova et al., 2014). The quantity and composition of exhaust gases depend on the design features and technical condition of vehicles, engine operation mode, quality and type of fuel, condition of the running gear of the car, road surface quality and weather conditions. It is known that moving motor vehicles produce emissions with up to 300 different compounds, including metals such as As, Cd, Cr, Cu, Hg, Ni, Pb, Zn, Sb, Co, Mn, V, Ba, Se (Tunakova et al., 2016). The variable chemical composition of aerosol dust emissions, the size of fine particles, their high specific surface area and toxicity, as well as the lack of the unified system of road transport emission accounting hinder the assessment and identification of the chemical composition of environmental pollution.

Lately, as the road network has been developing and traffic has become more intensive, emissions from the road and vehicle complex have been growing. Motorways often run through lands used in agriculture causing farmland areas along roads to be affected by traffic-related aerosol dust emissions. The heaviest impact extends for up to 100 meters off the roadway (Abroskin, 2017). According to some reports (Abroskin, 2017; Lyovkin and Lazeba), pollution from road facilities may spread to 200 m away or more, depending on a number of factors (topography, vegetation, vehicle types, weather conditions, etc.).

A weighty factor in the spread of emissions over agricultural landscapes is drainage arrangements channeling natural waters from the catchment area. According to L.V. Kireycheva and E.A. Lentyaeva (2020), drained farmlands are a large-scope, poorly controlled source of water ecosystem contamination with pesticides, mineral fertilizers, nutrients, heavy metals. On top of the substances that contaminate watercourses as a result of agricultural operations, another substantial source is surface runoff from settlements, roads, etc. in the catchment. Precipitation amounts influence the volume of water captured by drainage systems accounting for around 20–40% of the latter. The drainage flow peaks during snow melting and heavy rainfall. When contaminated effluents enter the water environment, much of the contaminants are sorbed within bottom sediments and suspensions, forming an internal secondary pollution source and posing hazard to both soil and aquatic ecosystems. It must be mentioned here that because of excessive moisture supply in Karelia, substantial farmland areas have been drained (43% or 62800 ha) to secure an optimal air and moisture regime of soils. As the parameters of human impact are changing rapidly and considering the general strategy of resuming the agricultural use of idle lands, enhancing soil fertility and augmenting crop yields, the assessment of agricultural landscapes state is still on the agenda.

Studying the chemical composition of the snow cover is an efficient and cost-effective way to collect data on the flow of pollutants from the atmosphere into the soil and natural waters (Bogatyrev et al., 2018). In the Northwestern region, where the snow cover persists for a long time (about 5 months), it is an adequate indicator of airborne anthropogenic fallouts during the winter period. Having a high sorption capacity, snow accumulates and retains all components of atmospheric pollution. The chemical composition of melted snow is the product of the input of various mineral elements with precipitation, absorption of gases, water-soluble aerosols and solid dust particles settling from the atmosphere (Bogatyrev et al., 2018; Vasilenko et al, 1985).

The aim of the study is to assess the contamination level of a drained agricultural landscape affected by motorized traffic by estimating the dust pollution load and examining the chemical composition of the snow cover.

## Material and methods

The surveys were carried out in the Republic of Karelia in 2018–2019 in farmlands along the federal highway R-21, drained by an open ditch network. Surveys were carried out in three drainage sites of the same type in Prionezhsky (sites no. 1 and no. 3) and Kondopozhsky (site no. 2) districts of the republic situated in the middle taiga subzone (Fig. 1, Table 1). These areas have been used as hayfields since the start of their agricultural use after drainage. In the absence of service maintenance, the canal network has become overgrown by trees and shrubs (birch, willow, pine, spruce). There are no gas and dust fences or vegetated dust buffers in the road sections adjoining the farmlands. The road/farmland contact length is 416 to 2200 m, and the traffic intensity in the motorways is 2105 ± 44 automobiles/h.

Many researchers (Abroskin, 2017; Lyovkin and Lazeba, 2014) have reported aerosol dust load to decline with distance from the roadway. It is the highest within 5 m off the road. Yet, gas and dust emissions may, depending on traffic intensity, vehicle types, landscape features, weather conditions and other factors, spread to greater distances (Lyovkin and Lazeba, 2014). In Karelia, the impact of road traffic-related emissions on the snow cover of agricultural landscapes has not been studied yet. The siting of the sampling plot was chosen based on the location of farmland relative to roadway (as a rule, the farmland starts at least 10–15 m away from the roadway), small-size landscape units, and availability of a drainage network with surface field canals spaced 30-40 m apart. In spite of the flat terrain, the limiting factor for the flow of gas and dust emissions to the farmlands was the tree and shrub vegetation in the drains (stand age over 15–20 years). Therefore, snow samples were collected along the distance gradient, at 15, 50, 100, and 150 m away from the road. Each sampling plot was a 50×15 m rectangle ($S = 750$ m$^2$) situated parallel to the motorway. Snow was sampled in triplicate as described in the RD 52.04.186–89 manual.[1]

The reference sampling plot (background) of the same size was selected in a drained agricultural landscape situated over 30 km away from man-made impacts in the same environment and climatic zone.

The solid residue of all snow cover samples consisted of natural particles (fragments of fodder plant organs, birch leaves, tree needles and bark), which were removed during sample pre-treatment. Snow samples from the contaminated sites additionally contained fine-grained dark-gray dust. The solid residue of snow was analyzed by X-ray fluorescence using ARL ADVANT'X (Thermo Scientific, Switzerland) and by ICP-MS using Series 2 Thermo Fisher mass spectrometer (USA) to determine the content of macro- (Na, Mg, Si, P, K, Ca, Cl, S, Al, Ti) and micronutrients (W, Mo, Fe, Sn, Sb, Cr, Ni, Zn, Cd, Cu, V, Co, Mn), respectively. The results are shown in Table 2. After melting the snow, the pH and content of macro- and micronutrients in filtered meltwater was measured by atomic absorption spectrophotometers AA-6800 and AA-7000 (Shimadzu, Japan).

The snow cover was studied in accordance with the methods guidelines (Metodicheskie rekomendatsii po geokhimicheskoi..., 1982). The mean daily dust pollution load on the farmlands was calculated by the formula:

$$P_{dl} = P_r / (S \times t),$$

where $P_{dl}$ is the dust pollution load, kg/(km$^2$×day); $P_r$ is the weight of solid residue of snow, mg(kg); S is the snow test pit area, km$^2$; t is the number of days since snow cover onset on the sampling date.

The sampling date was 148 days since a snow cover onset, so the snow samples reflected the pollutant input over approximately 5 months. The results can be extrapolated to the whole year, taking into account the fluctuations in the inflow and aerial transport of contaminants.

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[1] RD 52.04.186-89. Atmospheric Pollution Control Manual.

**Fig. 1.** Images of drained agricultural landscapes and federal motorways: **A** – site no. 1; **B** – site no. 2; **C** – site no. 3. Dots indicate sampling points (as of 15.03.2022).

**Table 1.** Characteristics of study sites in the motorized traffic impact zone in Karelia.

| Parameter | Site | | |
|---|---|---|---|
| | No. 1 | No. 2 | No. 3 |
| District | Prionezhsky | Kondopozhsky | Prionezhsky |
| Coordinates | N 61°87'68"<br>E 34°23'98" | N 62°08'78"<br>E 34°26'37" | N 61°83'24"<br>E 34°20'59" |
| Drainage site | "Kolino-Dolgii Bor" | "Suna" | "Tomitsy" |
| Site commissioning year | 1980 | 1981 | 1986 |
| Drained farmland area, ha | 253 | 125 | 209 |
| Surface drainage network length, km | 94 | 69 | 86 |
| Road/farmland contact length, m | 2200 | 416 | 1240 |
| Plant community | grass-forbs type | | |

As suggested in the methods guidelines (Metodicheskie..., 1982, Saet et al., 1990), the concentration coefficients of individual elements relative to the background level of the elements ($K_{ci}$) and the MPC ($K_{MPC}$) were estimated by the following formulas:

$$Kc_i = C_i / C_{bgi},$$
$$K_{MPC} = C_i / C_{MPC},$$

where $C_i$ is the actual content of the i$^{th}$ chemical element in precipitation, mg/kg; $C_{bgi}$ is the background content of the i$^{th}$ chemical element in precipitation, mg/kg; $C_{MPC}$ is the maximum permissible concentration of the i$^{th}$ chemical element in precipitation, mg/kg.[2]

The integrated pollution index (Zc), which represents the effect produced by a group of elements, was calculated by the following formula:

$$Zc = Kci + \ldots + Kcn-(n-1),$$

where n is the number of chemical elements included in the estimation; $K_{ci}$ is the i$^{th}$ pollution component's concentration coefficient greater than 1.

The total load ($P_{tot}$) generated by the input of a chemical element to the environment was calculated by the formula:

$$P_{tot} = C \times P_{dl},$$

where C is the content of the chemical element, $P_{dl}$ is the dust load, kg/(km$^2$×day).

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[2] Order of the Ministry of Agriculture of Russia No. 552 of December 13, 2016 "On approving water quality standards for fisheries water bodies, including standards for maximum permissible concentrations of harmful substances in the water of fisheries water bodies" (amended and supplemented).

**Table 2.** Content of chemical elements in the soil and melted snow from reference (background) agricultural landscapes of southern Karelia. Dash – element not detected.

| Element | Al | Ti | Fe | V | Cr | Mn | Cd | Zn | Mo | Co | Ni | Pb | Cu | Ba | W | Cd | Sn | Sb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Soil (old-tillage horizon), mg/kg | 19669.0 | 752.0 | 33280.0 | 70.0 | 24.0 | 675.0 | 0.2 | 83.0 | 0.5 | 11.0 | 28.0 | 13.0 | 26.0 | 618.0 | 0.4 | 0.2 | 1.7 | 4.3 |
| Melted snow, μg/ | 4.1 | – | 26 | – | 0.2 | 5.0 | 0.08 | 24 | – | 0.5 | 0.8 | 0.5 | 0.7 | – | – | – | – | – |

In addition, the coefficients of relative increase in the total load of an element ($K_p$) were calculated:

$$K_p = P_{tot}/P_{bg}$$
$$\text{with } P_{bg} = C_{bg} \times P_{dbg},$$

where $C_{bg}$ is the background content of the element; $P_{dbg}$ is the background dust pollution load, and $P_{bg}$ is the background load of that element.

The total pollution load index was calculated by the formula:

$$Z_p = \sum K_p - (n-1),$$

where n is the number of abnormal-level elements with $K_{Ci}$ and $K_p$ greater than 1.

The levels of snow cover pollution in terms of the integrated pollution index, dust pollution load and total pollution load were determined by the criteria suggested in the methods guidelines (Metodicheskie..., 1982) and are shown in Table 3.

## Results and discussion

Mean daily dust loads in our study varied from 6.5 ± 1.7 to 385.9 ± 37.5 kg/(km²×day) (Table 4). Such a wide range of mean daily dust pollution levels was due to the distance-to-the-road gradient: the average load was 253.7 kg/(km²×day) in sites closest to the road and 24.5 kg/(km²×day) in the remote sites. This is in agreement with some other studies. To wit, in a study by E. Adamiec et al. (2016) the aerosol dust pollution load within 2 m off the motorway was 1800 kg/(km²×day) versus 500 kg/(km²×day) at a 5 m distance. It is worth noting that the dust load along urban roads with intensive traffic is much higher than along motorways. For comparison, the level in urban areas within 5 m off roads with intensive traffic was 8800 kg/(km²×day) (Prokofyeva et al., 2015). Nonetheless, dustiness along motorways remains rather high. Saltation induced by moderately strong winds (> 10 m/s) can transport particles of 1 mm and larger size (Prokofyeva et al., 2015). Moreover, particles of 1 to 10 μm in diameter can hang in the air for several days, particles smaller than 1 μm – up to 10–20 days, and suspended particles smaller than 0.1 μm in diameter do not settle down (Nevmerzhitsky, 2016).

The average dust pollution load in our background area was 15 kg/(km²×day), generally matching the published data for the non-Chernozem zone of Russia with 10–20 kg/(km²×day) (Saet et al., 1990). Most of the dust pollution load values in the emission-impacted farmlands were below the “low” pollution level, especially at 100 m or more off the road, but even there the dust mass was 1.5–5.0 times that of the background. Pollution in the sampling plots of sites nos. 1 & 2 situated near the road was classified as medium and low (aerial fallouts 1.4–25.0 times that of the background) as opposed to site no. 3, where dust fallout was minor (Table 4).

### *Chemical composition of the snow cover of drained agricultural landscapes under road traffic impact*

The pH of melted snow mass from roadside strips of the farmlands ranged within 5.3–6.4, which is comparable to the average for precipitation in the Northwestern Federal District (pH = 5.9). The pH in the sampling plots declined gradually along the distance gradient towards a weaker reaction, likely indicating a reduction in human impact. Significant differences from the background were found only for site no. 1 (Table 4): the snow cover pH decreased uniformly with distance from the roadway from near-neutral to weakly acidic.

The content of elements in background snow cover samples was at a natural level, not exceeding the regional averages. The highest coefficients of contaminant concentration in the solid residue of snow relative to the background were detected both for macro- (Mg, K, Al, Na, Ti) – up to 3-fold, and for micronutrients (W, Mo, Fe, Sn, Sb, Cr, Ni, Zn, Cd, Cu, V, Co, Mn) – up to 74-fold (Table 4, Fig. 2). The MPCs were exceeded for Cd – up to 10-fold, Zn – 9.4-fold, Co – 9.0-fold, Mo – 7.9-fold, Cu – 3.2-fold, Ni – 2.4-fold, Fe – 2.1-fold.

**Table 3.** Snow cover pollution level (Saet et al., 1990).

| Pollution level | Integrated pollution index, Zc | Dust pollution load $P_{dl}$, kg/(km$^2$×day) | Total pollution load index, $Z_p$ |
|---|---|---|---|
| Low | 32–64 | 100–250 | < 1000 |
| Medium | 64–128 | 250–450 | 1000–5000 |
| High | 128–256 | 450-850 | 5000–10000 |
| Very high | > 256 | > 850 | > 10000 |

Our data on the chemical composition of traffic-generated dust point to correlations with the composition of the emissions resulting from tire and break shoe wear, components of flue gases, various gasoline and diesel additives, motor, transmission and hydraulic oil additives used to improve the operational properties of motor vehicles (Damdinov and Mitypov, 2021), and from road infrastructure wear.

It is known that the elements emitted into the air from break shoe wear include Cu, V, Mo, Ni, Cr, from tire wear – Al, Cd, Pb, Fe, Zn, Co, Cu (Golubev, 2007); catalyst erosion involves the emission of Pt, Pd, Rh, and break pad wear – Pb, Cu, Sb (Egorova et al., 2014). However, there is no consensus regarding key indicators of vehicle and road wear. According to Th. Grigoratos and G. Martini (2014) and D. Guo et al. (2021), break use results in the emission of copper and antimony, while A.V. Golubev (2007) revealed the presence of copper, vanadium, molybdenum, nickel and chromium, and E. Adamiec et al. (2016) named titanium as a priority substance in addition to copper and chromium since alkali metal titanates are used as inorganic fillers for stabilizing the friction coefficient.

The significantly elevated content of Cd and Zn in road dust is associated with the wear of asphalt concrete pavements and car tires (Adamiec et al., 2016). The contribution of tire and road wear to emissions is much higher in regions where studded tires are used for prolonged periods of the year. It has been demonstrated, for instance, that road pavement wear in Nordic countries is up to 6 times greater in winter (Usenko and Grinevich, 2024). Regional climatic and meteorological features (low or very high temperatures, very high precipitation, wind, solar radiation) have a significant effect on the pavement strength performance (Alekseev, 1987). The conditions most conducive to asphalt concrete pavement wear are slightly positive temperatures (up to +10 °C) combined with excessive water saturation (Lednev, 2018).

Detailed studies of the chemical composition of the dust fraction show that its components may vary, but all types of traffic-related emissions (flue gases, tire and break shoe wear, etc.) contain quite high amounts of V, Sb, Fe, Cu, Pb, Zn, Cd, Mn, and Mo (Egorova et al., 2014).

In our study, the insoluble residue of the snow cover of agricultural landscapes featured site-specific element accumulation series, but the highest concentrations in all cases were found for molybdenum, vanadium and titanium (Table 5).

Let us now examine more closely the accumulation patterns of the chemical elements with coefficients exceeding the MPC and the accepted background levels at least 10 times.

The input of Mo from the insoluble residue of snow to the farmlands' topsoil was 17.3 to 39.7 mg/kg, i.e. 34.6–79.4 times above the background. It should be noted that its accumulation in a major part of Northwest Russia's soils is quite low. Acidic soils are the poorest in available forms of molybdenum. Their accumulation is the lowest in Albic Podzols (0.05 mg/kg) (Kasimov and Vlasov, 2015; Pochvy Karelii, 1981). Gross molybdenum content in soils of the region varies from 0.6 to 3.4 mg/kg (Rybakov, 2017). Such significant variations are associated with local conditions: human impact, geochemical anomalies, etc.

Molybdenum has quite high biological significance: it is a component of the enzymes engaged in molecular nitrogen fixation by root-nodule bacteria and in reducing nitrates to ammonia, and is characterized by relatively high biological absorption coefficients. Molybdenum enlarges ascorbic acid

**Table 4.** Indices of snow cover pollution in drained agricultural landscapes under road traffic impact. Pollution levels are given after Saet et al. (1990). Numbers in the numerator are values for melted snow mass and in the denominator for solid residue of snow. Significant differences from the background ($p \leq 0.05$) are highlighted in bold; dash stands for values below threshold; asterisk indicates contaminants with concentration coefficients greater than 1.5.

| Site | Distance to pollution source, m | pH | Dust pollution load $P_{dl}$ | Dust pollution level | Integrated pollution index Zc | Pollution level | Total load increase factor $Z_p$ | Total load level |
|---|---|---|---|---|---|---|---|---|
| No. 1 | 15 | 6.2 ± 0.2* | 385.9 ± 37.5 | medium | $\frac{15.4}{95.4}$ | medium | 2643.0 | medium |
|  | 50 | 6.0 ± 0.1* | **129.8 ± 40.4** | low | $\frac{15.5}{–}$ | low | 242.4 | – |
|  | 100 | 6.0 ± 0.1* | 63.2 ± 2.9 | – | $\frac{34.1}{–}$ |  | 190.8 |  |
|  | 150 | 5.8 ± 0.04 | 51.4 ± 2.2 |  | $\frac{28.9}{–}$ |  | 126.3 |  |
| No. 2 | 15 | 6.2 ± 0.03 | **316.1 ± 60.7** | medium | $\frac{20.1}{170.1}$ | high | 2723.3 | medium |
|  | 50 | 6.0 ± 0.1 | 76.6 ± 21.9 | – | $\frac{7.2}{–}$ | – | 92.2 |  |
|  | 100 | 5.9 ± 0.1 | 57.1 ± 14.4 |  | $\frac{22.4}{–}$ |  | 113.1 |  |
|  | 150 | 5.8 ± 0.2 | 15.7 ± 5.5 |  | $\frac{28.1}{–}$ |  | 30.9 |  |
| No. 3 | 15 | 6.2 ± 0.1 | **59.2 ± 11.0** | – | $\frac{17.7}{132.7}$ | high | 1715.6 | medium |
|  | 50 | 5.9 ± 0.1 | 21.1 ± 9.5 |  | $\frac{15.0}{–}$ | – | 25.8 | – |
|  | 100 | 5.6 ± 0.3 | 7.3 ± 4.2 |  | $\frac{8.7}{–}$ |  | 5.4 |  |
|  | 150 | 5.8 ± 0.1 | 6.5 ± 1.7 |  | $\frac{11.7}{–}$ |  | 5.4 |  |
| Background |  | 5.9 | 15.4 ± 7.1 | – | – | – | – | – |

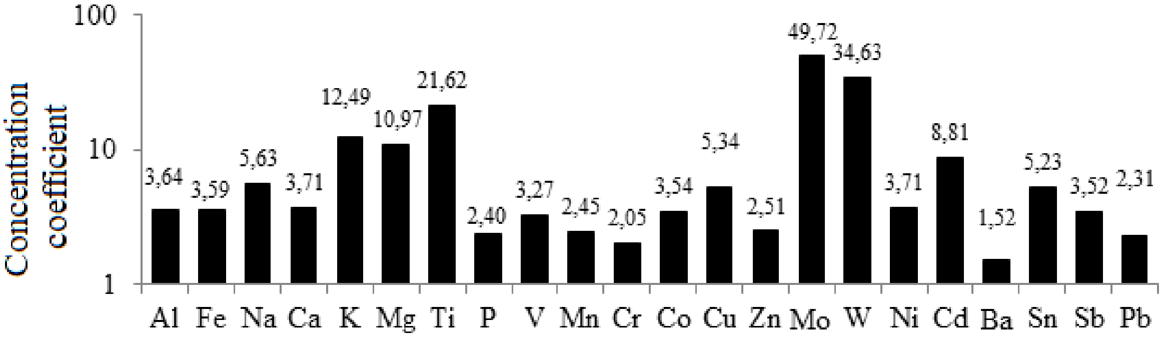

**Fig. 2.** Concentration coefficients of chemical elements in traffic-generated dust in roadside soils of agricultural landscapes (n=15) averaged over all sites (the vertical axis is in logarithmic scale).

and carotene quantities in green parts of plants, has a positive effect on the protein content and other qualities of cereal-grain legume crops, raises the yield of the legume component in the mixture and ultimately augments protein harvest per unit area. Molybdenum-deficient plants exhibit poorer growth, development and productivity, accumulate high amounts of nitrates, and their normal nitrogen metabolism is disrupted (Rana et al., 2020). Enrichment of farmland soils in our region with this micronutrient can benefit the plant community.

According to the literature (Afinogenov, 2008; Kabata-Pendias and Pendias, 1989), tungsten and vanadium can partially substitute molybdenum in their biological action. Our analysis showed the inflow of these micronutrients to topsoil with precipitation to be quite intensive – 10.7 to 246.9 mg/kg.

Tungsten is toxic to plants if the background levels are significantly exceeded. According to D.S. Rybakov and N.V. Krutskikh (2017), the average (background) content of W in mineral horizons of soils of Zaonezhsky Peninsula, Karelia (northern Lake Onego region) was 0.2 mg/kg and the maximum was 0.6 mg/kg, the average for the Earth's crust being 1.3. In our study, the average W concentration in the upper horizon of old-tillage soils was 0.4 mg/kg. It was intensively accumulated in traffic-related dust (11.8 mg/kg), with concentrations exceeding the background 29.6-fold.

Vanadium is a widespread element (Borisenko, 1973). The clarke of this micronutrient in soils is 90 mg/kg (Kabata-Pendias and Pendias, 1989). Like mercury, arsenic and cadmium, it is highly toxic. On the other hand, this micronutrient participates in the synthesis of some biologically active substances, in metabolic processes, photosynthesis, nitrogen fixation, etc. The toxic effects of vanadium for plants appear when its concentrations in soil rise to and above 140 mg/kg (Kabata-Pendias and Pendias, 1989). Its content in soil in the relatively clean reference farmland area in our study was below the toxic level – 70.1 mg/kg, whereas the insoluble residue of snow has accumulated an average of 229.4 mg/kg, i.e. three times that of the background.

Titanium is a fairly common element in the Earth crust, but has low lability in weathering and soil-formation processes. Its content in Podzolic soils is 3800 mg/kg, and in Histosols – 5200 mg/kg (Vinogradov, 1957). In our experiment, the titanium accumulation in the old-tillage horizon of the Anthric Luvisols (Siltic, Eutric) in the reference area was 3.0 times lower – 1250.4 mg/kg. The solid residue of snow on farmlands along roads accumulated 21.3 times more of this element than in the background (26625.8 mg/kg). Titanium is rarely used in crop cultivation practices (Hussain et al., 2021). Yet, some studies point out its positive effect on plant growth and development: it intensifies photosynthesis under abiotic stress (Sheudzhen et al., 2015; Tumburu et al., 2015), improves resilience to drought, salt stress, and low light stress (Gohari et al., 2020). On the other hand, high concentrations lower the efficiency of photosynthesis and escalate the oxidative process (Cigler et al., 2010).

Cadmium in our study was quite intensively accumulated in the insoluble residue of snow, especially in site no. 1 (3.3 mg/kg). Its content in snow samples varied among the study sites (coefficient of variation at 30%), with the lowest accumulation in site no. 3 (0.6 mg/kg). Overall, Cd accumulation was 2.8–13.6 times higher than its background content. High doses of this element are toxic to plants. They reduce the content of phosphorus, calcium, magnesium, iron, and zinc in plants (Ilin and Syso, 2001), thus inhibiting their growth and development and causing significant loss of productivity and sometimes even killing the

**Table 5.** Series of predominant accumulation of elements in the solid residue of the snow cover of agricultural landscapes.

| | |
|---|---|
| Site No. 1 | Mo > W > Ti > K > Mg > Na > Cu > V > Sb > Co > Cd > Al > Ca > Fe > Zn > Cr > Sn > P > Pb > Ba > Ni > Mn |
| Site No. 2 | Mo > W > Ti > Cd > K > Sn > Mg > Cu > Na > Al > Co > Sb > Ni > V > Zn > Ca > Fe > P > Cr > Pb > Mn > Ba |
| Site No. 3 | Mo > W > Ti > K > Cd > Mg > Na > Cu > Sb > V > Al > Co > Zn > Sn > Ba > Fe > Ca > Ni > Mn > P > Pb > Cr |

plants. This micronutrient is one of the few heavy metals capable of migrating to generative organs of cereals, raising its hazard to humans and animals. Oversupply of cadmium in soils disrupts the fixation of atmospheric nitrogen and reduces the rates of ammonification, nitrification and denitrification (Reuce and Kyrstya, 1986). It used to be widely involved in the manufacture of car batteries, tires, treads, brake shoes, and as anti-corrosion coating for vehicle fasteners. Because of the element's high toxicity, its use is now declining.

Average potassium input to roadside farmland soils was 1335.0 mg/kg, which is almost 12 times that of the background. Potassium compounds are widely used in the automotive industry in manufacturing fuel cells, synthetic rubber automobile tires, antifriction additives and lubricating mixtures for rolling and sliding friction units (Lavrentyeva and Batishheva, 2010).

Magnesium, due to its low density, is used in the manufacture of various automotive components (fuel tanks, seat frames, alloy wheels, etc.). Its accumulation in traffic-related dust was 18189.5 mg/kg (ca. 10 times that of the background). Although magnesium is usually regarded as a nutrient of secondary importance for crops, it is required for their proper growth and development (participating in photosynthesis, phosphorus transport, synthesis of sugars, starch redistribution, nitrogen fixation in legume nodules, etc.) (Akanova et al., 2021). There are also reports in the literature of soil physical properties deteriorated by high magnesium content (Akanova et al., 2021).

The rest of the elements in the solid residue of snow had concentration coefficients below 10 (Fig. 2). Their accumulation patterns will be examined elsewhere.

Analysis of the integrated indices of farmland snow cover (its insoluble part) pollution under traffic impact revealed a medium level in sampling plots of site no. 1, and a high level in sites nos. 2 and 3 (Table 4). Most of the contaminants settled down on roadside strips of farmland, within 15 m off the roadway. The amount of solid residue collected from the sampling plots more than 50 m away from the road was too small to permit the determination of the chemical composition, if at all present.

Some chemical elements in our study were also determined in melted snow mass. Table 6 shows only those of them that have concentration coefficients above 1. The increase in content in all sampling plots in general versus the background levels was up to 34-fold (Al, Mg, Ca, Fe, Cu, Mn, Ni, Zn, Cr). The distribution of the elements along the distance gradient was non-uniform. Their particularly high accumulation in the snow cover may reflect the specific patterns of mass transfer. Intensive accumulation immediately along the motorway was detected for Ca, Mg, Fe, Al, Cu, Cr, Cd – their concentration coefficients declined farther away from the road, as opposed to Ni, Mn, Zn, Pb, and Co. Significant deviation from the background was found for Ca and Mg in all sampling plots of sites no. 1 (up to 100 m distance) and no. 2 (150 m).

Noteworthy are the high concentrations of aluminum in the melted snow mass – 1.3 to 135.3 μg/l versus 4.1 μg/l in the background. Aluminum alloys are used in the automotive industry in the manufacture of engines, body parts (hoods, doors, frames), wheel rims and other car parts. The use of aluminum in this industry is growing every year as it enables making lightweight, durable and corrosion-resistant structures.

The input of aluminum-enriched snowmelt to farmland soils may affect soil fertility (Bojórquez-Quintal et al., 2017). Podzols accumulate some 30 mg labile aluminum per 100 g soil (Alekseev, 1987;

Tyantova et al., 2005). Its high concentrations are detrimental for crops (Amosova et al., 2007). On the other hand, there are some reports in the literature that small doses of aluminum ions can also favorably influence plant growth in some species (Bojórquez-Quintal et al., 2017; Klimashevsky, 1991).

Manganese in liquid-phase snow was also characterized by high coefficients of concentration relative to the background ($K_c$ up to 28.7). Furthermore, its distribution in the snow cover over the study area was also non-uniform, and like in the case of cobalt, zinc, magnesium, calcium and lead, its content did not follow the linear trend of decrease with distance from the pollution source (Table 6). Such a significant spatial variation of macro- and micronutrients is possibly associated with the aerosol form of pollutant dispersal. The results of our study of the snow cover along roads are in agreement with the published data on the accumulation of pollutants in the snow cover and soils of farmlands (Ashikkaliev et al., 2017; Wang, 2022).

Manganese accumulation in filtered meltwater in all sites varied widely – from 1.1 to 48.4 μg/l, the average values being 13.7, 9.6, and 20.9 μg/l at 15, 50, and 100 m distance from the roadway, respectively. Manganese is usually accumulated in the topsoil, where it is fixed by organic matter. The content of water-soluble compounds of this element usually increases in acidic soils (pH below 5.5) (Kabata-Pendias and Pendias, 1989). Manganese is an important agent in the growth and development of agricultural crops, being involved in oxidation-reduction processes, is a component of enzymes, contributes to the formation of sugars, proteins, synthesis of nucleic acids, enhances plant resistance to adverse environmental impacts, etc. (Shkolnik, 1974). However, high concentrations of this nutrient in plants negatively affect the metabolism (carbohydrate, protein, phosphate) and disrupt the initiation of generative organs (Pobilat and Voloshin, 2018).

Chromium, cobalt, nickel, copper, and lead content in the liquid-phase snow was less than ten times that of the background. The concentration coefficient was the highest (5.3) for Ni. Also, as opposed to other elements, the background levels were consistently exceeded by Cr and Ni in all sites. Cobalt was mainly accumulated in sites nos. 2 and 3, while lead and copper in site no. 3.

Generally speaking, the integrated index of pollution of the snow cover (liquid phase) in the agricultural landscapes along roads did not reach critical levels and atmospheric fallouts were regarded as uncontaminated, except for the plot 100 m off the road in site no. 1, which featured Zc = 34.1, corresponding to a low level (Table 6).

Mean-values of the integrated pollution index for melted snow mass on the farmlands reflect the distribution of contamination halos in the study area. Thus, the heaviest impact was found in the plots 100 and 150 m off the road (Fig. 3), which contradicts the Zc estimates based on the solid residue of snow. No reliable differences were detected in the pollution of the melted snow mass along the distance gradient.

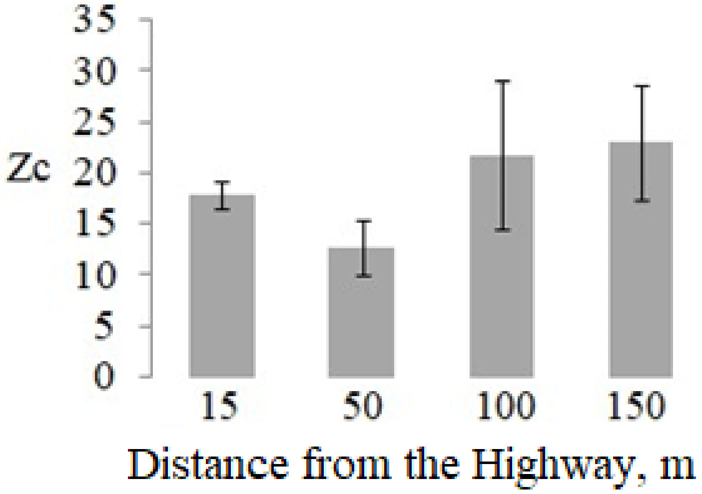

**Fig. 3.** Integrated pollution index (Zc) of melted snow mass in the agricultural landscapes under traffic impact.

**Table 6.** Coefficients of concentration of macro- and micronutrients in melted snow mass on farmlands under road traffic impact. Dash – element not detected.

| Distance to pollution source, m | Element | | | | | | | | | | | | Integrated pollution index (Zc) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ca | Mg | Fe | Mn | Zn | Al | Cu | Ni | Co | Cr | Pb | Cd | |
| Site no. 1 | | | | | | | | | | | | | |
| 15 | 2.9 | 5.1 | 5.0 | 10.0 | 0.3 | 33.0 | 1.5 | 2.9 | 0.9 | 2.3 | 0.1 | 0.4 | 15.4 |
| 50 | 2.5 | 3.9 | 1.3 | 11.7 | 0.1 | 2.4 | 0.9 | 3.7 | 0.6 | 1.8 | – | 0.2 | 15.5 |
| 100 | 2.5 | 4.7 | 0.8 | 28.7 | 0.4 | 1.2 | 0.8 | 5.3 | 0.8 | 2.1 | – | 0.2 | 34.1 |
| 150 | 1.8 | 2.8 | 1.2 | 27.0 | 0.3 | 1.1 | 0.6 | 2.3 | 0.9 | 1.4 | 0.1 | 0.2 | 28.9 |
| Site no. 2 | | | | | | | | | | | | | |
| 15 | 3.1 | 3.6 | 0.9 | 16.3 | 0.4 | 3.4 | 0.5 | 4.6 | 0.7 | 1.2 | 0.1 | – | 20.1 |
| 50 | 2.6 | 3.4 | 1.6 | 3.7 | 0.4 | 1.7 | 0.5 | 3.1 | 1.2 | 1.6 | 0.1 | – | 7.2 |
| 100 | 1.8 | 2.4 | 1.7 | 18.7 | 0.3 | 0.3 | 0.6 | 3.3 | 0.8 | 2.1 | – | – | 22.4 |
| 150 | 1.3 | 2.0 | 0.6 | 23.7 | 0.2 | 0.8 | 0.3 | 3.5 | 1.1 | 2.8 | 0.2 | – | 28.1 |
| Site no. 3 | | | | | | | | | | | | | |
| 15 | 1.7 | 2.3 | 0.9 | 10.9 | 0.3 | 4.5 | 0.3 | 3.1 | 1.8 | 4.8 | 1.1 | – | 17.7 |
| 50 | 1.4 | 1.6 | 1.5 | 10.7 | 0.2 | 1.4 | 0.1 | 0.7 | 2.0 | 3.8 | 0.9 | – | 15.0 |
| 100 | 1.2 | 1.4 | 0.6 | 1.0 | 1.5 | 3.3 | 4.0 | 4.6 | 0.9 | 1.3 | 1.3 | – | 8.7 |
| 150 | 3.3 | 3.7 | 0.6 | 9.5 | 0.2 | 1.6 | 0.1 | 0.3 | 0.7 | 2.7 | 1.5 | – | 11.7 |

### *Total traffic-related pollution load on the agricultural landscapes*

While dust pollution was relatively low, the total pollution level varied from medium to high. The total traffic-related pollution load ($Z_p$) on the agricultural landscape in the plots closest to the road was classified as medium in all sites (Table 4).

The series of prevalent accumulation of elements in the snow cover along motorways had common features (Table 5) and lists of the elements exceeding the background levels were nearly identical. The significant increase in Cd and Zn was probably associated primarily with tire wear, while Mo, Cu, and Ni emissions – with brake shoe wear.

## Conclusions

Motorized traffic in Karelia proved to be a weighty source of man-made emissions carrying a wide spectrum of chemical elements. The snowfall formed under traffic impact had medium and low levels of dust pollution, with the impact decreasing with distance to the motorway. The integrated pollution index was medium to high. All the surveyed farmland sites lying along federal motorways received high concentrations of Mo, W, Ti, Al, K, Cu, Na, Mn, Ca, Mg, Fe, Ni, Cr, Cd ($K_c$ from 1.5 to 74.0 relative to the background). The MPCs were exceeded for cadmium (up to 10-fold), zinc (9.4), cobalt (9.0), molybdenum (7.9), copper (3.2), nickel (2.4), antimony (3.3), and iron (2.1). The total man-made pollution load ($Z_p$) on farmlands in all sites was ranked as medium (1715.6–2723.2) in the plots situated the closest to the road and was below minimum thresholds in the remote plots (5.4–242.4). In order to form ecologically resilient and highly productive agricultural landscapes, gas and dust fences and dust buffers of trees and shrubs should be created along roads (Dubina-Chekhovich, 2023).

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