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Urban Trees in the Arctic City: Case of Nadym

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Abstract: Trees in Arctic cities perform not only important provisional and regulating ecosystem services, but also bring predominantly settler population closer to the visual images and household standards of their home southern regions. However, maintenance of green infrastructure in the Arctic has specific difficulties associated with the harsh climatic and environmental conditions. This paper focuses on state and dynamics of vegetation in the city of Nadym, Russia, with a particular focus on native and introduced trees as the main ecosystem service providers and an articulation of local values towards green spaces. The research is based on interdisciplinary approach which includes interviews with local residents, geobotanical survey and analysis of remote sensing data. The results of the study show that maintaining of natural vegetation requires specific measures due to environmental the critical impact of anthropogenic activity. The active introduction of plants from more southern regions is manifested both in the deliberate practice of landscaping the city's streets and courtyards, and in spontaneous attempts to introduce plants from more southern (not Subarctic) agricultural regions of Russia, which are privately brought by city residents from other regions.

Keywords: green spaces; urban trees; arctic city; ecosystem services; remote sensing; geobotanical survey; Nadym

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1. Introduction

In the Arctic and similar natural and climatic conditions (underlaid with permafrost, above 10 °C July isotherm, the northern extent of trees and so on), provision of ecosystem services remains poorly understood. Arctic tundra ecosystem services in general remain understudied [1]. A few existing works have been focused mostly on natural ecosystems [2–9]. Urban ecosystem services are hard to estimate as urbanization itself in Arctic conditions is challenging and costly endeavor [10–12]. Dilemma of creating more "homely" environment in harsh climatic conditions have been especially evident in case of the Russian Arctic which has the most urbanized and populated cities in the world. Indigenous peoples represent only 5% of Arctic population which means that the cities been formed by settlers from more western and southern part of the country [13–15]. For people unaccustomed to local environment, architects were devising artificial microclimat (a covered passages between the buildings) or single house cities both to defend the residents from the extreme weather and represent "the modern soviet city idea" [16,17]. While isolation from and modification of existing environment prevail in Arctic urban planning, there are a few calls for adaptation to the given natural conditions, such as the work devoted to the concept of the "winter city". According to this concept, specific ecological and recreational functions of available green areas are appreciated [18,19] and considered as key sources of urban sustainable development and resilience [20–22].

Short summer, low temperatures in the cold season, an insignificant thickness and poor nutritional soil properties, presence of permafrost, as well as a specific radiation regime associated with polar days and nights, transform the greening of northern cities into a complex task. To address these issues, scholars have made scrupulous inquiries of green spaces for urban planning since 1940s [23–26]. In the 1960s–1980s, the Leningrad Zonal Research Institute for Experimental Design (LenZNIIEP) and other research teams paid particular attention to the development of green infrastructure in the natural and climatic conditions in design of Arctic cities [27–30]. Researchers found more significant influence of urban heat islands on the dynamics of green spaces in the Arctic cities in comparison with more southern (not Subarctic) cities which have to be taken into account both for urban sustainability and adaptation to climate change [31–33].

Trees in many ecosystems hold strong, almost existential value to city residents. Together with shrubs and grass, they form green spaces which provide removal of air and noise pollution [34], carbon sequestration [35], purification of water and air, regulation of the urban microclimate, improving habitat quality, cultural, recreational and other ecosystem services [36–39]. As such, they stay in the focus of urban development planners and environmental activists [31,40]. Careful engineering, planting and maintaining efforts as well as unintended human modification of green spaces in the cities allow researchers to consider them as components of green infrastructure [41]. As any human endeavor, they are the subject of concerns for social inclusivity, accessibility, and justice [42,43]. In the Arctic, trees also provide protection from wind and resemblance of more southern (homeland) conditions for Arctic urbanites [18,44–48].

Therefore, trees in the Arctic cities are illustrative for understanding provisional, regulating, supporting and cultural ecosystem services of green spaces when maintenance of green infrastructure in challenging. Better understanding of ecosystem services where not only distribution, but also qualities of green spaces are taken into account is possible with current development of remote sensing analysis methods. Very high-resolution imageries allow to make precise estimations of green space qualities [49]. For instance, the WorldView-2 images allow to estimate tree species using spectral signature characteristics and segmentation algorithms [50]. WorldView-3 images are found to be useful for calculating vegetation indices measuring tree health [51], With development of active sensors, researchers explore three-dimensional distribution of vegetation using multispectral images of medium resolution for urban planning [52]. Drone imageries allow to obtain high accuracy assessments of single trees [53]. The use of Unmanned Aerial Vehicle (UAVs) has already been proven to be a fairly effective method for assessing species diversity and monitoring urban vegetation [54]. At present, UAVs use not only conventional cameras with shooting in Red, Green, Blue (RGB) mode, but also with using specialized multispectral, thermal sensors and lidars [55,56]. As recent studies indicate, not only horizontal extent, but also height of urban trees is important for capturing carbon and dust and creating microclimate [57]. Moreover, as recent research indicates, the tree species composition plays also important role in urban development, affecting its biodiversity [58]. Light Detection and Ranging (LIDAR) and aerial orthophotos have been utilized for estimations of ecosystem services of individual trees [59]. However, as [60] noted, in a situation with scattered vegetation, identification of urban trees species is more challenging. While there is potential for implementation of multi-sensor data fusion for urban tree species classification [59], ground observations and studies of local greening practices and preferences are needed for better understanding of provision, quality and dynamics of green spaces for informed decision making [61].

This paper focuses on urban trees distribution and maintenance in a relatively small city of Nadym as a typical example of a modern Arctic city, which was built from a "blank slate" on a territory practically unchanged by anthropogenic impacts. Thanks to the opportunity to record the memories of local residents almost from the beginning of construction (the city officially will turn 50 in 2022), with the help of visual inspection of green spaces, documentary sources and remote sensing data, it is possible to track the qualitative dynamics of transformations of urban open green spaces in general and trees in particular. To date, the green spaces of Nadym have been explored only fragmentarily. In particular, the team of the Ural State Forestry Institute assessed the state of plantations in the Park of culture and recreation named after E.F. Kozlov (Kozlov's park) [62], and the staff of the Nadym branch of the Center for Arctic Studies investigated the green spaces of the main streets of Nadym [63], E.V. Pismarkina described occurrences of invasive species in the territory of Nadym [64]. Only a few publications considered the green spaces of Nadym as indicators of urban sustainability [21,65,66].

The paper aims to examine urban trees in residential areas and public spaces in the city of Nadym as an example of maintenance of green spaces for provisioning, regulating and cultural ecosystem services in the Arctic conditions. To achieve the goal, it utilizes novel approach that combines remote sensing (analysis of satellite images and UAV surveys, GIS (Geographic Information System) analysis), geobotanical (field descriptions and observations) and sociological (interviews, analysis of public sources) methods. The trees in the city are considered as the most important and socially important part of the green spaces. Therefore, the paper first discusses the state of vegetation in the city with the focus on tree and shrub species' diversity, distribution and condition (on the example of individual sites). Second, it provides understanding of dynamics of vegetation in the city from foundation of its main part and with illustration of changes in conditions of trees in two main streets. Third, it discusses greening practices by urban residents that lead to current state and distribution of different species of native and introduced trees and shrubs. Finally, it provides a calculation of the provision and accessibility of green spaces across different microdistricts and open green spaces. Based on these findings, the authors discuss that combination of methods for analyzing trees and urban vegetation is important for assessment of ecosystem services and could have practical implications in improvement of open and residential green spaces. The authors argue that while trees in the Arctic city provide important diverse ecosystem services, the role of cultural services provided by trees is no less and even more important for predominantly settler population.

2. Study Area

The city of Nadym, located in the central part of the Yamal-Nenets Autonomous Okrug, about 100 km south of the Arctic Circle, was founded in 1972 on the site of a workers' settlement, which in 1967 was created as a support base for the development of the Medvezhye oil and gas condensate field, discovered in 1967 (Figure 1). As many other Arctic settlements, it attracted workers from all over the Soviet Union, mostly from its western and southern parts, such as the Tyumen oblast, Republic of Bashkortostan, Omsk oblast, Belgorod oblast and Kurgan oblast [14]. The working settlement, in turn, arose on the site of the Nadym station of the Chum-Salekhard-Igarka railway. The station was founded on 22 April 1949 [67] and mothballed in mid-September 1953. As of 1 January 2021, the population of the city is 45,584 people [68].

The official area of the municipality of Nadym is 185 sq.km, which includes the territory of the main part of the city, an industrial zone near the airport and a site near the pier on the river Nadym "107 km" (the river port area which is situated on 107 km from the Nadym River estuary). In this study, only the main part of the city, with an area of 8.35 sq.km, is considered, including the residential area, where the vast majority of the population lives, and the adjacent industrial zone. The residential area is organized in the form of 18 compact microdistricts (microdistricts are a widespread in Russia kind of a city district which includes residential buildings bounded by streets and objects of local social infrastructure–shops, clinics, schools, etc.), with a total area of 1.28 sq. km. (there are 19 microdistricts in total in the city, microdistrict 8a includes only administrative buildings). The zone of low-rise and individual buildings in the northern part belongs to the Kedroviy microdistrict, the villages of Lesnoy and Finskiy.

Figure 1. Study area. Open green spaces: 1. Cedar Grove; 2. Kozlov's park; 3. Square of Eternal Flame; 4. Square named after V.V. Remizov; 5. Square near Yubileiny hotel complex; 6. Boulevard on the embankment named after S.A. Orudzhev; 7. Strizhov Square; 8. Strizhov Boulevard; 9. Square at the Prometheus House of Culture; 10. Tree alley along Komsomolskaya street; 11. St. Nicholas Church Square; 12. Square at the city administration; 13. Tree alley along the Yamalskaya street.

Nadym is located in the northern taiga subzone of the taiga zone of the West Siberian Plain [69]. It was built on the second above-floodplain terrace of the Nadym River, composed of river sandy sediments which, from one side, allowed to avoid problems of construction on permafrost, from another–made greening of the city more challenging [66].

3. Methods

3.1. Remote Sensing Component

To assess the spatial distribution and condition of vegetation, a multiscale series of remote sensing data was used:

- Drone-based images from UAVs with a resolution of 0.13 m;
- Very high-resolution satellite images with a resolution of 0.4–2 m
- High resolution satellite images with a resolution of 30 m.

The assessment of the Normalized Difference Vegetation Index (NDVI) dynamics for the entire city as a whole was carried out using the Landsat harmonized data archive in the GoogleEarthEngine platform [70]. The NDVI median values were calculated for the 1 July to 28 August period of each year from 1985 to 2021.

To combine heterogeneous remote sensing data from 3 and 4 April 2021, geodetic measurements of ground control points were carried out using GPS Trimble GeoXR. The survey was done in Real Time Kinematic (RTK) mode, with corrections transmitted in real time from the base station of the Geodetika company, located in the city center. In total, measurements of longitude, latitude, and altitude were obtained for 235 points with location and height accuracy of no less than 2 cm. Subsequently, the points of the plane-height substantiation were used to clarify the georeferencing of all of the remotely sensed data of the highly detailed and detailed levels.

Image capture from the DJI Phantom 4 Pro 2.0 UAV was carried out on 13–14 July 2021, from an altitude of 250 m at noon, mostly without direct sunlight (to minimize shadows from high-rise buildings. A total of 1844 photos were captured, covering the entire observed territory of the city. The images were processed using AgiSoft MetaShape Professional 1.6.3 software, resulting in an orthophotomap with a resolution of 6.6 cm and a Digital Surface Model (DSM) with a resolution of 13.2 cm. In addition, the classification of the point cloud was carried out and a Digital Terrain Model (DTM) was obtained using the "earth surface" point class. The difference between the DSM and the DTM shows the height of vegetation and buildings within a city.

WorldView-2 satellite images were obtained from the Polar Geospatial Center (University of Minnesota, USA). For the study, 3 images were selected taken during the period of the greatest accumulation of phytomass at the maximum angles of sunlight (Table 1).

Table 1. Characteristics of satellite images utilized for analysis.

Satellite	Date	Resolution (Meters)	ID
WorldView-2	1 July 2016	1.76	10500100052CF700
WorldView-2	17 July 2019	2.05	1030010095BFE200
WorldView-2	20 July 2020	1.83	10300100AA2ECD00

Images are presented in the corrected form in reflectance values, which allows for a direct analysis and calculation of the NDVI that characterizes the vegetation greenness in the city [71]. The only improvement made in georeferencing was that the images were aligned with each other with subpixel accuracy based on existing ground control points in ArcGIS 10.8 software.

The methodology for obtaining a city vegetation mask is based on the Object-Based Image Analysis (OBIA) [72] approaches and includes the following operations:

- Segmentation of orthophotomap using Orfeo Toolbox 7.4;
- Calculation of the NDVI index for each WorldView-2 image;
- Calculating NDVI zonal statistics for each of the resulting segments using ArcGIS 10.8 and calculating the average and maximum values among the available data;
- Calculation of zonal statistics of the relative heights for each of the obtained segments using ArcGIS 10.8 based on the raster of the difference in heights of the DSM and DTM;

- Classification of segments with an average NDVI value > 0.05 and relative heights in the range from 0.01 to 25 m based on a combined image from an orthophotomap and DSM using the Support Vector Machine (SVM) method using SAGA GIS 7.8 [19].

When classifying the segments, the vegetation class was extracted from other classes, such as built environment and barren grounds. An evaluation of overall accuracy and construction of a confusion matrix was carried out in SAGA GIS 7.8. After the classification and accuracy assessment, visual filtering of the segments was carried out to improve the accuracy of the vegetation mask-more than eight thousand segments were additionally removed from 186 thousand total segments.

To estimate the reference vegetation area within the city, the Corona KH-4a image from survey date 21 August 1968 was used, ID: DS1104–2217DA034_34_b. The resolution after georeferencing and processing was about 2 m. The image was obtained using the EarthExplorer geoportal [73]. The image analysis was also carried out using OBIA methods-at the first stage, segmentation was performed, at the second stage, on the territory of the future city the vegetation class was extracted from other classes.

Microdistricts and open green spaces of Nadym were digitized based on the master plan of the city [74] and available open-source maps [75,76]. For estimations of population distribution within the city area population density map was created based on an orthophotomap in ArcGIS 10.8, where all residential buildings (multi-storey, low-rise and individual) within the city limits were digitized. The living area and other reference information (year of construction, address, number of stories, total area, condition, etc.) of each building were obtained from the GIS Housing and Communal Services reference system [77]. The living area is translated into the number of inhabitants on the basis of normative and reference information using the following calculation:

- 20 sq.m per 1 person in apartment buildings;
- 60 sq.m per 1 person in private houses.

The total potential capacity of residential buildings in Nadym in use as of 1 November 2021 amounted to 52,580 people, which is slightly higher than the current official population (45,584 people) but is comparable to the peak figure of 1989 (52,586 people). Taking into account the constant presence of labor migrants (shift workers, seasonal workers), the authors estimate that the obtained calculated population number may differ by no more than 5% from the real population of the city in 2021.

The provision of green spaces to households within microdistricts was calculated using "greenness" of micro-districts (GM) indicator calculated using the following formula:

$$GM = ((NDVI_{mean} * H\_Veg_{mean} * PG)/PM) * 100$$

$NDVI_{mean}$-the average NDVI value within the microdistrict

H_Veg_{mean}-average value of vegetation height within the microdistrict

PM-the total potential number of residents of the microdistrict

PG-the share of green vegetation in the total area of the microdistrict

Spatial analysis of the classification results and the creation of resulting maps were performed using ArcGIS 10.8 software.

3.2. Geobotanical Survey

Studies of the vegetation composition, health and aesthetic state of tress on the alleys along the main streets (Komsomolskaya and Yamalskaya) in the city of Nadym were carried out in 2015 in the previous work [63] and in July 2021. In addition, in 2021, the ground-based observations were conducted in Cedar Grove, Kozlov's park, Square of Eternal Flame, St. Nicholas Church (Figure 2). To assess the species composition in the Kozlov's park and Cedar Grove, test plots with the dimensions 25 m by 25 m were created, 5 for each area. In other areas of observations, all trees and shrubs were taken into account. A total of 2954 specimens of trees and shrubs were identified in the city using the identification guides of V.A. Glazunov and Yu.P. Khlonov [78,79].

Figure 2. Trees in the city: (**a**) Square of Eternal Flame; (**b**) Tree alley on Yamalskaya street; (**c**) Tree alley on Komsomolskaya street; (**d**) Boulevard on the embankment named after S.A. Orudzhev; (**e**) Kozlov's park. Photo by Yulia Pechkina, July 2021.

To assess the health of the vegetation, trees and shrubs were divided into three groups: I-in good condition (1 point), II-in satisfactory condition (2–3 points), and III in unsatisfactory condition (4–6 points) [63]. For assessment, the following parameters were also taken into account:

- type of woody plants;
- trunk diameter (cm) at a height of 1.3 m;
- tree height (m);
- biomorphological features: leaf color, crown density, proportion of dry branches, bark condition, signs of stem pest infestation, etc.

Based on the gathered information about the study area that was entered, the vegetation inventory was created with quantitative indicators calculated in Microsoft Excel.

3.3. Social Research

For understanding tree planting and maintenance practices and tree species preferences of the local residents, interviews and observations were gathered. Authors gathered 12 interviews remotely–by phone and via Zoom, and 17 interviews–in-person in 2020 and 2021 in the city of Nadym. The interviewees were recruited using the snowball method and gave informed consent in accordance with the George Washington Institutional Review Board (IRB) protocol and Ethical Principles and Guidelines for the Protection of Human Subjects of Research [80]. The age of interviewees ranged from 30 to 70, there were 15 women and 14 men interviewed. All interviews were transcribed. The data was coded and analyzed to identify persistent topics using NVivo software. Based on the analysis, the topics of trees and vegetation were extracted and the contexts in which these topics were mentioned were analyzed. In total, 12 interviews were analyzed, where the quality and quantity of green spaces were discussed.

4. Results

4.1. State of Vegetation in the City

According to the results of geobotanical survey, the native vegetation on the territory of the city is formed by sparse larch-birch forests interspersed with spruce (*Picea sp.*) and cedar (*Pinus sibirica* Du Tour). The streets of Nadym are dominated by such trees as downy birch (*Betula pubescens* Ehrh.), willows of various species (gray-gray, blueberry, filiform) (*Salix sp.*), and, to a lesser extent, coniferous trees-larch (*Larix sibirica* Ledeb.), pine (*Pinus sibirica* Du Tour) and spruce (*Picea obovata* L.) (Table 2). Among woody plants, there are willows of various types (gray, blueberry, filiform) (*Salix sp.*), aspen (*Populus tremula* L.), alder (*Alnus*), bird cherry (*Padus avium* Mill.), downy birch (*Betula pubescens* Ehrh.), needle rose (*Rosa acicularis* Lindl.), juniper (*Juniperus communis* L.). Herbs are dominated by the cereal (*Poaceae*) and sedge (*Cyperaceae*) families.

Table 2. Characteristics of trees in the major open green spaces.

Open Spaces	Vegetation Health			Mean NDVI	Mean Hectares	Major Tree Species
	Good	Fair	Bad			
Square of Eternal Flame	52.8	33.8	3	0.5	5.26	*Betula pendula* Roth., *Salix sp.*, *Betula pubescens* Ehrh., *Sorbus sibirica* Hedl.
Square near St. Nicholas Church	41.1	51.7	2.8	0.39	1.36	*Betula pubescens* Ehrh. with *Larix sibirica* Ledeb., *Salix sp.* & *Sorbus sibirica* Hedl.
Kozlov's park	21.6	68	4.4	0.44	4.92	*Larix sibirica* Ledeb. with *Pinus sibirica* Du Tour
Cedar Grove	25.5	64.5	2.3	0.4	3.26	*Betula pubescens* Ehrh. & *Pinus sibirica* Du Tour
Komsomolskaya street	21.2	66.1	2.8	0.49	5.51	*Betula pubescens* Ehrh. with *Salix sp.*
Yamalskaya street	16.9	46.4	9	0.49	4.91	*Betula pubescens* Ehrh. with *Salix sp.*

Most of the conifers growing on the streets have been remains of natural vegetation existed before the city was built up. Some natural vegetation has been preserved within the city in Kozlov's park and Cedar Grove and in hard-to-reach or abandoned areas-on wastelands, along fences, utilities, etc. It includes such species as birch (*Betula sp.*), Siberian larch (*Larix sibirica* L.), spruce (*Picea sp.*), Siberian pine (*Pinus sibirica* Du Tour) and others. Native shrubs are represented by willow (*Salix sp.*), wild rose (*Rosa acicularis* Lindl.), mountain ash (*Sorbus sibirica* Hedl.). Herbs are dominated by sedge (*Cyperaceae*), bluegrass (*Poaceae*), wormwood (*Artemisia sp.*), chamomile (*Matricaria*), dandelions (*Taraxacum officinale* FH Wigg.), narrow-leaved fireweed (*Chamerion angustifolium* L.), tansy (*Tanacetum sp.*), there are also blueberries (*Vaccinium uliginosum* L.), cranberries (*Vaccinium vitis-idaea* L.), and crowberry (*Empetrum nigrum* L.).

The results of analysis of the WorldView-2 images show uneven spatial distribution of vegetation in the city. Higher NDVI values and vegetation heights are characteristic for the western and northern parts of the city (Figure 3). This is facilitated primarily by the presence of areas of natural vegetation along the western border of the city, as well as relatively large public green spaces-the Kozlov's park and Cedar Grove. In the eastern part of the city, the projective vegetation cover is significantly lower due to dense residential buildings and the presence of an industrial zone. An increase in greenness here can only be noted along the city's eastern border.

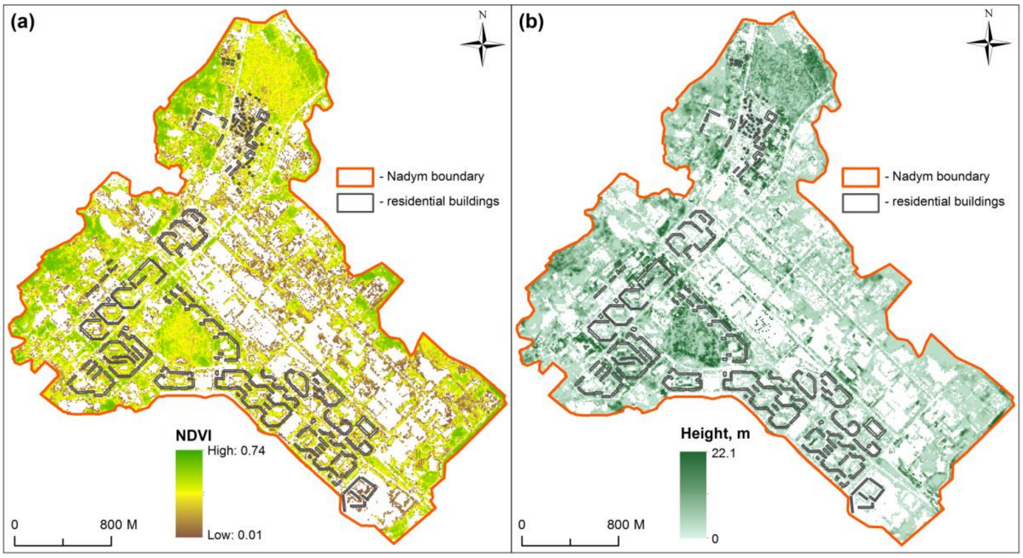

Figure 3. Distribution of the NDVI (**a**) and height values (**b**) across the city.

The highest NDVI value is found at the Square of Eternal Flame where the vegetation is healthiest, and trees have significant height. However, results of the survey demonstrate that even if the vegetation health is fair, as is the case for Komsomolskaya and Yamalskaya streets, tall deciduous trees show high NDVI values. Taller coniferous trees in the Kozlov's park are associated with higher NDVI value than mixed forest with shorter trees in the Cedar Grove. Lowest height of trees in the Square near St. Nicholas church are associated with the lowest NDVI values.

Comparison of health of individual tree species in the Kozlov's park and the Cedar Grove showed differences in health conditions between different tree species, such as Siberian pine (*Pinus sibirica* Du Tour), downy birch (*Betula pubescens* Ehrh.), Siberian mountain ash (*Sorbus sibirica* Hedl.). For example, the average score of the health of Siberian pine (*Pinus sibirica* Du Tour) in the Kozlov's park is 1.8, i.e., corresponds to the categories of healthy and damaged trees, in the Cedar Grove—2.3, belongs to the category of damaged and severely damaged trees. In addition, on some specimens of Siberian pine, apothecia of the pathogen shute ordinary, a fungal disease that affects conifers, was found. This is most likely due to their location near highways used by freight vehicles. The territory is also used by residents for picnics, in some areas littering with household waste is noted which also has been harmful for the tree health.

Comparison of open green spaces and residential areas shows significant differences. In particular, open spaces have wider range of vegetation heights, while the mean values are comparable). Moreover, open green spaces (OGS) demonstrate significantly higher NDVI values (mean, median, range) (Figure 4).

Among residential microdistricts, there are lower NDVI values than in parks (from 0.43-microdistrict 2a to 0.25-microdistrict 18) and vegetation height (from 5.35 m-microdistrict 2b to 1.41 m-microdistrict 5b) (Table 3). In part, there is a connection with the average age of houses in the microdistrict-the older the houses, the higher the proportion of woody vegetation with high NDVI values. Obviously, the lowest NDVI values are found for the microdistrict 13 (NDVI 0.18; average vegetation height-0.28 m). The average age of houses here is 3 years, the landscaping of the local area was completed in 2020, and most of the territory of the microdistrict as of July 2021 is a construction site.

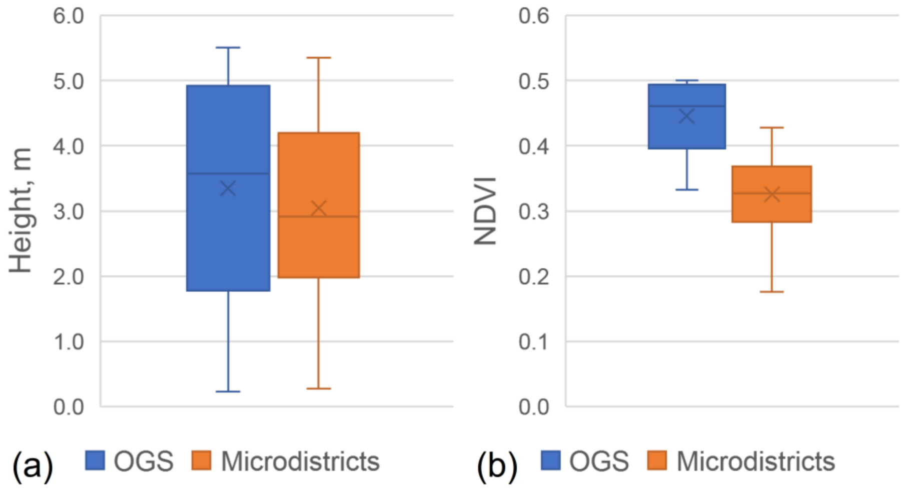

Figure 4. Comparison of vegetation characteristics of OGS (**a**) and microdistricts (**b**).

Table 3. Characteristics of microdistricts.

Microdistrict	Year of Construction	Population (People)	Mean NDVI	Mean NDVI STD	Mean H	S	Share of Green Areas
2a	1981	1411	0.43	0.17	4.56	6.59	0.42
4	1974	1634	0.41	0.16	4.86	7.38	0.40
Finskiy	1984	243	0.40	0.14	4.98	2.67	0.54
2b	1980	1524	0.39	0.17	5.35	6.65	0.46
Lesnoy	1990	932	0.38	0.15	4.65	14.00	0.29
5a	1976	1194	0.36	0.17	2.45	4.47	0.27
4a	1987	591	0.35	0.18	3.79	3.19	0.40
7	1983	4371	0.34	0.17	3.52	14.24	0.40
7a	1979	2644	0.33	0.18	3.20	9.73	0.34
6	1979	1063	0.33	0.19	2.36	4.45	0.27
8	1981	1400	0.33	0.15	2.91	6.52	0.25
5b	1976	1371	0.32	0.15	1.41	4.17	0.29
3a *	1996	904	0.32	0.16	2.12	5.04	0.20
3	1978	441	0.32	0.20	3.66	1.69	0.30
9 **	1984	7454	0.30	0.16	2.00	23.57	0.29
Kedroviy	2012	1582	0.28	0.17	2.70	13.13	0.25
17	1990	759	0.28	0.17	3.83	2.17	0.30
11	1988	5424	0.28	0.16	1.95	18.55	0.29
10	1990	9985	0.26	0.16	1.74	25.14	0.25
18	1995	4194	0.25	0.17	1.60	13.81	0.18
13	2018	3459	0.18	0.13	0.28	21.21	0.09

* include square named after Yuri Topchev.; ** include boulevard on Leningradskiy Avenue and boulevard on the Zvereva street.

4.2. Dynamics of Vegetation Change in the City

Initially, almost a third of the territory of the city (32.9%) was occupied by bare sands with elements of the modern aeolian relief (dunes, up to 1.5 m high). This feature is typical for coastal areas along the entire course of the Nadym River, up to the headwaters. Analysis of satellite data showed that the total area of vegetation on the territory of Nadym from 1968 to 2021 decreased by 34% from 425.71 ha to 280.1 ha (Figure 5).

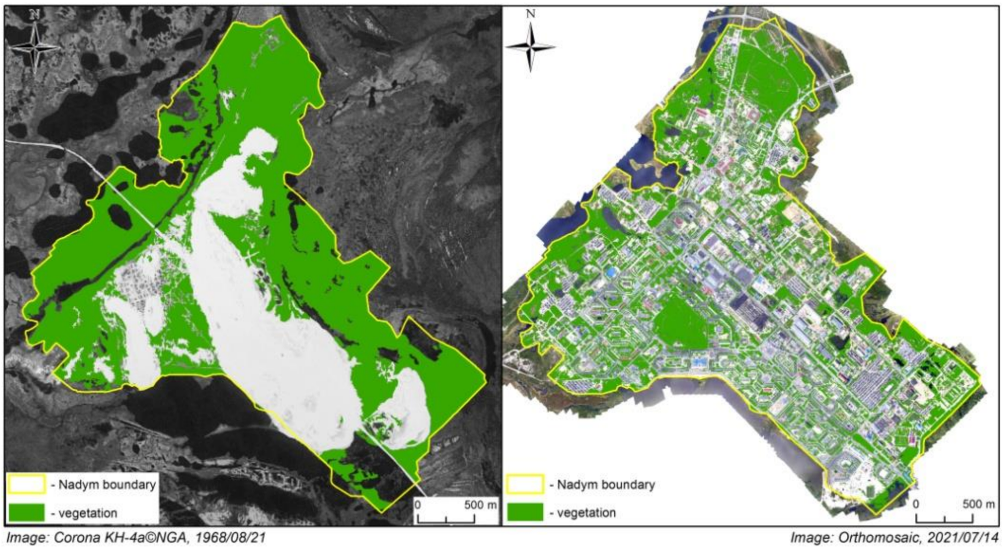

Figure 5. Green space distribution in 1968 and 2021.

The largest reduction in green spaces is related to the period of active city construction from 1981 to 1990. In the interviews, the respondents remarked that the sand was all over the place. Residents remember flying sand as the most disturbing element of urban landscape.

The analysis of dynamics of the Landsat derived NDVI index was hindered by lack of data availability for several years. Number of cloudless satellite images rarely exceed one-two per year. The possibility of using UAVs to analyze the vegetation cover in the summer under favorable weather conditions is also available only for a couple of weeks due to short vegetation season and inclement weather conditions hindering work [81]. However, compared against the background of the dynamics of construction, it shows gradual restoration of vegetation since 1991, after the end of the active period of the city's development, and especially noticeable since 2000 (Figure 6).

Comparison of the results of ground-based observations in 2015 [63] and 2021 shows decrease in the share of trees and shrubs in good condition. In particular, on Komsomolskaya Street share of trees and shrubs in good condition decreased by 2.3 times and on the Yamalskaya Street - from 49.0% to 16.9%. It coincides with the increase in the age of the trees and the share of those in a satisfactory condition. On Komsomolskaya Street, the proportion of specimens in a satisfactory condition increased by 2.0 times. At the same time, the proportion of trees and shrubs in unsatisfactory condition decreased from 12.5% to 2.8%, possibly due to sanitary felling during this period. on Yamalskaya street, the proportion of trees and shrubs in satisfactory condition increased from 46.8% to 74.1%. The share of woody vegetation in unsatisfactory condition increased from 4.2 to 9.0%.

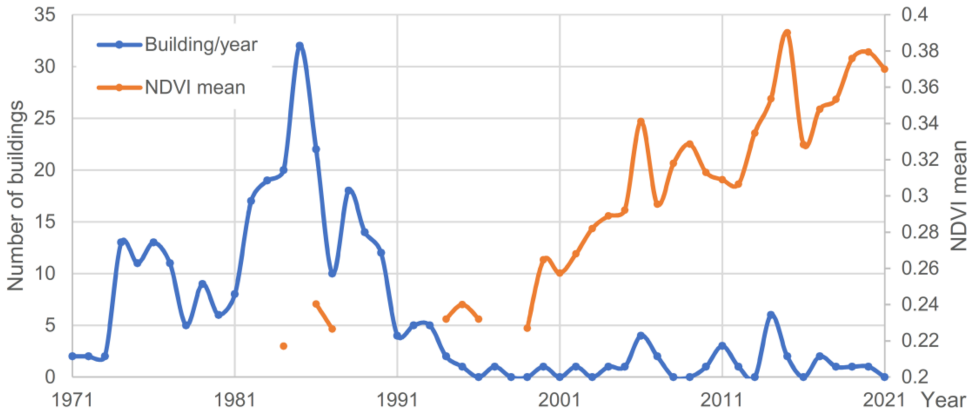

Figure 6. Dynamics of construction of residential buildings in Nadym and dynamics of NDVI within the city.

4.3. Tree Planting and Other Greening Strategies

As the Sub-Arctic environment did not offer wide diversity of green spaces for the settlers who mostly were arriving from more southern regions. Inspired by and striving for visual images of more forested regions of Russia which are situated South of Nadym, settlers undertook both collective and individual efforts to green the city. According to the interview by representatives of the administration of the Nadym region, these efforts led to the provision of 12.7 sq.m public green spaces per person, which corresponds to the regulatory requirements [82]. To achieve that goal, residents both preserved existing vegetation and invested in growing a new one.

Residents from school-age children to adults were mobilized to plant trees on the main streets as soon as the city was constructed in the 1980s–1990s. Seedlings for landscaping the city were most often brought from the vicinity of the villages of Yagelny, Priozerny and Longyugan (southern part of the Nadym region). Quite often seedlings were dug in the right of way of the gas pipelines and power lines, where large undergrowth followed infrastructure development. The trees often failed to root in the city's poor with minerals sandy soils, so the planting was repeated sometimes several times. To improve soil, authorities would bring silt from the Nadym River floodplain and dig up peat from swamplands, let it dry for a year, and then cover sand before planting the trees.

According to the recollections of senior residents, in 1986, birch seedlings were planted on the Square of Eternal Flame. Other trees were planted along major streets and highways, in the courtyards of residential buildings, as well as in areas near public buildings and memorial structures. As a result, small squares were formed (Remizov, Prometheus, etc.).

Residents often would bring some plants and shrubs from the "mainland" and plant next to their houses or workplaces. In some cases, such plantings turned into small front gardens. According to the recollections of the old residents of Nadym, dwellers of temporary houses managed to successfully grow potatoes, red currants, black currants, bird cherry, viburnum, gooseberries and other garden plants. Such practices persist even these days and search for plants resilient to local bioclimatic conditions even intensified with the opportunities to order plants and seeds online. Residents choose frost-resistant plants for gardens and others–for growing in apartments. The apple (*Malus sp.*) and lilac (*Syringa josikaea J. Jacq. ex* Rchb.) trees in the microdistrict 3 are examples of the introduction of new species of trees and shrubs into the urban environment by local authorities and organizations. The planted lilacs bloom in July (more than a month later than in more southern conditions). The apple trees also bloom, but do not bear fruit. Some residents experiment with growing trees and shrubs in their courtyards:

> *"We have tried to grow oaks from acorns. Yes, of course, they do not take root well, but for five years the oaks have been growing, they are undersized, somehow not very tall, but there are apple trees growing with us. Well, we cover, we throw in snow, we throw in*

the apple trees, we have someone who brings apple trees. And I did it, I tried to improve the soil for the oak, I made vegetable waste such as compost and decided to compost the soil near my oak tree. Here and there were apple cores, but unfortunately the oak did not survive, but now in this place I have an apple tree growing near the entrance where I live"

(female, 40, Nadym, 5 January 2021).

Dedication of local residents to natural vegetation can be observed on the following example. In 2020, municipality offered of the project for the renovation of the Kozlov's park and build new attractions and other recreational facilities. During the discussion a significant part of the residents of Nadym expressed their concern on their placement in the park as that that could harm the trees. Thus, for many residents of the city, the preservation of natural vegetation in the park is a higher priority than the development of its entertainment functions. According to the park representatives, preservation of native trees in these parks under heightened anthropogenic loads and changes in the microclimatic features of the urban environment, requires a number of special measures. For example, in some areas of the Kozlov's park, larches, Siberian pine and birches have a bare root system due to the trampling of paths by visitors [65]. To restore vegetation, in 2021 in the park, seedlings were brought from the Akhmechet Tyumen garden nursery (almost 1700 km distance).

Respondents also mention spending time in the forested areas beyond the city limits to compensate lack of trees and vegetation in the city. Among other concerted efforts there are an initiative of the major political party Russia to take care of trees near the World War II memorial and the major city-forming enterprise Gazprom Dobycha Nadym to plant trees in the city, especially around its property. The Gazprom Transgaz Yugorsk company has created a greenhouse, which grows tropical and subtropical plants. The place is very popular among local residents: excursions for schoolchildren are organized in the greenhouse, local residents demand it for photo shoots at weddings and other events.

4.4. Green Space Provision and Accessibility

An analysis of the availability of green spaces shows that only 12.1% of the potential population (6364 people), located mainly in the southeastern part of the city, is outside the buffer zone of 400 m around open green spaces. Moreover, if consider the largest OGS (Kozlov's park and Cedar Grove), then 37.9 of the potential population (19,918 people) live within walking distance (Figure 7).

The GM values range from 0.1 to 9.1 with the average value within the microdistricts of 4.8. The GM value reaches the maximum in the Finskiy microdistrict is associated with a low density of residents and a significant age of houses. The minimum GM value is shown in microdistrict 13 which is associated with dense settlement in multi-storey buildings against the backdrop of continued construction work. The deficit of landscaping is detected in the areas with GM values less than 2, which is confirmed by ground-based observations in microdistricts of the city. With such values, there is practically no woody vegetation, and the lawns are in a depressed state (Figure 8).

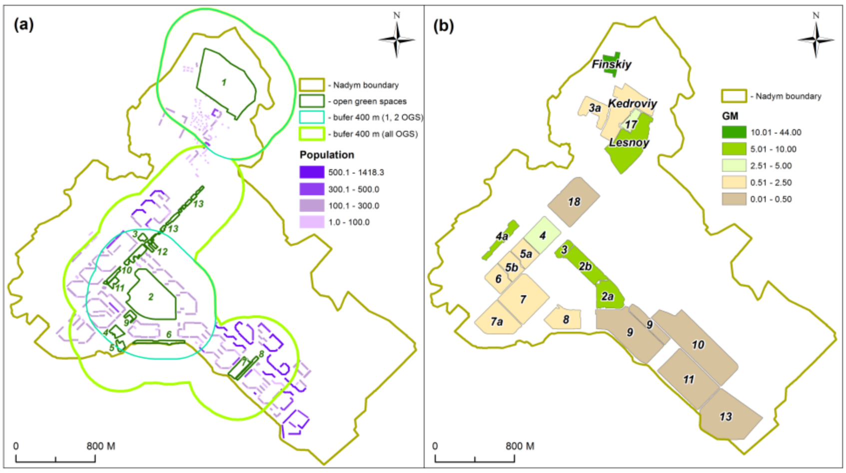

Figure 7. Accessibility of open green spaces (**a**) and "greenness" (provision of vegetation) by microdistricts (**b**) of Nadym.

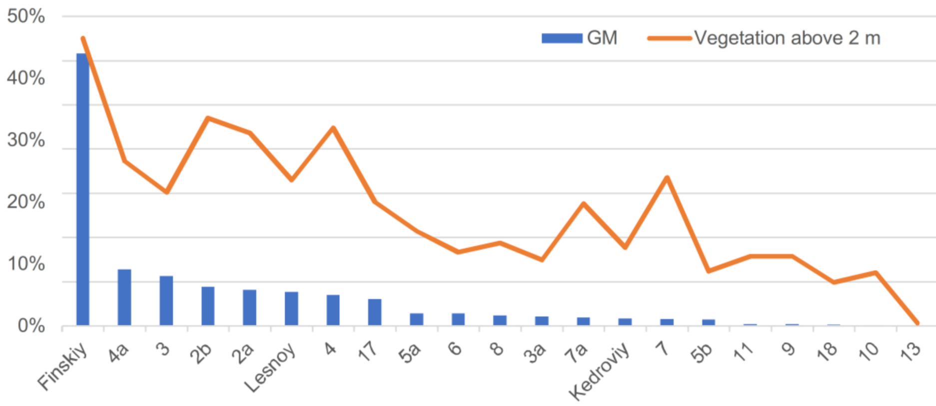

Figure 8. The share of woody vegetation in relation to the value of GM in the microdistricts of Nadym.

5. Discussion and Conclusions

The results of geobotanical and remote sensing analysis confirm the need to consider not only horizontal, but also vertical urban densification for better understanding of urban growth and green space availability [52]. Combination of UAV and satellite imaging utilized in the research allowed to obtain the most detailed vegetation mask with determination of its height from UAV, satellite images made it possible to collect statistics on the state of vegetation for several years. This approach shows the possibility of a retrospective analysis of vegetation for a selected city, which is an advantage of combining remote data from various sources. However, it is noted, that relation between vegetation health and high NDVI values is not always positive and depends on tree species. The use of satellite imagery to estimate NDVI has also other limitation limitations, such as unresolved problem of shading from large houses-part of vegetation is in the shade or simply not visible. Thus, to improve the results, it is also necessary to obtain multispectral imaging from UAVs and LIDAR which will allow to achieve maximum accuracy in determining NDVI and vegetation height throughout the city, including lawns near multi-storey buildings. Nevertheless, data obtained from the satellite images and ground-based observations have higher accuracy than the GIS system used for housing and communal services. The latter have inconsistencies and gaps, such as exact and complete characteristics of the buildings, as well as data on building occupancy which are not available in principle.

Observations of dynamics of vegetation changes have shown that significant areas have restored vegetation which helped to improve well-being of the urban residents that initially suffered from excessive sand in the area. During the development of the city, there was a vegetation area decrease, which reached a maximum in the period of active construction in the 1980s. After the completion of active multistory housing up to the present time there has been a steady increase of vegetation area, which is explained by active landscaping measures and the warming of the local climate.

Regarding the composition of trees, it has to be noted that preservation of areas of natural vegetation requires special measures to maintain its species composition and satisfactory quality, due to the critical impact on them of anthropogenic load, as well as changes in the microclimatic features of certain areas of the city. Our study demonstrates that in extreme climate conditions, development of green spaces takes significant efforts, and it takes decades for trees to achieve some height. In general, steady increase in the proportion of vegetation is explained by active landscaping activities against the backdrop of softening climatic conditions. Natural changes have been related to the effects of climate change which researchers found in greening and browning tundra [26]. Active introduction of plants from more southern regions into the territory of the city and its environs resulted from both human and natural changes.

Human-caused changes include purposeful practice of landscaping the streets and courtyards of the city; spontaneous attempts to introduce more southern plants, which were privately brought by residents of the city from other regions; technogenic disturbances of soils, which entail a shift in the distribution areas of some plant species [68]. The challenges arise both for protection of native coniferous trees and for introduction of decorative southern plants. While in temperate climates, researchers recommend planting native trees [81], this option is not always available for the Arctic residents. The best practice that the residents came up with is preserving those trees that have already been growing in the area. Therefore, the situation is quite opposite to the one described by Kronenberg as an institutional failure [83].

Trees exist in interviews as an important topic of conversations about quality of green spaces. An additional value is assigned to an opportunity to create environmental conditions closer to the more familiar homely landscapes and visual images of more southern agricultural regions of Russia, giving sense of the fullness of the daily living environment of the Arctic city. Ecological, recreational and aesthetic qualities of vegetation such as decorative qualities of trees and shrubs and flowers are highly important as providers of rather cultural than other ecosystem services. It's important to keep that in mind when taking into account the need in constant care and maintenance efforts without which condition of local trees and shrubs rapidly deteriorates. During the Soviet time, large free labor was mobilized for tree planting. Currently, labor efforts are available on a smaller scale. While there are still numerous efforts by citizens themselves to plant trees and flowers in the residential areas that aid municipal efforts, it is difficult to put monetary value on provisional and regulating ecosystem services given the cost of labor.

Regarding provision and distribution of open green spaces, there is their sufficient availability within the city. Lack of vegetation is observed within the residential areas of microdistricts. Introduction and implementation of GM indicator allows to estimate trees (vegetation above 2 m) spatial distribution for identification of microdistricts most in need of greening strategies. The share and quality of green spaces depends inversely on the population density and the average age of residential buildings.

The results of the study have practical significance as the basis for further regular monitoring of the state of the green spaces of the city according to the developed methodology and the compilation of a detailed ecological atlas with a detailed description of vegetation for urban planning and refinement of plans for the development of planning strategies of Arctic cities that take into account the environmental needs of local residents in measures to maintain green infrastructure. The application of the developed interdisciplinary methodology in other cities of the north of Western Siberia (Salekhard, Muravlenko, Noyabrsk, Novy Urengoy) will allow a comprehensive approach to understanding ecosystem services of urban trees in the Arctic cities. Such understanding is important in the context of global strategies for sustainable development, and within the framework of regional programs to improve the quality of life of people living in the Arctic cities.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The city vegetation mask and a detailed map of buildings are available by request.

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