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Information technologies as a new tool for reindeer pastures monitoring in arctic Russia

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At the start of the twenty-first century, the historically rooted sector of pastoral reindeer husbandry in European Russia entered a period of rapid transformation driven by both environmental and social dynamics. Environmental shifts associated with the climatic reconfiguration of Arctic ecosystems, evaluations of the likely consequences of the explosive acceleration of regional industrial development, the advent of near-real-time monitoring of pasture components, and the deployment of GIS and GPS-based reindeer tracking have together defined the principal strands of a twenty-year research programme undertaken by the Computer Systems, Technologies and Modelling Group at the Institute of Biology, Komi Science Centre, Ural Branch of the Russian Academy of Sciences. This study aims to synthesise that experience into an integrated account, to identify "hot spots" for traditional resource use, and to show how these advances have been translated into practical natural-resource management and land-use applications. Since 2011, new information technologies for monitoring the condition of pasture vegetation resources, tracking daily and seasonal migration of animals (using satellite and radio collars), and accounting for pasture loads have been tested and implemented in land surveying practices for reindeer herding farms in the European North of Russia. The availability of pasture resources in the region varies significantly, ranging from 14 ha per head in the aboriginal community "Yamb-To" to 394 ha per head in "Druzhba narodov," with an average of 151 ha per head based on statistical data. For all large reindeer herding farms, pasture area utilisation projects have been updated, and detailed vegetation mapping, including temporal changes, has been conducted. The primary sources of spatial data are high-resolution unmanned aerial vehicle images and satellite imagery. Calculations of optimal reindeer-intensity indicators, accounting for green and lichen fodder reserves, have been carried out. The resulting data has been integrated into an information system dedicated to reindeer herding in the European North. The main trends in pasture changes in the region are driven by climatic shifts, variations in grazing load, and active industrial expansion. According to MODIS satellite imagery, over 89% of East-European tundra areas exhibited an increase in the green phytomass of vascular plants by 50%–150% in 2024 compared to 2000. Nearly 10% of areas showed biomass storage increases exceeding twofold. Warming and industrial activities have triggered the incorporation of various chemical elements, including heavy metals, into trophic chains, which may adversely affect the quality and safety of reindeer industry products. New information technologies

are crucial for reindeer pasture monitoring, and the integration of diverse data into a single system can have a positive impact on reindeer husbandry and ecosystem monitoring of region.

KEYWORDS

climate and environmental changes, information technology, monitoring, pasture ecosystems, reindeer husbandry

Introduction

Reindeer herding has long been one of the primary forms of traditional natural resource exploitation in the northern territories of Russia, holding significant economic, social, and cultural importance, as noted by numerous researches (Jernsletten and Klokov, 2002; Klokov and Khrushchev, 2004; Mukhachev and Laishev, 2006; Baskin, 2009; Perevalova and Kisser, 2024.). At the same time, grazing by domestic reindeer serves as a key factor in the transformation of natural ecosystems. It influences biodiversity indicators (Estafiev and Mineev, 1981; Golovatin et al., 2012), vegetation cover productivity (Veselkin et al., 2021), and the balance of vegetation taxa and plant life forms (Morozova and Magomedova, 2004; Bernes et al., 2015). Additionally, it impacts microbial composition and the cycling intensity of various nutrient elements (Olofsson et al., 2001; Olofsson et al., 2004). Given the numerous factors influencing reindeer husbandry in the Arctic region, as well as their complex interactions and feedback mechanisms, there is a constant need for improvements in the system of pasture inventory, management, and monitoring.

In 1975, the Council of Ministers of the RSFSR established regional subdivisions of land management enterprises with the aim of "improving the organisation and quality of survey work on land management in the Far North regions, conducting vegetation research, and developing projects for the redistribution of reindeer pastures and hunting grounds among landowners and their utilisation"[1]. The newly formed Land Management units, which included the Murmansk and Angarsk (Bratsk) survey expeditions of "Roszemproekt" as well as the Yakutsk and Magadan branches of the Far Eastern Research and Design and Survey Institute for Land Resources and Land Management (DalNIIgiprozem), began the systematic inventory of northern territories. These organisations compiled the results of field research (primarily focusing on vegetation and economic studies) and primary materials related to pasture allocation projects, including maps and attribute-format data. These materials were typically updated every 10–15 years. In some cases, the archives of the organisations have been preserved and can now be supplemented with new research or used to update pasture allocation projects.

Domestic reindeer grazing in the European part of Russia spans an area of 49.1 million hectares, predominantly within the tundra and forest-tundra zones, with lesser activity in the forest zone. The largest pasture areas are situated in the Nenets Autonomous Okrug (61.9%) and the Komi Republic (23.9%), while smaller areas are found in the Murmansk (12.9%) and Arkhangelsk (1.3%) regions. A distinctive feature of the reindeer herding industry in this region is the concentration of extensive land resources within large reindeer herding enterprises. For instance, 31 independent reindeer herding farm are currently registered in the Nenets AO but 98% of pasturelands are allocated among 11 large agricultural cooperatives (most of which are former Soviet-era sovkhozes) and the Nenets Agro-Industrial Company (Figure 1A). In the Komi Republic, five large reindeer herding enterprises are registered, holding exclusive rights to all reindeer herding pasturelands within the Republic, excluding those used by enterprises from the Nenets AO. As is evident, some enterprises (all in the Komi Republic) own land in both the Republic and the Okrug. Figure 1A illustrates the land allocation among 20 reindeer herding enterprises in the region. The largest pastureland areas are owned by "Izhemskii olenevod" (3.37 million hectares), "Severnyi" (3.01 million hectares)[2], "Nenetskaja obshchina 'Kanin'" (1.97 million hectares), and "Bol'shaya Inta" (1.83 million hectares). However, the distribution of reindeer among enterprises only partially mirrors the distribution of land. The largest reindeer owners are "Izhemskii olenevod" (24.1 thousand animals), "Olenevod" (19.7 thousand animals) and "Severnyi" (18.8 thousand animals) (Figure 1C).

Among the large reindeer herding enterprises, the average pasture load ranges from 139 to 160 ha per reindeer. The "Olenevod" enterprise experiences the highest grazing pressure (49.4 ha per head), while "Druzhba narodov" has the lowest (394 ha per head) (Figure 1D). The average pasture load for the region as a whole is 151 ha per head. In present time the lowest grazing pressure can be fixed for Kolguev Island following the mass mortality of reindeer in 2013 (Okorokov and Kuznetsov, 2024), following which the population declined from more than 12,000 individuals to only 153 by the end of

1 The Resolution of the Council of Ministers of the RSFSR of 10.04.1975 No 225. On improving the organization of execution and quality of design and survey works on land management http://www.businesspravo.ru/Docum/DocumShow_DocumID_33244.html

2 Part of the pastures went to the obshina "Yamb-To".

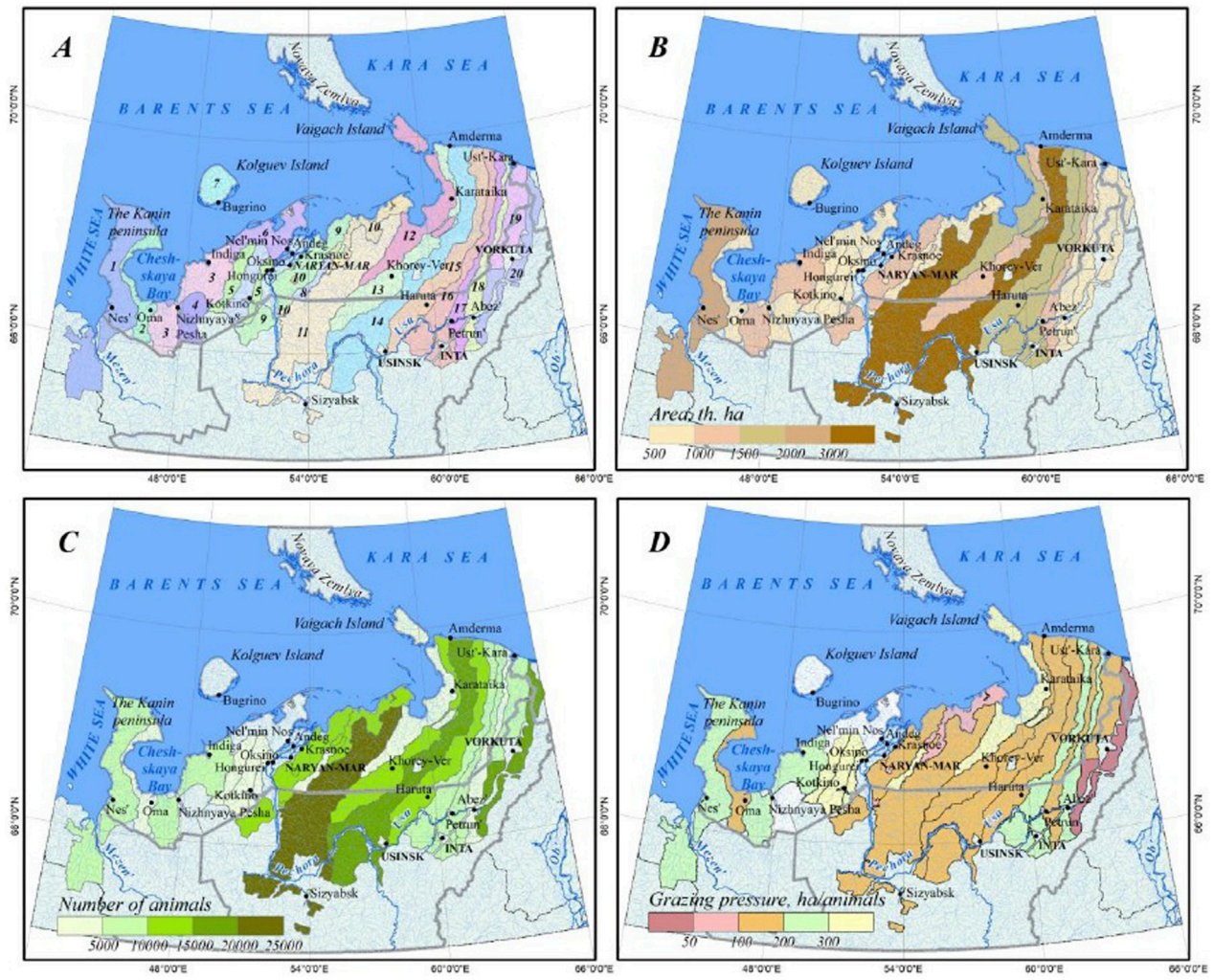

FIGURE 1
Main reindeer herding farms in the north-east of European Russia **(A)** and some of their features: area (thousand ha) **(B)**, number of animals **(C)** and grazing pressure (number of animals per area) **(D)**. The numbers indicate the pastures of the farms: 1 - obshina "Nenetskaja obshchina 'Kanin'", 2 – reindeer herding cooperative "Voskhod", 3 - reindeer herding cooperative "Indigskii", 4 - reindeer herding cooperative "Zapolyar'e", 5 - reindeer herding cooperative "Nar'yana-Ty", 6 - reindeer herding cooperative "Imeni Vyucheiskogo", 7 - reindeer herding cooperative "Kolguev", 8 - reindeer herding cooperative "Nenetskaya agrokompaniya", 9 - reindeer herding cooperative "Kharp", 10 - reindeer herding cooperative "Erv", 11 - reindeer herding cooperative "Izhemskii olenevod", 12 - reindeer herding cooperative "Druzhba narodov", 13 - reindeer herding cooperative "Put' Il'icha", 14 – Stock-share company "Severnyi" and obshina "Yamb-To", 15 - reindeer herding cooperative "Rassvet Severa", 16 - Stock-share company "Bol'shaya Inta", 17 – Komi republican state enterprise "Petrun'skii", 18 -– Komi republican state enterprise "Abez'", 19 - reindeer herding cooperative "Krasnyi Oktyabr'", 20 - reindeer herding cooperative "Olenevod". The borders of the farms are as per Elsakov, 2011.

2014. No reliable data exists for the pasturelands of closed farms, such as "Imeni Vyucheiskogo." Conversely, grazing pressure can be extremely high in newly established enterprises. For instance, the "Yamb-To" aboriginal peoples' obshina ("The Long Lake") has a grazing pressure of 14 ha per head. As of 1 January 2025, this obshina's 14,2 thousand reindeer[3] grazed approximately 200 thousand hectares of allocated pastureland. However, botanical research from 2019 estimated the carrying capacity of the "Yamb-To" area at only 2.0 thousand animals (LLC, 2019). The pastures near Vashutkiny lakes experience some of the most intensive grazing pressures in the region. At the same time, this area has been designated as a protected zone (the "Vashutkinskiye Ozera" Regional Natural Reserve), necessitating biodiversity monitoring. The strategy of increasing the number of private farms, often associated with uncontrolled herd growth and unauthorised access to the

3 https://gubernator.adm-nao.ru/news/37647/.

pastures of neighbouring farms due to land shortages, risks degrading pastureland vegetation, as has been observed in the Yamalo-Nenets AO (Golovatin et al., 2012). It also has the potential to generate conflicts between adjacent enterprises. Therefore, integrating land use planning with regular vegetation monitoring appears to be the most sustainable approach.

In all large reindeer herding enterprises of the region, where land has been leased on a long-term basis, grazing is regulated by individual land-use projects (or plans). These projects provide detailed descriptions of the pastures, including their vegetation, the stock of green and lichen forage, the grazing season or period for each range, and the calculated reindeer carrying capacity. Additionally, these projects form the primary legal basis for calculating damages caused by industrial development projects (such as oil drilling) and determining the corresponding compensations to be paid to the enterprises. Regular updates to land-use projects are required, based on new land surveys. In the north of European Russia, the institution responsible for conducting these surveys and updating or creating new land-use projects is LLC "Murmansk Land Management Company" (LLC "MLMC"), formerly the Murmansk Expedition of "Roszemproekt" during Soviet times. This organisation maintains and updates archives of data from earlier land surveys, some dating to the 1970s and conducted by outsourced research organisations. Spatially organised data from regular surveys conducted over extended periods can provide invaluable material, enabling the identification and analysis of prevailing trends of change in the Arctic region in recent decades.

The improvement and development of GIS methods, digital modelling, and data processing tools have significantly expanded the possibilities for monitoring and reorganising traditional nature management areas. One of the first computer programs designed for creating reindeer herding land-use projects was developed by Y.M. Gordova at LLC "MLMC" in the early 2000s. This software, called TUN (abbreviation of 'tundra') remains in use today. Whether using paper, pencil, and electronic calculator as in previous decades or specialised software like TUN, developing a reindeer herding land-use project essentially involves calculating three key variables: the reindeer carrying capacity, the maximum herd size, and the maximum duration of grazing without causing irreducible damage to vegetation. These calculations are based on empirically determined values for the dominant vegetation classes (condition, ratio, and availability of green or lichen fodder) and both local and global constants, such as duration of grazing seasons, the structure of reindeer diet by season, and the normative area of pastures required per reindeer per day for each grazing season. In recent decades, traditional methods of land surveys, monitoring, and land-use projects development have been enhanced by new opportunities provided by satellite remote sensing data of vegetation cover and advanced equipment for monitoring the migration activities of animals.

In recent decades, a new non-contact instrument for monitoring migration activity of domestic (Terekhina et al., 2023) and wild reindeer (Khaimina et al., 2021) has gained popularity among herders and researchers alike. These are satellite reindeer collars, which enable real-time tracking of the wearer's movements. In recent years, such collars have started to be manufactured in Russia,[4] and their use for monitoring animal migrations is becoming increasingly widespread. For instance, "Pulsar" collars, equipped with satellite beacons produced by the LLC "ES-PAS" company (Moscow), were first introduced to the market in 2010 (Salman & Rozhnov, 2010). This equipment has been utilised to monitor the migrations of wild reindeer in Krasnoyarsk Krai (Taimyr Peninsula) (Savchenko et al., 2018), the Republic of Yakutia and the Archangelsk region (Mamontov and Genikova, 2018), and Karelia (Mamontov, 2020; Panchenko et al., 2024).

Reindeer interact with ecosystem components across vast territories, with individual herds travelling up to 300–400 km annually to access seasonal pastures. This makes them valuable indicators for analysing background conditions of regional geosystems. The interconnected network of grazing areas across enterprises provides a solid basis for geochemical monitoring of the entire region. In 2016, the Rosselkhoznadzor (Federal Service for Veterinary and Phytosanitary Surveillance) of Russia reported significant exceedances of normative indicators for the toxic chemical element content [dioxins, cadmium (Cd), mercury (Hg), and, less frequently lead (Pb)] in reindeer by-products (liver, kidneys) produced by agricultural enterprises in most Arctic regions. The European part of the Russian Arctic was no exception (Elsakov and Makarkin, 2016). From this period we regularly analyze geochemical background of pastures and reindeers. The primary sources of pollutants found in reindeer bodies are, unsurprisingly, their fodder and surface water. The increase in pollutant content in animals has been linked to technogenic factors, including local pollution, long-range transboundary atmospheric transport of contaminants from industrial centres outside the region, and climatic changes in recent years (Elsakov and Makarkin, 2016).

The aim of this article is to synthesise and analyse 20 years of research generated through collaborations with regional land-management and reindeer-husbandry enterprises during the sector's adoption of new information technologies. This period coincided with the emergence and maturation of satellite-based methods for monitoring pasture vegetation and a transition to GIS-based pasture planning. The resulting comprehensive longitudinal dataset has enabled us to characterise contemporary trends linked to climatic transformation and industrial expansion, and to identify risks

4 The legal use of foreign-made collars in Russia requires considerable effort to overcome administrative restrictions.

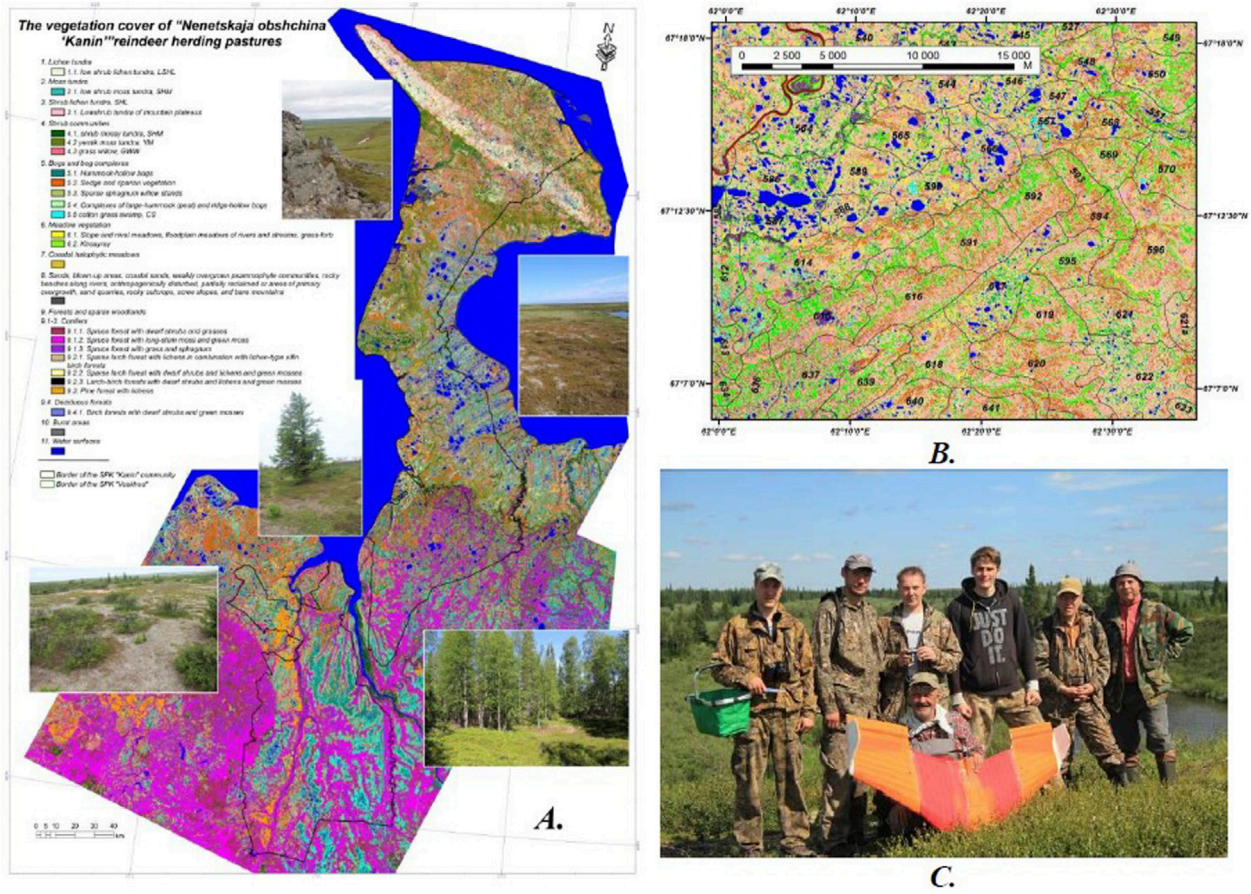

FIGURE 2
A sample vegetation map of pastures belonging to the "Obshchina 'Kanin'" and "Voskhod" enterprises, based on the classification of Landsat satellite images **(A)**; the division of the territory into land units with different compositions of vegetation classes **(B)**; and the Institute of Biology field team, conducting a study of reindeer pasture vegetation, July 2012 **(C)** (Author's photo).

to sectoral development. In the near term, these data will underpin the development of an integrated information system, "Reindeer pasture resources of the Nenets AO and the Komi Republic."

Materials and methods

Remote sensing based vegetation cover change analyses

Since 2011, LLC "MLMC" and the Institute of biology have started developing algorithms for processing and utilising satellite imagery data (primarily Landsat and Sentinel-2) and unmanned aerial vehicle (UAV) data for resource assessment of pastures vegetation. This assessment focuses on vegetation cover and is intended for use in developing an information system for reindeer herding in the European North. The core data in this system are geospatial datasets, which include vegetation and soils descriptions, chemical analysis of samples, vegetation biomass measurements, thematic maps (vegetation classes as shown in Figure 2A at a base scale 1 : 100 000), biomass distribution, infrastructure, and satellite collar locations of reindeers. The fundamental unit of data storage in this information system is the so-called "landscape-geobotanical contour" (Figure 2B). This unit represents a combination of homogeneous landscape complexes and plant communities. Each contour is assigned a unique identification number that remains constant over time, enabling year-to-year comparisons of pasture parameters. For generation and verification results of vegetation mapping field research are carried out (Figure 2C).

The detail description of methods and theoretical issues related to algorithms for processing satellite and UAV imagery data in the conducted research are presented in

earlier publications (Elsakov et al., 2017; Elsakov, 2023). These include methods for guided classification, step-by-step threshold segmentation, the use of neural networks, and the estimation of biomass storage and vegetation projective coverage, as well as patterns of pasture changes (Elsakov and Kulyugina, 2014; Elsakov, 2017; Elsakov and Shchanov, 2019; Elsakov et al., 2022; Elsakov, 2024). Part of algorithms have been integrated into the design of our analytical tools, which are officially registered and protected by the Russian Federation patent (No 2521755). Once the relationship between the satellite imagery data and field instrumental measurements (primarily productivity and stocks of green phytomass) was established, it became possible to convert dimensionless physical quantities into biomass volumes and analyse the annual quantitative indicators of the plant communities (Elsakov et al., 2022).

Migration observations with GPS collars

Since 2021, improved collars "Quasar"(LLC "ES-PAS" company, Moscow), specially designed for use on domestic reindeer, have been produced by LLC "ES-PAS" as part of the Russian-European project SISMA-2 (Space Innovation System for Monitoring Animals). These collars, referred to as "intelligent collars", can recognise animal behaviour and are tailored to the needs of the northern reindeer herding industry in Russia. Approximately 200 test collars of this type were distributed among reindeer herding enterprises across six northern provinces of Russia, with 39 devices allocated to the Komi Republic and the Nenets AO. The new collars were also fitted to wild reindeer of region. The pilot demonstration relied heavily on the involvement of scientists working in the demonstration regions and their established formal and informal relationships with reindeer herding communities and local governments. It is worth noting that, prior to this initiative, some attempts to organise monitoring of domestic reindeer migration activity had been made in certain northern regions of Russia (JSC 'ITC APK RS' in Yakutia[5] and 'STECCOM' in Chukotka[6]). However, these efforts were not particularly successful. In the Komi Republic and Nenets AO, this initiative marked the first time that many reindeer herding enterprises were able to monito[7]r the daily or seasonal movements of their herds. A questionnaire survey about experiences with collars was sent to approximately 50 enterprise managers, foremen, and reindeer herders, of which 18 returned completed questionnaires.

Geochemical monitoring of the reindeer pastures system

Samples of vegetation (plants and lichens), soils, surface water and animal tissues were collected in accordance with established protocols and analysed elements content (Cu, Pb, Cd, Zn, Ni, Co, Mn Fe, Hg, Cr and As) at the accredited chemical-analytical laboratory of the Institute of Biology, Komi Science Centre, Ural Branch of the Russian Academy of Sciences (Syktyvkar, Russia). Samples of animals (liver, muscle and kidneys) were collected per period 2015 – 2022 mainly in November from slaughterhouses of different farms in frozen condition and were labelled with information on sex, age, rank and farm/brigade. After transportation, the samples were lyophilised (freeze-dried) using a Beta-2-8-LSCbasic unit (CHRIST, Germany) to constant weight. The results were evaluated by comparison with relevant standards. In the Russian Federation, pollution levels in reindeer-herding products are regulated by the standards outlined in TR CU 021/2011[8].

Results

Vegetation and biomass dynamic

Between 2011 and 2024, all reindeer herding enterprises in the European North underwent surveys. These surveys included botanical research and vegetation mapping (Scale 1: 100 000), the creation of fodder resource contours, the calculation of reindeer carrying capacity indicators, and the renewal of pasture land-use projects for each enterprise. Analysis of reindeer pastures vegetation using archived and online optical satellite data [Landsat, Sentinel, and MODIS (MOD13Q1.005)], since 1980 has demonstrated significant changes, particularly in the European part of Russia. The initial stages of vegetation modifications in the European Arctic occurred predominantly during 2000–2009, following the rise in surface air temperature (SAT) in 2000. The analysis of satellite thematically image of biomass distribution (Figure 3A) demonstrated that the highest reserves of green fodder in the Arctic region's reindeer pastures are found in the tundra of European Russia: in 2024, the average phytomass value in the region was 1.88 tonnes/ha. Localised growth of green mass (phytomass exceeding 2.0–3.0 tonnes/ha) was observed in areas where highly productive shrub and grass communities predominated, such as the shrub communities in the northern part of the Kanin Peninsula, characterised by a

5 https://sakhapress.ru/archives/164758

6 https://www.steccom.ru/equipment/

7 https://prochukotku.ru/news/selskoe_khozyaystvo/osheyniki_s_shagomerom_dlya_severnykh_oleney_protestiruyut_na_chukotke/

8 Technical Regulations of the Customs Union 021/2011 "On food safety" (as amended on 8 August 2019). Appendix 3 is a part of TR CU 021/2011 (https://eacgroupcompany.com/en/regulations/trcu021-2011).

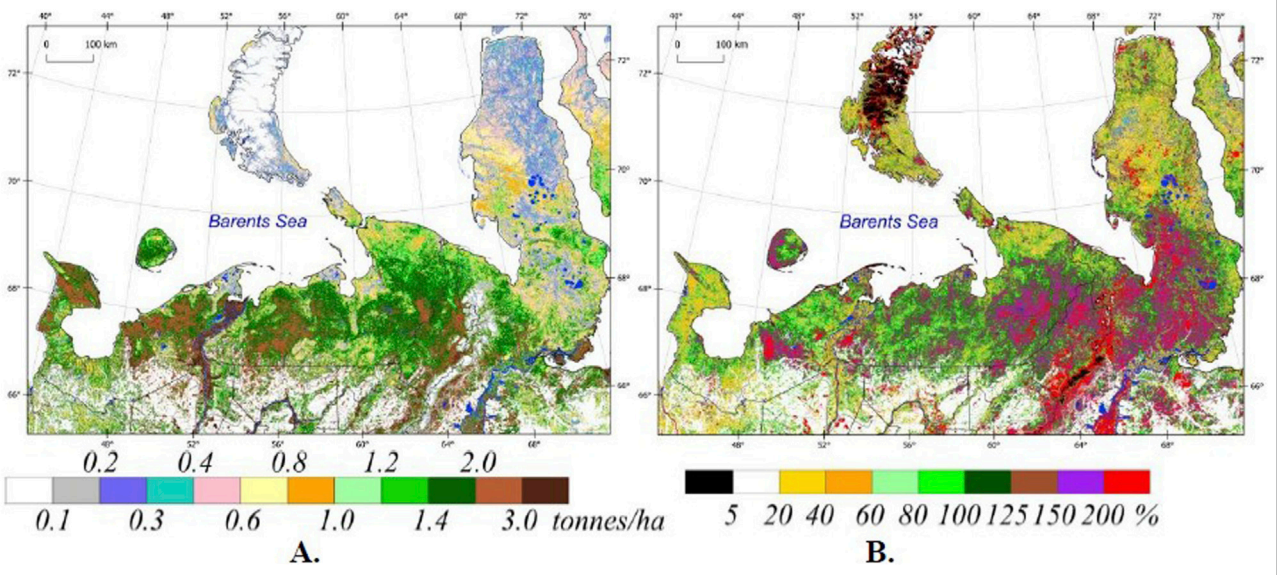

FIGURE 3
The distribution of green vegetation biomass (tonnes/ha) on tundra pastures in 2024 **(A)**; changes in green biomass storage (%) between 2000–2024 **(B)**. Data processed by the author using annual maximum satellite NDVI MODIS sets.

developed cover of *Betula czerepanovii* and *Salix* species shrubs. In contrast, the tundra vegetation of Western Siberia exhibits significantly lower values: 1.39 tonnes/ha in the southern part, decreasing further towards the north of the Yamal Peninsula. Further eastwards, in the Central and Eastern Siberian Arctic, these values decline even more, ranging between 0.52 and 0.60 tonnes/ha. The results of satellite image processing clearly reflect the existing zonal and longitudinal disparities in green phytomass distribution.

"Greening" of the Arctic region is a process widely noted by researchers in the literature over the last decades (e.g., Raynolds et al., 2006; Forbes et al., 2010; Elsakov, 2017; Myers-Smith et al., 2020). The phenomenon is associated with an increase in the productivity of tundra plant communities due to the growth of green phytomass in herbaceous plants and shrubs. In our observations more than 89% of the eastern European tundra areas in 2024 experienced an increase in green phytomass by 50%–150% compared to the year 2000. Nearly 10% of the area doubled its biomass storage (Figure 3B). The most significant growth was recorded in the Northern Timan, Pai-Khoy foothills, and the slopes of the Subpolar and Polar Urals. These areas of phytomass growth often coincide with zones of permafrost degradation and are therefore confined to the southern boundaries of the continuous permafrost zone.

One of the most notable increases of dry green phytomass in the Nenets AO occurred in the low shrub lichen tundra of the Timan hill range dominated by *Betula, Arctous* and *Empetrum*. Analysis of vegetation cover changes in this territory was conducted using Landsat, Sentinel and MODIS satellite images from 1985 to 2017 as well as field observations from 2017–2018. Green biomass increased by more than 70% between 2000 and 2009. The growth of surface air temperature (mainly in the autumn-winter period), alongside increased winter precipitation, were the main factors responsible for changes in plant communities. Additionally, a significant reduction in reindeer numbers (the total herd of the "Indigskii" enterprise declined from 16.1 to 16.4 thousand animals in the early 1990s to 8,2 thousand animals in 1999) likely favoured vegetation growth. Interannual NDVI change trends were confirmed through a combination of the mean spatial resolution MODIS and high resolution Landsat 5 and 7 images for matching intervals. The calculated linear trends (β) in NDVI change based on survey data from different sensors were statistically equivalent, showing a significant positive correlation ($r = 0.72$, $p \leq 0.05$). Expressed as dry green phytomass of low shrubs (*Betula, Arctous*, and *Empetrum*), the increase amounted to 0.185 tonnes per hectare. The greatest changes occurred in low shrub lichen tundra communities (chlorophyll content growth by 1.26 kg/ha, dry green phytomass by 0.25 tonnes/ha). There was a 29% increase in the reindeer-feeding capacity of green foodstuffs from 1985 to 2009; adjacent areas experienced a 15% increase. A more detailed description is presented in Elsakov and Shchanov (2019).

Significant biomass growth (over 150%–200% between 2000 and 2024) was recorded for shrub communities of the Jugorskii Peninsula with Pai-Khoy hill range. Notable increases in green biomass occurred in shrub tundra dominated by willows, *Salix lanata* and *S.phylicifolia,* and low-growing willow stands dominated by *S.glauca*, alongside actively

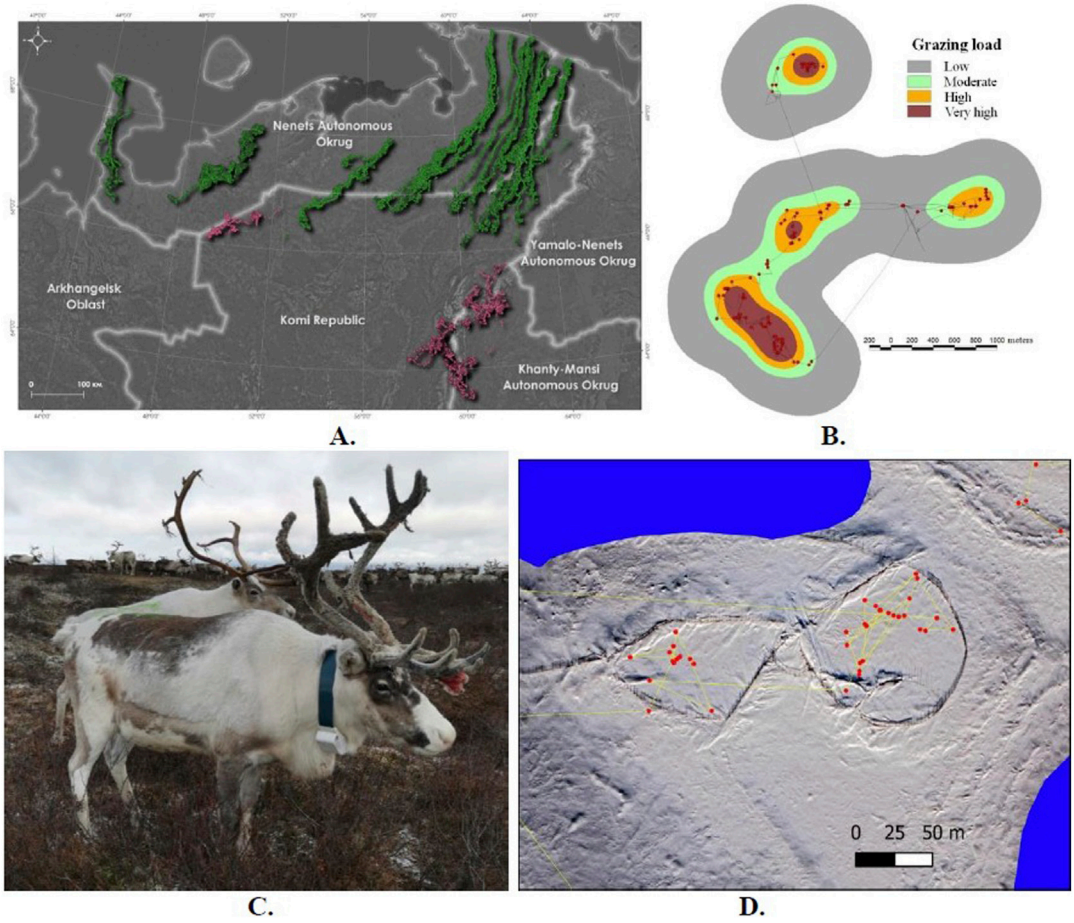

FIGURE 4
(A) Tracks of domestic reindeer movements in reindeer herding enterprises (green) and wild reindeers (pink) in 2021–2022 recorded using satellite collars; **(B)** calculation of grazing pressure in tundra pasture areas based on GPS collar data; **(C)** A test collar "Pulsar" (produced by ES-PAS) fitted on a domestic reindeer, Tazovskii region of Yamal-Nenets AO 11/10/2021); **(D)** maximal aggregation of recorded GPS locations, typically associated with reindeer corrals used for vaccination, counting, sorting, etc. The clusters of GPS collar dots reflect the animals' stay in the corral for 18.5 h (east of Bolshezemelskaya tundra, Nenets AO*) (Author's photo).*

expanding coastal tundra in the northern part of Yugorsky Peninsula (Elsakov and Kulyugina, 2014). Similar trends have been observed in other Arctic regions: a comparison of 1980 and 2013 images of natural areas in western Canada revealed a twofold increase in shrub vegetation (from 41% to 80%), coupled with a decrease in ground lichens (from 48% to 13%) (Fraser et al., 2014).

The greatest growth of green phytomass stock (up to 68.0%) from 2000 to 2024 was seen in the pastures of the Kolguev Island enterprise. Aside from rising temperature indices, this increase was facilitated by rapid reindeer herd reduction due to catastrophic mortality in spring of 2013 (Okorokov and Kuznetsov, 2024). Less active green phytomass growth (37.6–46.0%) was recorded in the marginal permafrost areas and adjacent zones in the east of Bolshezemelskaya tundra. Conversely, the lands of the "Nenetskaja obshchina 'Kanin'" and "Voskhod" enterprises, located in the western part of Nenets AO exhibited the lowest increase (24.0–27.6%), as the main vegetation changes there had occurred earlier.

GPS collar monitoring of reindeer migrations

A total of 588 thousand animal locations were collected, averaging 10,500 positions per device for 2020–2022 (Figure 4A). The location data with the consent of the reindeer herders was available online and could be used to locate groups of animals that had separated from the main herds as well as to manage the timing of herd movements. For many enterprises, this marked their first experience with radio-electronic devices. Following the conclusion of the

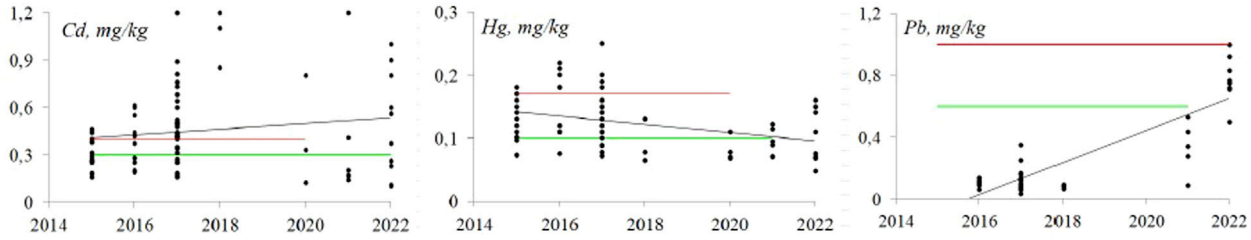

FIGURE 5
The concentration of selected heavy metals in reindeer liver across different years of observation. The normative limits (green) established by TR CU 021/2011 and probability thresholds levels (PTL) (red). Exceeding the PTL is likely to trigger a ban on trade in meat products. Black line depicts the linear trend.

project, several enterprises chose to purchase the equipment and continue using it independently.

A questionnaire survey of the enterprise managers, foremen, and reindeer herders showed that satellite collars were a useful working tool by most respondents (only one rated the usefulness of the technology as "50/50"). For a reindeer herding team (brigade), from 2 (96% of respondents) to 10 collars were reported as being necessary. Many respondents noted the relatively high cost of the devices (approximately €470 for the collar and €30 monthly maintenance), but also expressed a willingness to purchase them if 70% of the cost would be subsidised by the government. The main limitation to the use of collars is the lack of Internet connectivity in the field camps (100% of respondents). Nearly 90% of respondents reported downloading the collars' data to their desktop computers, implying that data analysis and usage typically occur at home or in the office. Only a few access the data using specially developed mobile applications, limiting its use in tundra camps. Reindeer herding in Russia remains both a traditional and a traditionalistic industry, with new information technologies and gadgets (including drones, electronic tags, etc.) not yet widely embraced. The primary purpose of the collars for herders is to monitor animal movements and control grazing boundaries (Figures 4B,D). Other potential applications are often left to research organisations, which require the data to be transferred to a common database. Attitudes towards data sharing vary among enterprises: some are willing to make the data publicly available, others prefer bilateral agreements with potential users, and a few are unwilling to release the data for further analysis under any conditions.

Geochemical monitoring of pastures area

According to TR CU 021/2011 standard, over 50% of reindeer liver samples from the region focused on in this study exhibited high Cd concentrations, a smaller percentage showed elevated Hg levels, and some contained high Pb levels (Figure 5). Muscle tissue samples, however, did not demonstrate such exceedances. Interannual monitoring of elements concentrations indicated a slight increase in Cd and Pb levels, while Hg concentration showed a decline. Calculations made on the relationships between elemental concentrations in various organs allowed the determination of volumes of probability threshold levels (PTL) at which regulatory restrictions for meat products would apply. These threshold were identified as Hg concentrations in deer liver exceeding 0.17 mg/kg (Bolshakova, 1979), Cd concentration above 0.4 mg/kg and (Kochkarev and Mikhailov, 2016) and Pb concentrations exceeding 1.0 mg/kg (Kochkarev, 2015) (red lines in Figure 5).

Discussion

The analysis of vegetation satellite maps from recent decades indicates that the majority of reindeer herding enterprises in the north-east of the European part of Russia face pressing issues related to pastureland shortages and degradation, caused by high grazing pressure and active industrial development. Nenets AO contains 97 hydrocarbon fields (including 84 oil fields) with technologically recoverable reserves[9]. Between 2021 and 2023 alone, official data (Report, 2024) indicate that nearly 1,0 thousand hectares of agricultural land (mainly reindeer pastures) were reclassified as "land for subsoil use". According to the administration of the "Izhemskii olenevod" enterprise, about 3,0 thousand hectares of its land were confiscated by companies "Lukoil", "Bashneft", "Zvezda Arktiki", "LLC NNK", etc., between 2021 and 2024, with a further 530 ha slated for confiscation soon by "Layavozhneftegaz". In 2023, nearly 403,7 thousand hectares of "derelict" land was entered into the cadastral registration in Nenets AO (Table 1).

9 State Balance of Mineral Reserves of the Russian Federation for the 01.01.2023 (Report. . ., 2024).

TABLE 1 Changes in the land register of the Nenets AO by categories, 2019–2023 (Report, 2024).

Land categories	2019/2020	2020/2021	2021/2022	2022/2023
Agricultural lands	−0.5	−0.4	−0.8	−0.2
Industrial lands	+0.5	+0.4	+0.8	+403.7
Reserve land[a]	0	0	0	−403.6

[a]Land plots were put on the state cadastral registration.

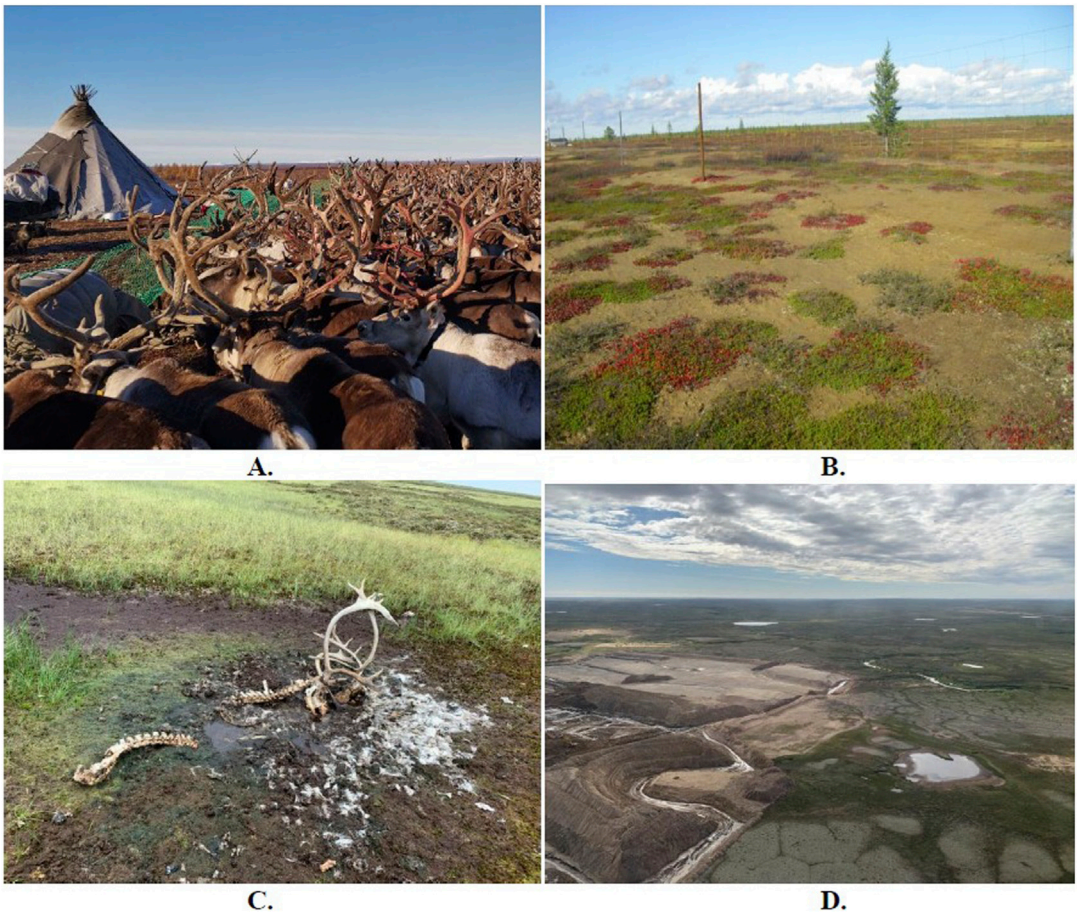

FIGURE 6
Reindeers near a chum (Priuralsky district of Yamal-Nenets AO, September 2023) **(A)**; The expansion of clumps of low shrubs (*Arctous alpinum, Empetrum nigrum, Ledum decumbence*), which are resistant to overgrazing (Tazovsky district of Yamal-Nenets AO, September 2021) **(B)**; "mire trap" for reindeer engaged in mating battle **(C)**; sand pits on oil well sites and local roads result in destruction of lichen (winter) pastures (The Yaigor'yu sand pit covers approx. 46 ha in the west of Bolshezemelskaya tundra, Nenets AO, August 2022) **(D)** *(Author's photo).*

Most components of ecosystems in the region have reflected trends associated with stable climatic changes. This is visually reflected in an increase in the proportion of biomass of shrubs, low shrubs and herbaceous plants, and the development of thermokarst. The vegetation cover of pasturelands serves as a natural indicator, often reflecting the influence of factors that either amplify or mitigate the effect of these changes. Notably, high grazing pressure partially or entirely offsets the increase in plant primary production and the expansion of shrub ranges prompted by climate change (Plante et al., 2014). The principal triggers of large-scale vegetation restructuring in the region include, apart from climate change, variation in grazing load

(Bernes et al., 2015), localised impacts of industrial facilities and transport infrastructure (Forbes et al., 2009), and natural fires (Racine et al., 2004; Sizov et al., 2020).

Temperature increases have enhanced the productivity and phytomass of green plants in most Arctic areas, with this trend supported by the active replacement of tundra vegetation classes and the observed expansion of shrub and forest vegetation at the southern edge of the region (Kaplan and New, 2006). According to most existing scenarios, over half of Arctic phytocenoses will undergo significant changes by 2050, with woody vegetation areas projected to increase by 52% (Pearson et al., 2013). High pastoral pressure reduces the forage reserves of the most valuable lichens and plants, alters vegetation cover, and consequently leads to the formation of communities dominated by more trampling-resistant but less forage-valuable plant and lichen species (Figure 6B). Even in Western Siberia pastures, where the number of grazing animals greatly exceeds the established carrying capacity (Figure 6A), and many plant communities show high level of degradation (Veselkin et al., 2021), signs of green phytomass growth are being recorded. These processes are most clearly observed through comparisons of satellite images from different years and analyses of calculated spectral vegetation indices, such as NDVI and EVI.

However, these vegetation changes signify the onset of profound restructuring within ecosystem components and their interrelations: shifts in permafrost condition, hydrological regime, and the balance between vegetation forms (especially plants, mosses and lichens). This is particularly important for the traditional management of reindeer husbandry. The widespread decline of lichen fodder reserves, the main limiting factor for reindeer husbandry in the region, even amidst increasing green fodder reserves, explains the negative trend in herd numbers. Winter fodder shortages in recent decades are also linked to the active destruction of lichen pastures caused by industrial developments, well sites, and sand quarries (Figure 6D).

Modern climatic changes cause multiple cascading transformations of pastureland ecosystem components, which are often interconnected through various intermediate links. First and foremost, changes in temperature indices directly alter the optimum temperature balance for reindeer species (mainly summer temperature), potentially initiating shifts in their grazing range (Mikhailov et al., 2013; Makeev et al., 2014). Additionally, the frequency of rain-on-snow events is increasing (Callaghan et al., 2021). Warming also triggers processes of permafrost degradation. The lowering of the upper permafrost layer leads to waterlogging and the formation of water leaks, in which animals can get "stuck" and even perish (Figure 6C). Thawed peat soils may harbour active spores of microorganisms. The thawing of 'old' peat layers has been linked to the outbreak of anthrax epizooty among reindeer in Yamal in 2016 (Selyaninov et al., 2016).

The lowering of the permafrost table is also responsible for the increasing heavy metal concentration in components of the circumpolar tundra ecosystems. Frozen soils in the Northern Hemisphere contain a mercury (Hg) pool twice as large as all other natural sources combined (Schuster et al., 2018). At natural sites in the west of Nenets AO, Hg content in the profile of seasonally thawed tundra peat soils ranged from 116 to 140 μg/kg compared to an average of 7–20 μg/kg in mineral horizons of other soils. Meanwhile, cadmium (Cd) concentrations were 0.14–0.17 mg/kg in mineral and 0.2–0.3 mg/kg in peat soils (Elsakov, 2011). Scenarios projecting increased atmospheric Hg emissions from thawing permafrost suggest that by 2200 these emissions will reach a level equivalent to all industrial emissions (Schaefer et al., 2020). Mobilisation of Cd^{2+} ions, which exhibit low chemical affinity for humic acids (Lodygin et al., 2020), leads to a greater transport of this element into the hydrological network. These contaminants will consequently enter the food chains of reindeer pasture ecosystems. The impact of Cd on the normal reproductive function of animals has been previously documented (Ermishkin, 2004). If the observed trends in elemental content growth continue, cases of restrictions on the sale of reindeer products are likely to emerge. Such restrictions would almost certainly precipitate a profound crisis in traditional nature management.

The generalised results of analysis of reindeer breeding products samples, conducted by the Rosselkhoznadzor departmental institute (FGBU "VGNKI"), demonstrated a reliable and significant increase in the levels of polluting elements over a 15-year period in the Arctic zone of Russia. For instance, Cd and Hg concentrations were found to be 7–10 times higher in Murmansk Oblast and 1.6–3.2 times for Nenets AO when comparing data from 2001 to 2014–2016 (Makarov et al., 2018).

The growth in pollutant concentrations is most often attributed to industrial impacts as traditional point of view. Indeed, halos of chronic pollution have formed around all major industrial sites in the Russian Arctic, many of which overlap reindeer pastures. Our studies indicate higher-than-natural concentrations of pollutants in lichens up to 50 km from a non-ferrous metallurgy plant in Nikel (Kola Mining and Metallurgic Company (Kola MMC) of "Norilsk Nickel") (Elsakov et al., 2018). At some locations near the heating station of the Vorkuta industrial hub, mercury (Hg) content was found to exceed normal levels by more than 100 times (Vasilevich et al., 2019). The recent transition of Vorkuta heating station from coal to gas has, however, led to a significant reduction in pollution levels.

The development of the extractive industry and oil transport pipelines introduces polluting elements and compounds into the pastureland ecosystems of the region. Local technogenic emissions, both planned and accidental, adjacent to production facilities often contribute to the rise in pollution indicators. On average, a single drilling well generates

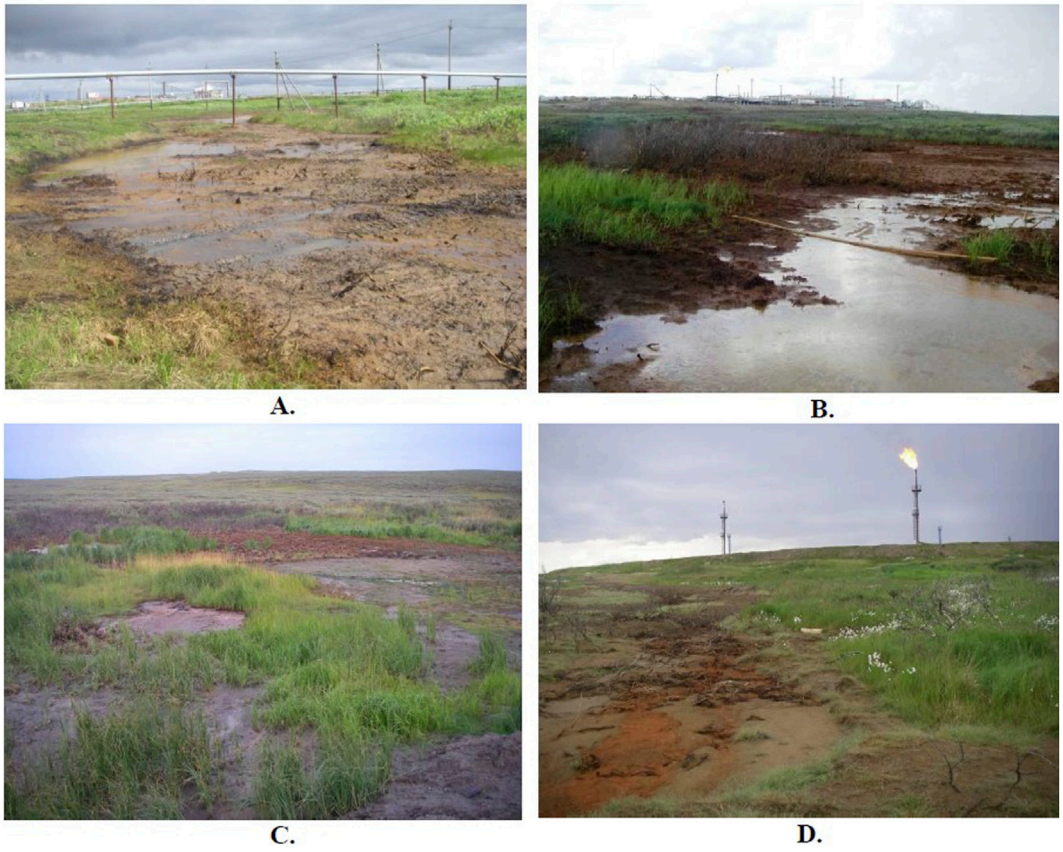

FIGURE 7
Pollution plumes caused by water discharge from industrial sites of "Sredne-Kharyaginskoye" (2019) **(A)**, "Vostochno-Sarutayuskoye" (2016) **(B)**, «Titov name» (2016) **(C)**, "Inzyreyskoye" (2016) **(D)** oilfields.

2.5–3.0 thousand tons (approximately 1.5 thousand m^3) of dewatered drill cuttings (DSC) containing oil products, a range of chemical reagents, and heavy metals. A typical DSC sample include oil products (2000 mg/kg), lead (Pb: 1.0 mg/kg), cadmium (Cd: 0.277 mg/kg), zinc (Zn: 4.158 mg/kg), copper (Cu: 1.617 mg/kg), manganese (Mn: 19.4 mg/kg), chromium (Cr: 3.2 mg/kg), nickel (Ni: 4.13 mg/kg), cobalt (Co: 0.631 mg/kg) (Rybina, 2004). These elements are often considered to have relatively low toxicity for large herbivorous animals (Kapelkina et al., 2013); however, the evolving composition of chemical additives remains an ongoing cause for concern. The deterioration of pit structures, loss of waterproofing, and subsequent discharge of water (e.g., formation water leaks) are not uncommon in oilfields. These incidents result in the migration of contaminants into the pasturelands, often forming pollution plumes that extend for up to 1–1.5 km (Figure 7). These areas are typically discernible in satellite images by the outlines of dead vegetation. Reindeer are particularly drawn to these contaminated water sources, which remain unfrozen during winter and are therefore more appealing than snow. This behaviour has led to mass fatalities. For instance, in May 2024, approximately 150 reindeer belonging to the "Izhemsky olenevod" enterprise perished after drinking polluted water near Leg-Kharyaginskoye oil field, where an accidental discharge of pollutants had occurred (Nvinder, 2014). Tragically, in 2025, another 35 animals died at the same location under similar circumstances.

Landfill sites associated with infrastructure facilities, as well as roads, also contribute to the pollution of pastureland. For example, along certain sections of the motorway that runs parallel to the main gas pipeline 'Bovanenkovo-Ukhta' and cuts through the pasturelands of the "Olenevod" enterprise, significant dust emissions have been recorded at distances of 250–1,000 m from the roadway. Research indicates that up to 5 g of dust containing toxic substances is deposited on the shrub leaves per square m of pastureland during the summer period. This accumulation results in pollutant concentrations that are up to 160 times higher than normal levels (Patova et al., 2016).

Long-range atmospheric transport also contributes to the presence of pollutant elements (mainly heavy metals group) in reindeer pastures of region. These elements are often mapped as

region-specific background values. Calculating the trajectories of reverse transport of air masses allows for the identification of territories (particularly industrial agglomerates of Murmanskaja and Vologodskaja oblasts and Usinskii and Vorkutinskii departments of Komi Republic) where the air masses originate, which subsequently reach the study area carrying materials that potentially affect the chemical composition of precipitation. This was achieved with the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model available on the NOAA website[10].

The development of an integrated information system for reindeer husbandry enables the identification of potential sources of pollutant elements and facilitates the consideration of related risk when planning pasture utilisation projects. By accurately locating contaminated sites in relation to reindeer grazing and migration routes, herders can minimise grazing time in affected areas, thereby reducing risks to the herds. Furthermore, the parameters of land units described within a pasture utilisation plan can be used to calculate economic losses caused by pollution. These calculations can then serve as a basis for legal claims, allowing reindeer herding enterprises to seek compensation for damages in court.

Satellite collar technologies are particularly useful in the Russian Arctic, characterised by vast territories, low population density, and underdeveloped terrestrial communication networks. These technologies can track animals and collect data on their behavior - estimate pastoral pressure on resources, and facilitate communication with nomadic communities. The data collected on herd movements is utilised to validate the operational status of land-use projects, identify dominant landscapes and plant communities preferred by reindeer during different grazing seasons and pinpoint lichen pastures in winter (Kumpula and Colpaert, 2007). The main benefits of using satellite-based animal positioning systems include:

1. Real-time tracking of model animals, track recording, possibility to compare tracks from different years. Long-term (several years) remote monitoring of movements and behaviour of a model animal;
2. Possibility to integrate the data with other GIS as well as with data of aerial and satellite surveys and their derivatives, for example, thematic maps of vegetation, spectrozonal indices, phytomass reserves of different forage groups, and stand density;
3. Ability to calculate, plan, and later control grazing loads for each reindeer herding enterprise. Ability to identify areas of high pasture loads which are typically pastures with high pasture cover and take necessary measures such as recommending fertilisers to restore the vegetation cover;
4. For veterinarians, ability to improve veterinary services and mechanisms for traceability, disease early detection and warning, and risk management;
5. Early detection of various environmental effects that affect reindeer husbandry, ecosystem damages, changes in reindeer behaviour, and monitoring vegetation biomass;
6. Analysis of reindeer migration tracks, effective planning for the pipeline crossings constructions, and calculations of lost profits incurred by industrial development projects (gas and oil extraction, mining, and mineral resources exploration) to determine compensation.

Thanks to detailed pasture utilisation plans updated every 10–15 years, reindeer herding enterprises in the European part of Russia have largely preserved their pasture resources despite a long history of extensive grazing. This success is due to herd size management and adherence to pasture rotation. In contrast, the situation with vegetation resources in Western Siberia, where approximately 760 thousand of the 2 million domestic reindeer in Russia are concentrated, is approaching catastrophic. This pattern is particularly pronounced on the pastures of the Yamal Peninsula. By 2017, the reindeer population in the Yamal District of the Yamalo-Nenets AO was estimated at 273.8 thousand head[11]. The mean stocking rate in the region is two to three times that in enterprises of the European North, at fewer than 26 ha per head (Loginov et al., 2017). An area accounting for one-fifth of the administrative unit's total pasture resource supports 40% of the Okrug's herd. Destruction of vegetation and depletion of vegetation resources create the preconditions for mass deaths of animals against the backdrop of unfavorable weather conditions (rain-on-snow) -, near 75–90 thousand animals died here in 2013–2014 (Volkovitskiy and Terekhina, 2020), and anthrax outbreaks near 2,3 thousand animals in 2016.

For modern reindeer husbandry, adapting to rapid climatic fluctuations, which entail large-scale transformation in the composition and stock of fodder plants, as well as societal changes and industrial expansion, is more relevant than ever. Information technologies can provide significant support in this adaptation. In 2025, winners of the annual Reindeer Herder's Day competitions in the Yamalo-Nenets AO were awarded quadcopters alongside the usual snowmobiles. In total, 70 snowmobiles and 22 drones were distributed, reflecting the growing use of drones for locating straggler reindeer and managing herds. To support these practices, a pilot programme for indigenous peoples in drone operation was launched in Yamal in2025[12].

10 http://www.arl.noss.gov

11 Data from the Veterinary Service of the Yamalo-Nenets AO.

12 https://arctic-russia.ru/article/kiberkochevniki-tundry-bespilotniki-i-solnechnye-batarei-dlya-olenevodov/

As we demonstrate, new information technologies are crucial for reindeer pasture monitoring, and the integration of diverse data into a single system can have a positive impact on reindeer husbandry and ecosystem monitoring. This integrated system can also help to eliminate overgrazing and mitigate the effects of industrial expansion in the region. And effective instrument for that can be integrated information system "Reindeer pasture resources of the Nenets AO and the Komi Republic."

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The figure nr. 2C of this paper contains identifiable human images. All the persons depicted were contacted by the author and expressed their free and informed written consent to publish this photo. The studies reported in this paper did not involve any experiments with live reindeer or other animals. The reported analysis of reindeer tissues involved samples taken from reindeer corpses after commercial slaughter, and, therefore, this analysis did not require an ethical committee approval. The same is true regarding the data from a written anonymous survey of reindeer herding enterprises concerning their interest in using of satellite collars.

Author contributions

The author of the article, VE, developed, interpreted and performed the entire data analysis.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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