ENVIRONMENTAL RESEARCH
LETTERS

Zooming in on Arctic urban nature: green and blue space in Nadym, Siberia

IOP Publishing Journal Title
Journal **XX** (XXXX) XXXXXX https://doi.org/XXXX/XXXX

Zooming in on Arctic Urban Nature: Green and Blue Space in Nadym, Siberia

R. Fedorov[1], V. Kuklina[2], O. Sizov[3], A. Soromotin[4], N. Prihodko[4], A. Pechkin[5], A. Krasnenko[5], A. Lobanov[6], I. Esau[7]

[1] Earth Cryosphere Institute, Tyumen Scientific Center SB RAS, Tyumen, Russia
[2]Department of Geography, George Washington University, Washington, DC, USA
[3]Laboratory of Integrated Geological and Geophysical Study and Development of Oil and Gas Resources of the Continental Shelf, Oil and Gas Research Institute RAS, Moscow, Russia
[4] Institute of Ecology and Natural Resources Management, Tyumen State University, Tyumen, Russia
[5] Environment sector, Arctic Research Center of the Yamal-Nenets Autonomous District, Nadym, Russia
[6] Laboratory of Physical Factors, National Medical Research Center of Rehabilitation and Balneology, Moscow, Russia
[7]Nansen Environmental and Remote Sensing Center/Bjerknes Center for Climate Research, Bergen, Norway

E-mail: r_fedorov@mail.ru

Received xxxxxx
Accepted for publication xxxxxx
Published xxxxxx

Abstract

Urban landscape combines built-up areas with strongly altered natural (green and blue) and other open spaces. Voluminous literature examines urban socio-environmental interactions in tropical and temperate cities, whereas high-latitude cities are rarely considered. Here, we create a historical perspective on urban green (vegetation) and blue (water) spaces in a sub-Arctic city of Nadym in Russia. Our study explores a novel way to combine quantitative information from satellite imagery and biometric studies with qualitative information from interviews with stakeholders and residents. Such a joint analysis helps to understand dynamics of the urban green and blue space as well as its value for society. Furthermore, we propose objective indicators reflecting societal values of spaces in connection with recreational and ecological services. By contrast to temperate city studies, we found that green space is less used in summer, but still highly valued, deep lakes are used and valued more than warmer shallow lakes, and winter white space do not shrink but enhance the urban public space. Satellite images reveal inevitable loss of green space to urban construction and its remediation by artificial plantings (almost by 30% at present), whereas less valued blue space decreased almost three-fold. . Interviews reveal that shallow lakes have reduced recreational values due to ice bottom and algae bloom. High values are attributed to deep artificial lakes, which are more than ten times deeper than natural lakes and do not freeze throughout in winter. Our biometric studies show that trees in urban environment are significantly taller than in the corresponding undisturbed areas. Since majority of the Arctic cities are built using very similar planning ideas and technologies, our findings shall help objective appreciation of green and blue spaces in other settlements.

Keywords: green spaces, blue spaces, high-resolution remote sensing, Arctic, Nadym

1. Introduction

The creation of safe, inclusive, and accessible public spaces is included in Goal 11 (Sustainable cities and communities) of the United Nations Millennium Sustainable Development Goals. This goal, however, is difficult to achieve in densely populated cities where public spaces must compete for valuable land plots or the requirements for infrastructural development are difficult to fulfill. While compact cities have been receiving renewed attention for their ability to reduce greenhouse gas emissions (Russo and Cirella 2018), the availability and composition of green and blue space still play an important role in determining the quality of public spaces. Researchers have compiled extensive evidence of the socio-environmental value of urban green space conceptualizing it as an anthropic biome (e.g., Pincetl and Gearin 2005). Blue (water) space improves the quality of life and air quality in cities, helps moderate urban climatic anomalies (Steeneveld *et al* 2014), and supports higher health standards (Roe *et al* 2019). Moreover, combined green and blue spaces bring synergistic benefits to urban ecosystems (Gunawardena *et al* 2017; Bockarjova, Botzen and Koetse 2020).

Voluminous literature exists on urban green and blue spaces in low latitude cities, whereas cities in high latitudes are only rarely studied. City planning in high northern latitudes has historically maximized human isolation from inhospitable environments (Jull 2016; Hemmersam 2016). The harsh, cold climate and high costs of construction in those regions have prompted the creation of dense urban built environment; single-house cities have been proposed by some architects (Jull 2016). Although this environmental isolationism has never been fully implemented and has been heavily criticized (Pressman 1996), the concept of a compact Arctic city remains dominant in urban planning (Tunström *et al* 2018). Such an isolationism has influenced urban public (green and blue) spaces, which have not been truly incorporated in the urban living space.

Arctic urban populations often comprise settlers from southern regions that have their own specific configurations of place attachment, conceptions of environment, and human-nature relations (e.g., Stammler and Sidorova 2014; Laruelle *et al* 2019; Lyarskaya 2016; Orttung *et al* 2020). Shift worker camps in the Arctic transform into permanent settlements when a new sense of place emerges among their inhabitants (Stedman 2003). This occurs when local residents begin incorporating nature into their living space (Kaltenborn 1998; Brown and Raymond 2007; McBride and Douhovnikoff 2012). Kareiva *et al* (2007, 3) point out that urban landscapes are among “the most domesticated landscapes on the planet, in which every element of the environment has been consciously or unconsciously selected to accord with human desires.” In this sense, Arctic and sub-Arctic cities are particularly extreme cases of human-induced transformations of nature.

It is not easy to quantify societal attitudes with objective indicators. Diverse approaches that utilize geoinformation systems (GIS) to combine qualitative social information (interviews) and quantitative remote sensing information have become popular (Sherrouse *et al* 2011). Satellite imagery dating back to the 1960s (e.g., the declassified Corona images) also helps researchers to assess the true scale of localized human impact (Frost *et al* 2013; Yu *et al* 2015). The application of high-resolution remote sensing to Arctic urban studies, however, remains sparse (Esau *et al* 2016; Esau and Miles 2016; Lappalainen *et al* 2016).

This knowledge gap justifies our examination of human-induced changes in the archetypal sub-Arctic Russian city of Nadym. Its significant and influential climatic anomalies related to an urban heat island have already been documented (Esau *et al* 2016; Kirilyuk 2006; Kirilyuk and Buganov 2007; Kirilyuk and Buganov 2008). We propose a novel way to combine quantitative information from satellite imagery analysis and biometric studies with qualitative information from interviews with stakeholders and residents. We consider the urban environmental changes that have occurred in the city from its foundation days to the present and identify the local social values and perceptions of nature that are embedded in transformations of the green and blue spaces in Nadym.

In this study we first examine changes to land cover and to the boundaries of bodies of water that occurred between 1968 and 2012. It allows us to identify factual changes in the space use. Then, we study local practices and values attached to development, maintenance and enhancement of green and blue spaces; urban planning documents and interviews are used in this analysis. We juxtapose these changes against population and climate dynamics in order to estimate the input of each factor in changing land use. Second, we review changes in green spaces both spatially (in comparison with changes in corresponding rural areas) and compositionally (in comparison with past changes). Third, we determine changes in blue spaces by comparing the size and depth of natural and artificial lakes. We then compare these results with those of additional field studies in and around Nadym. In conclusion, we examine the contribution of the present study to the body of research on human-environment interactions and resilience to global change.

2. Area of study, data, and methods

2.1 Area of study

The city of Nadym (65° 32' 0" North, 72° 31' 0" East) is located in the Yamal-Nenets Autonomous Okrug, Russia. Nadym has a continental subarctic climate. It is located on territories that have traditionally been occupied by the Nentsy nomadic indigenous people (Figure 1). Contemporary Nadym was founded as a base for shift workers in 1960s. In 1972, it transformed into a city with a permanent population.

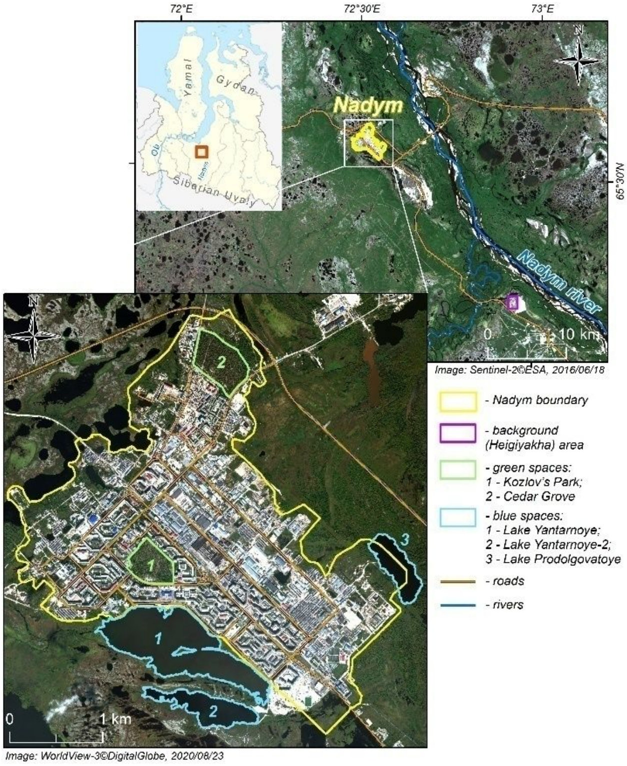


Figure 1. Area of study demonstrating location of the city of Nadym and the background area for comparison of tree heights.

Nadym is a typical Soviet city consisting of microrayons. Mirorayons are residential areas that are densely built following the “closed contour principle” to protect people from strong winds and snow, especially in the winter. Schools, kindergartens, and other facilities are located within walking distance inside of the microrayon (Romanov 2016; Jull 2016). Construction in the city was more dense than usual, however, because architects had originally planned to build a dome over the city to isolate it entirely from the Arctic environment; the project was later abandoned due to its high cost (Leontyeva and Karpova 2016). The first urban plan estimated that the city’s population would only be 12,000 people (NII PG 2017). The population, however, exceeded 26,000 by 1979 (Stas’ 2014). The population peaked in the 1980s and, after declining in the 1990s, has stabilized at about 46,000 people. Nadym is one of the major oil cities in Siberia. It is experiencing an economic boom brought about by the oil and gas industry. Construction work is still ongoing.

The development of the Nadym area has induced climatic and ecological transformations. LULC changes have resulted in significant ground warming (Yakubson *et al* 2012), followed by the greatest loss in ground bearing capacity (over 40%) among the Russian Arctic cities (Streletskiy *et al* 2012). Soils on aeolian sands in this area experience particularly significant warming, in part because of deep heating caused by penetrating precipitation and meltwater (Kurchatova *et al* 2018). Large changes in sandy plots are reported for other areas of the Arctic as well (Lara *et al* 2018). More than half of Nadym is built on aeolian sand dunes on the second terrace of the Nadym River. Other parts of the city include areas of large, hilly bogs, floodplains, and Siberian pine/larch woodlands. LULC changes following climate warming could be also significant here, as shown in plot studies (Moskalenko 2009).

The Nadym municipal area (3.7 thousand ha) includes the city of Nadym, an airport, the Nadym railroad station, and an industrial area known as “the 107th km.” Only the city has residential and business areas and has been developed following a master plan, with designated open public spaces. Urban green spaces include natural vegetation at the margins of the city and artificially planted vegetation (mainly white birch trees, different kinds of willow trees, and flowers) along the main streets and squares (Pechkina 2019). In this study, we focus only on the city itself and its adjacent industrial zone. The total area under consideration comprises 835.878 ha.

2.2 Data and methods

Our selection of data and methods for this study is guided by the aim to find informative objective indicators to valuate subjective public attitudes to the urban natural environment. Urban green and blue spaces in Nadym are under high anthropogenic pressure. High urban density (see Figure 1) and the harsh climate each reduces the regenerative capacity of nature, making human pressures more easily detectable. We take a non-traditional, interdisciplinary approach to examining the impact of those pressures by combining quantitative information from very high-resolution satellite remote sensing systems with qualitative analyses of urban planning documents and interviews. More specifically, this analysis included both existing scholarly works on the subject and municipal and other local open access documents and web-based social media sources.

We gathered twelve semi-structured interviews including three with former local stakeholders responsible for the city planning and management and nine with ordinary residents. The respondents’ recruitment was conducted using a “snowball” approach. To receive the written answers, we sent to the respondents the standardized guides of the interviews with questions on the green and blue spaces, their use and structure (see Supplementary materials). The structure of interviews was a combination of standardized guide and open questions that varied depending on the area of the competence of the interviewees. The interviews with the former stakeholders included additional questions on their expertise in the area of urban planning and development. Interviews with other residents contained more detailed questions about their individual experience of usage of green and blue spaces. The answers were then thematically coded.

We apply a content analysis methodology to analyze the coded interviews and municipal documents. We identify local practices and values attached to development, maintenance and enhancement of green and blue spaces in the city. These practices and values were compared with quantitative indicators derived from satellite imagery. In addition, the census data gathered in 1979 and 1989 and more detailed data from the local source My City (http://www.mojgorod.ru/janao/nadym/index.html) were involved in the study.

After qualitative characterization of the societal values of the specific urban places we look at their quantitative characteristics that would open for further routine statistical analysis and perhaps modeling and prediction. We identified buildings and infrastructure using OpenStreetMap (Barrington-Leigh and Millard-Ball 2017) and satellite imagery. We assessed the dynamics of green space in Nadym by comparing vegetation cover in 1968 (from CORONA imagery) and 2012 (from WorldView imagery). We then applied object-oriented processing (Blaschke 2010): we first segmented satellite imagery using eCognition software and manually identified vegetation class by attributing the corresponding segments. Then we estimated the Normalized Difference Vegetation Index (NDVI), which characterizes vegetation greenness in the city (Walker *et al* 2012). Our new data are of much higher resolution than NDVI estimations that are based on the Moderate Resolution Spectroradiometer (MODIS) data products. The MODIS NDVI data for Nadym have already been analyzed in Esau *et al* (2016) and Esau and Miles (2016; 2018). For convenience, our methods, data, and data sources are listed in Table 1.

Table 1. Data and sources.

Methods	Data	Sources
Remote sensing analysis	2-meter resolution scene for 1968/08/21	Corona KH-4; ID: DS1104-2217DA034_34_b earthexplorer.usgs.gov/
	0.5-meter resolution scene for 2012/07/13	WorldView-2; ID: 1030010019750E00, DigitalGlobe via PGC
Tree height measurements	DEM 2020/08/23; 0.05 m	DJI Phantom 4 Pro, AgiSoft Metashape Professional 1.6.3
Bathymetry	Depth values from 2020/07/25 and 2020/08/07 at a speed of 5–10 km per hour. Measurement points ranged from 440 to 735, depending on the size of the body of water.	Garmin EchoMAP 42CV
GIS-analysis	Spatial datasets, state land cadaster	ArcGIS 10.4.1 software (ESRI; Redlands, CA) (pkk.rosreestr.ru/)
Analysis of meteorological data	Data on precipitation and air temperature; 1960–2018	Roshydromet AISORI (http://meteo.ru/it/178-aisori)
NDVI measurements	30-meter resolution archive of harmonized Landsat data on annual mosaic of median values from July 1 to August 28 (1985–2019)	Landsat, GoogleEarthEngine (earthengine.google.com)
Analysis of population changes	Census and statistical data on population change	http://www.demoscope.ru/weekly/ssp/rus79_reg2.php; All-Union Population Census 1989 http://www.demoscope.ru/weekly/ssp/rus89_reg2.php; Data from http://www.mojgorod.ru/janao/nadym/index.html; Municipal database

One of the tasks we must solve for the urban green spaces is to quantify their difference from undisturbed green plots. Both urban and undisturbed green areas are experiencing climatic variations. Urban impact is an additional factor that must be estimated having only one contemporary review of both green areas. To solve this problem, we compared the vegetation traits of urban green space with those of natural, undisturbed green space in similar geomorphological conditions and with similar vegetation composition. We selected a lichen thin forest (Siberian pine, Scots pine) on fixed aeolian sands 35 km southeast of Nadym, near the mouth of the Heigiyakha river. We collected measurements with unmanned aerial vehicles. We calculated tree height in ArcGIS by subtracting Digital Terrain Model (DTM) values (the height of the surface without vegetation) from Digital Surface Model (DSM) values (the height of the surface with vegetation). We used the Gaussian normal distribution function in order to obtain the differences between individual and average tree canopy heights using MATLAB. We analyzed the influence of climate on NDVI variability from 1985 to 2019 through an analysis of precipitation and Growing Degree Days (GDD) (Spinoni *et al* 2015; 2018; Box *et al* 2019).

Similarly, for the urban blue space, we must find quantitative indicators that characterize values of water bodies for the public. We assessed the dynamics of blue space in Nadym by manually comparing the digitized boundaries of bodies of water as seen in Corona (1968) and WorldView (2012) imagery. We conducted our own direct depth measurements in the largest and most socially significant lakes in Nadym. We performed depth interpolation by using the inverse distance weighted (IDW) method, with a grid cell of 4 m.

3. Results

3.1 Overview of city growth and composition

The current composition of the green, blue, and built spaces in Nadym is influenced by a variety of factors, that form a compromise between the need for housing and infrastructure, environmental maintenance, available resources, and the desires of residents. Although Nadym is a densely built city with limited parking and courtyards spaces, its planning indicates a strong hierarchy of environmental values among inhabitants, at least among stakeholders in the administration and cornerstone industry. Figure 2 reveals that they have preserved forests within the city and clear-water lakes at urban margins.

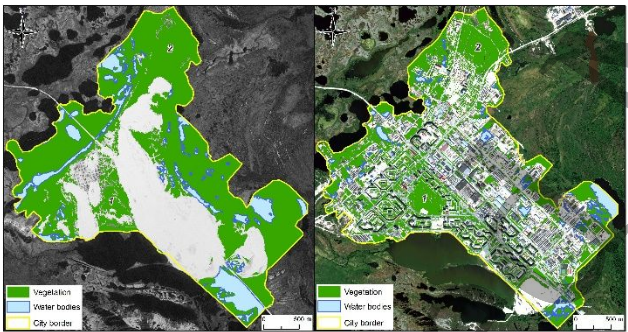


Figure 2. The development of modern Nadym in northern West Siberia, Russia. Land cover changes are shown on co-registered images from CORONA, 1968 (left) and WorldView-2, 2012 (right).

Comparison of satellite images from 1968 and 2012 shows that the urban core was built on barren land (Table 2). Simultaneously, a significant loss of green space within the urban area was partially remediated by the gain in vegetation cover from artificial plantings (almost one third of its current green space). In contrast, the share of blue space decreased almost three-fold. Construction work blocked many channels and water bodies in the center, while, in the margins they have been preserved. Other spaces, including built-up areas, barren lands, and disturbed areas such as waste landfills and areas covered with asphalt, almost doubled in 44 years.

Table 2. Changes in land cover between 1968 and 2012 in the city of Nadym.

Nadym	**8/21/1968**		**7/13/2012**		**Lost from 1968–2012, ha**	**Gained from 1968–2012, ha**
	ha	%	ha	%		
	835.9	100	835.9	100	0	0
Green	463.54	55.50	273.65	32.70	277.26	87.37
Blue	84.65	10.10	28.53	3.41	72.16	16.04
Other*	287.71	34.4	533.72	63.89	164.07	410.08

3.2 Green spaces

Socio-environmental interactions are perhaps the most apparent in changes and tending of urban forest. Residents alter green spaces in Nadym directly through mechanical disturbance and indirectly through artificial planting of trees and bushes. They preserve native trees and introduce other, more resilient plants. This "domestication" of nature has led to a specific urban composition of native and non-native tree species enhancing biodiversity and public attractiveness of green areas (Figure 3).

This study looks at dynamics of two larger parks — Cedar Grove (area: 23.2 ha) and Kozlov's Park, a forest named after E. F. Kozlov (area: 15.9 ha) — that are found within the city margins. Efforts to meet all-Russian standards for public green space in urban areas are especially noticeable in the parks. The most recent master plan of the city envisions the conservation and maintenance of the Cedar Grove Siberian pine woodland (Pechkina 2019) and of Kozlov's Park in the city center (Popov *et al* 2014; Pechkina *et al* 2016; Pechkin *et al* 2018; NII PG 2017). The latter is popular among citizens and serves as a focal point for the city: most of the city's public institutions, such as sports facilities, cultural centers, the registry office, school, and kindergarten, are concentrated around the park, making it attractive for public use (NII PG 2017). By contrast, Cedar Grove is seen as a natural conservation area; local authorities carefully manage and maintain its tree composition. In the 1970s, Cedar Grove was threatened by birch expansion, which was supposedly caused by changes in soil structure, moisture, and microclimatic conditions after the construction of multi-story buildings nearby (source: Interview with the former deputy head of the Nadym municipality). The unwanted trees were cut down. These public places did not exist in the original master plan and were a bottom-up initiative from city builders, constituting a rather unique movement for the oil cities of Western Siberia (Museum of History and Archaeology of Nadym; Stas' 2014).

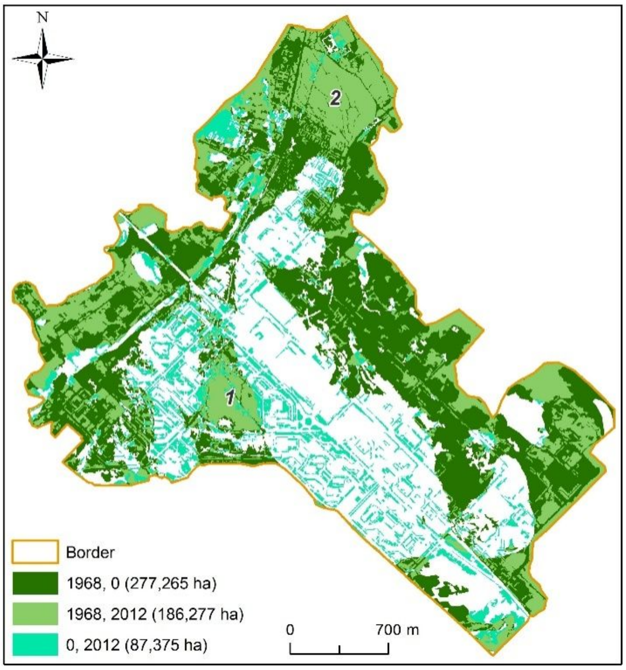


Figure 3. Changes in green space allocation during city construction. From 1968 to 2012, the share of green spaces decreased from 55.5% to 32.7% of total urban space. Some formerly sandy areas, however, have been "greened": silt was brought from the Nadym River flood plain to cover the sand with soil.

An analysis of satellite imagery clearly reveals considerable efforts to preserve, sustain, and even expand the city's green spaces. Figure 3 shows new green areas in immediate proximity to apartment blocks and along streets. According to Pechkina (2019), most of the artificial plantings take place along the central streets of the city. The industrial zone, in contrast, is often covered by spontaneous vegetation (Kuklina, Sizov and Fedorov, 2021). That distribution of artificial and natural green areas is indicative of residents' attribution of higher societal value to green urban construction and afforestation near their homes (Riley *et al* 2018). Annual tree planting events are part of the local Gasprom office's corporate ecological policy (Gasprom Nadym Dobycha 2020).

Yet, the public use of the green spaces is limited in summertime. Respondents explain that both green and blue spaces have high concentrations of bloodsucking insects (midges). Midges plague walkers, who prefer to communicate "on their feet" rather than stop or rest on park benches. During the summer, residents often prefer open, windy areas outside the city where midges are blown away, such as the banks of the Nadym and Longyugan rivers, hills, the roadsides of country highways, etc. On warm days during the off-season, however, urban green spaces are in demand. In the fall, e.g., the residents pick mushrooms, berries, and pinecones in Cedar Grove.

Urban park maintenance requires significant efforts from the residents and contributions from the municipal budget. Therefore, it can be seen as an objective indicator of the green space significance for the residents. In the Arctic climate, we propose the height of tree canopies as such an objective indicator. The fits are shown in Figure 4. McBride and Douhovnikoff (2012) study emphasized high public significance of and attention to trees in the Arctic settlements. We found that trees in Kozlov's Park are significantly taller (the mean height is 982 cm with 95% statistical confidence interval ± 220 cm) than in corresponding undisturbed areas (827 ± 218 cm). This difference indicates that the tree heights in these two areas are statistically different with at $p < 0.05$ in a standard t-test (Krzywinski and Altman, 2013). Moreover, the difference in 155 cm is outside the 95% confidence interval given by the two standard deviations for the interannual variability of the natural NDVI over the last 17 years (the MODIS data over 2001-2018; Esau et al. 2016).

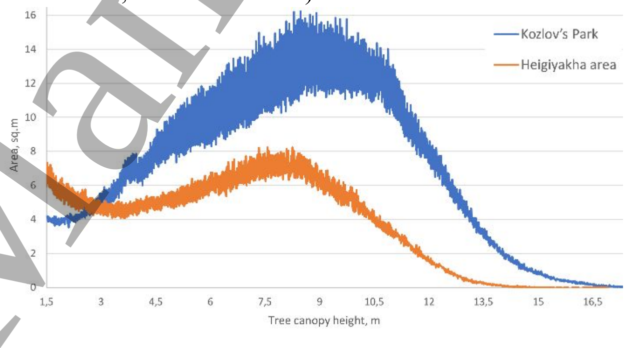


Figure 4. Distribution of canopy heights in Kozlov's Park (blue) and Heigiyakha (red). The park has a greater proportion of taller trees than does natural woodland with similar vegetation.

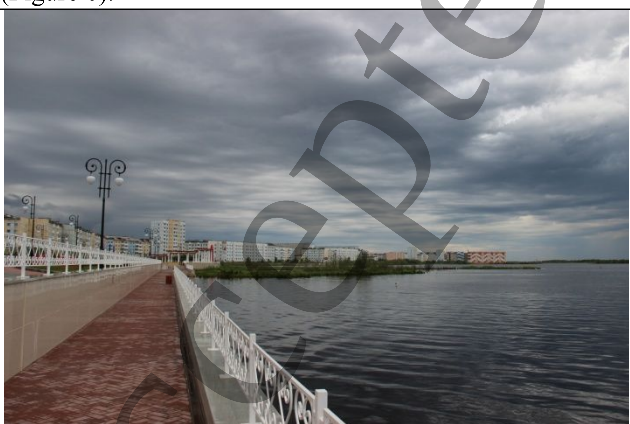
3.4 Blue spaces

Surprisingly, the residents value urban blue space far less than it could be expected on the basis of extrapolated results from temperate latitudes (Bokarjova *et al* 2020). Open blue spaces in Nadym study area include several lakes. Lake Yantarnoye is the biggest natural lake in the area, with a length of about 2 km, area of 0.8 km^2, and depth of 2 m. In 2018 and 2019, as part of a program for the improvement of the urban environment, city authorities built an embankment along the lake's shore.

Two artificial lakes (sand dugouts), unofficially called Second Yantarnoye and Prodolgovatoye, were created during the development of the city. The maximum depth of these dugouts is 22 m, more than ten times deeper than that of natural lakes (Figure 5). In the cold local climate, natural lakes have rather distinct hydrological and temperature characteristics (Pointner *et al* 2019) — unlike them, the artificial lakes do not freeze through to the bottom and do not have an ice floor. That makes them more attractive for summertime recreational activities. These dugouts have become popular public spaces.

Figure 5. A bathymetric survey (depth) of the largest natural and artificial bodies of water (lakes and dugouts) and lake recreational areas. The organized recreational area has been developed by the municipality; the spontaneous recreational area lacks municipal funding and has been developed by urban residents themselves.

Unlike green spaces, which benefit from anthropogenic interference, blue spaces demonstrate more varied effects of human involvement. While artificial lakes, which coincidentally obtained desired physical traits, benefit from their acceptance as public space, shallow natural lakes are poorly maintained. For example, Lake Yantarnoye is unsuitable for swimming or fishing due to chemical contamination, and its algae blooms cause a foul smell. In the summer, residents often walk at some distance from the shore to avoid gnats. Insect density reduces residents' use of the lake's constructed waterfront. Moreover, blue spaces located in the industrial zone of the city face littering. Littering often takes place along the shores of bodies of water that the local residents find unattractive, significantly reducing their recreational potential and highlighting the distinct boundaries between domesticated and 'wild' nature (Figure 6).



(a)

(b)

Figure 6. An illustration of residents' attitudes toward waterfronts in Nadym. (a) The well-developed shore of Lake Yantarnoye (photo by A. Pechkin, 2020) contrasts that (b) of a lake in the industrial zone at the margins of the city (photo by A. Soromotin, 2020).

3. Discussion

In recent decades, the old academic perception of the urban environment as a disturbance of nature has shifted; research now views it as an urban or anthropic biome. Increased interest in socio-environmental interactions has motivated a search for the material footprints of societal attitudes toward urban nature. It is important to introduce quantitative indicators that would characterize public values of diverse objects of the anthropic nature. Indeed, urban environment is modified in accordance with human ideas and values; seemingly similar landscapes might follow rather different transformational pathways (Kareiva *et al* 2007). These differences are evident in a comparison of Nadym's urban green spaces (Cedar Grove and Kozlov's Park) and urban blue spaces (Lake Yantarnoye and Second Yantarnoye). Even though the city is surrounded by green space, the "wild" nature of that space discourages residents from using it. Instead, the sparse vegetation of a sandy river terrace facilitated a bottom-up residential movement to create cultivated green spaces that align with the residents' own attitudes. Deliberate cultivation efforts include fertilization, tree planting, and the removal of unwanted undergrowth (Srodnykh 2005). Urban green spaces have the higher NDVI values and tree heights than their natural counterparts. Yet humans also indirectly impact these spaces by creating warmer microclimates and causing carbon dioxide pollution. More detailed studies are needed, however, in order to evaluate different factors contributing to urban greening.

Climate warming in this area favors a gradual increase in biological productivity, as reflected in increasing NDVI values. Figure 7 compares NDVI values of similar (in terms of species and age) areas of Kozlov's park and Heigiyakha. Since the 1980s, vegetation in Kozlov's park has exhibited greater productivity than has natural vegetation in Heigiyakha. As Srodnykh (2005) and Koronatova and Milyaeva (2011) have shown, the successional dynamics of vegetation communities explain this accelerated urban "greening." Srodnykh (2005) compared the composition and biological state of green spaces of different ages in 8 northern Siberian cities, revealing that green spaces in the cities are populated by fast-growing species. For example, different willow and birch species constitute 95% of the trees in Tarko-Sale. The NDVI values of such trees are maximized within 15–20 years after planting. In a 13-year study of sand quarries, Koronatova and Milyaeva (2011) discovered the increasing dominance of more productive herbaceous and woody plant communities. NDVI changes in the two relatively small places that we selected for our study agree with the areawide NDVI increase that Srodnykh (2005), Koronatova and Milyaeva (2011), and other authors describe (e.g., Miles and Esau 2017). Bhatt *et al* (2013) and Miles *et al* (2019) relate these changes to an increasing number of growing degree days (GDD). The most affected LULC types are grassland and larch woodland. Air temperature and GDD are the primary drivers of the NDVI increase (Barichivich *et al* 2014). Other factors, however, also impact the observed trends, indicating the existence of additional influences on urban greening that need further exploration.

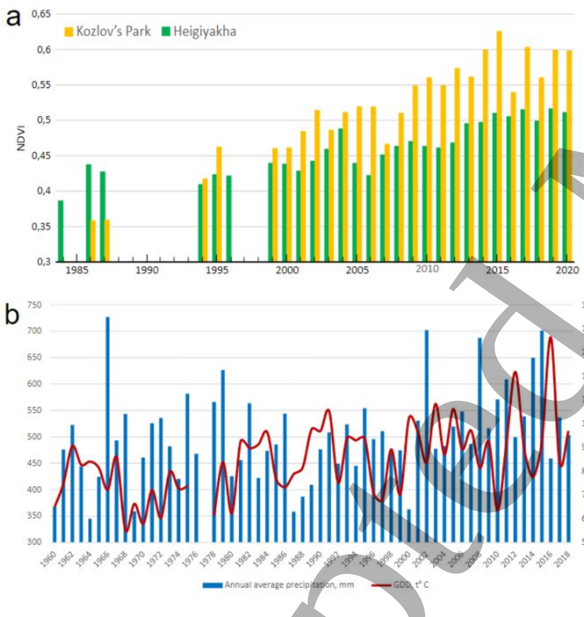


Figure 7. A comparison of NDVI mean values for Heigiyakha and Kozlov's Park, including a) annual precipitation and b) growing degree days.

Green and blue spaces both reflect local attitudes. On one hand, blue spaces are reduced by city builders, who fill some of them in with sand. On the other hand, blue spaces are impacted by the creation of new deep dugouts. The city's development has negatively impacted the ecological state of Lake Yantarnoye, leading to paludification and the destruction of fish habitats (Krasnenko *et al* 2018). Littering in and the contamination of natural lakes in the industrial zone illustrate their low importance for urban residents; these blue spaces are analogous to neglected green spaces (Rupprecht *et al* 2015). Such spaces, located on the border between domesticated and "wild" landscapes, are also distinguished by their liminality. They conform the call by Pitt (2018) to distinguish brown, gray and green watery environments. Meanwhile, residents care for and maintain better the artificial dugouts that provide recreational services.

The results of our studies demonstrate wide variety of human impact on urban green and blue spaces and dynamics of their transformation. Incorporation of this knowledge into the urban planning and identification and support of some local initiatives to enhance these places would increase urban sustainability can contribute to increasing sustainability and resilience of Arctic cities.

4. Conclusion

Urban landscapes are known for their extreme diversity and complexity of anthropogenic pressures on included natural objects. Quantitative indicators that account for social attitudes might be helpful for creating of more systematic review and modeling of the socio-environmental interactions in such urban anthropic biomes. We conclude that informative indicators could be introduced using measurable characteristics of vegetation productivity and lake bathimetry. By examining the green and blue urban spaces in Nadym, we have revealed extremely different pathways of development, patterns of use, and care for such spaces. It would be impossible to assess these pathways without understanding the attitudes of stakeholders and residents toward different green and blue spaces in the city.

We found that NDVI and tree density are informative indicators that reflect the intended and unintended human effects on urban green spaces in Nadym. The limited usage of green spaces in summertime contradicts the conclusions of many studies of temperate cities (Tyrvainen, Makinen and Schipperijn 2007). The interviews that we conducted resolve this contradiction—high tree density reduces wind and intolerably increases pressure from midges. Despite this detrimental factor, residents still push for further "greening" of the city for rather their symbolic than practical value.

We found that the lake depth and the free freshwater flow are informative indicators for determining the recreational value of bodies of water: they determine the quality and temperature of water, to which residents are very sensitive.

More studies are needed, however, to identify the effect of different factors on vegetation growth and water quality within the city and the actual local practices of forming, using, and maintaining green infrastructure.

Acknowledgements

The reported study was funded by Belmont Forum project №1729 SERUS (NRC no. 311986), National Science Foundation # 2024166, and RFBR project No. 20-55-71004. Some parts of Roman Fedorov's contribution to the article were supported by the Tyumen Scientific Center SB RAS research project No. AAAA-A19-119071990006-3.

References

Administration of Nadym district 2020 *History of the city* http://www.nadymregion.ru/nadym-raion/nadym/nadym-history.php (In Russian)

Assmann J J, Kerby J T, Cunliffe A M and Myers-Smith I H 2019 Vegetation monitoring using multispectral sensors – best practices and lessons learned from high latitudes *Journal of Unmanned Vehicle Systems* **7** 54–75

Barrington-Leigh C and Millard-Ball A 2015 A century of sprawl in the United States *Proc. Natl. Acad. Sci. U.S.A.* **112** 8244–9

Barichivich J, Briffa K R, Myneni R, van der Schrier G, Dorigo W, Tucker C J, Osborn T J and Melvin T M 2014 Temperature and Snow-Mediated Moisture Controls of Summer Photosynthetic Activity in Northern Terrestrial Ecosystems between 1982 and 2011 *Remote Sens.* **6** 1390–1431 https://doi.org/10.3390/rs6021390

Bhatt U S *et al* 2013 Recent Declines in Warming and Vegetation Greening Trends over Pan-Arctic Tundra *Remote Sens.* **5** 4229–4254 https://doi.org/10.3390/rs5094229

Blaschke T 2010 Object based image analysis for remote sensing *J. Photogramm. Remote Sens.* **65(1)** 2–16 https://doi.org/10.1016/j.isprsjprs.2009.06.004

Bockarjova M, Botzen W J W and Koetse M J 2020 Economic valuation of green and blue nature in cities: A meta-analysis *Ecological Economics* **169** 106480 https://doi.org/10.1016/j.ecolecon.2019.106480

Box J E *et al* 2019 Key indicators of Arctic climate change: 1971–2017 *Environ. Res. Lett.* 1**4(4)** 045010 https://doi.org/10.1088/1748-9326/aafc1b

Brown G and Raymond C 2007 The relationship between place attachment and landscape values: Toward mapping place attachment *Appl. Geogr.* **27** 89–111 https://doi.org/10.1016/j.apgeog.2006.11.002

Construction project 501 http://www.nadymregion.ru/nadym-raion/history/501-building.php (In Russian)

Esau I *et al* 2016 Trends in normalized difference vegetation index (NDVI) associated with urban development in northern West Siberia *Atmos. Chem. Phys.* **16** 9563–9577

Esau I and Miles V 2016 Warmer urban climates for development of green spaces in northern Siberian cities *Geography. Environment. Sustainability* **9** 48–62

Esau I and Miles V 2018 Exogenous drivers of surface urban heat islands in northern West Siberia *Geography. Environment. Sustainability* **11(3)** 83–99 https://doi.org/10.24057/2071-9388-2018-11-3-83-99

Frost G V *et al* 2013 Patterned-ground facilitates shrub expansion in Low Arctic tundra. *Environ. Res. Lett.* **8(1)** 015035 https://doi.org/10.1088/1748-9326/8/1/015035

Gasprom Nadym Dobycha 2020 Nature preservation https://nadymdobycha.gazprom.ru/ecology/ (In Russian)

Gunawardena K R, Wells M J and Kershaw T 2017 Utilising green and blue space to mitigate urban heat island intensity *Sci. Total Environ.* **584–585** 1040–1055

Hemmersam P 2016 Arctic Architectures *Polar Rec.* **52(4)** 412–422

Jull M 2016 Toward a Northern Architecture: The Microrayon as Arctic Urban Prototype Journal of Architectural Education **70(2)** 214–222

Kaltenborn B P 1998 Effects of sense of place on responses to environmental impacts. A study among residents in Svalbard in the Norwegian high *Arctic. Appl. Geog.* **18(2)** 169–189

Kareiva P, Watts S, McDonald R and Boucher T 2007 Domesticated Nature: Shaping Landscapes and Ecosystems for Human Welfare *Science* **316** 1866–9

Kirilyuk L I 2006 Hygienic significance of heavy metals in assessing the health status of the population of the far North *Dissertation to obtain degree of the Doctor of Biological Sciences.* Nadym: Institute of Medical Problems of the Extreme North (In Russian)

Kirilyuk L I, Buganov A A 2007 Formation of the principle of ecological infrastructure of small northern cities *Forestry* **4** 28–29 (In Russian)

Kirilyuk L I, Buganov A A 2008 Features of lead accumulation by woody plants in the Far North *Forestry* **4** 28–29 (In Russian)

Koronatova N G and Milyaeva E V 2011 Plant community succession in post-mined quarries in the northern-taiga zone of West Siberia *Contemp. Probl. Ecol.* **4** 513

Krasnenko *et al* 2018 Yantarnoie lake – state, problems, and prospects *Nauchny ivestnik Yamalo-Nenetskogo avtonomnogo okruga* **4(101)** 37–43 (In Russian)

Krzywinski M and Altman N 2013 Significance, P values and t-tests. Nat Methods 10, 1041–1042 https://doi.org/10.1038/nmeth.2698

Kuklina V, Sizov O, Fedorov R 2021 Green spaces as an indicator of urban sustainability in the Arctic cities: Case of Nadym Polar Science 100672 https://doi.org/10.1016/j.polar.2021.100672

Kurchatova A and Poskonina E 2018 Simulation of thermal interaction of sand embankment and frozen soils of the base *Foundations, Foundations and Soil Mechanics* **4** 28–33 (In Russian)

Lappalainen H K *et al* 2016 Pan-Eurasian Experiment (PEEX): Towards a holistic understanding of the feedbacks and interactions in the land–atmosphere–ocean–society continuum in the northern Eurasian region *Atmos. Chem. Phys.* **16(22)** 14421–14461 https://doi.org/10.5194/acp-16-14421-2016

Lara M J *et al* 2018 Reduced arctic tundra productivity linked with landform and climate change interactions *Scientific Reports* **8(1)** https://doi.org/10.1038/s41598-018-20692-8

Laruelle M *et al* 2019 Arctic cities as an anthropogenic object: a preliminary approach through urban heat islands *Polar J.* **9** 1–22

Leontyeva N M and Karpova J I 2016 Nadym is the city under the dome *Design and arts: theory, methods and practice* St. Petersburg: St. Petersburg State University 417–421 (In Russian)

Lyarskaia E 2016 "Someone also needs to live in the city ... ": some features of the transformation of the social structure of the Yamal Nenets. *Etnograficheskoye obozreniye* **1** 54–70 (In Russian)

McBride J and Douhovnikoff V 2012 Characteristics of the urban forests in arctic and near arctic cities *Urban Forestry and Urban Greening* **11** 113–119

Miles V and Esau I 2017 Seasonal and Spatial Characteristics of Urban Heat Islands (UHIs) in Northern West Siberian Cities

Remote Sensing **9(10)** 989 https://doi.org/10.3390/rs9100989

Moskalenko N G 2009 Permafrost and vegetation changes in the Nadym region of the West Siberian northern taiga due to climate change and technogenesis *Earth Cryosphere* **13(4)** 18–23 (In Russian)

Museum of history and archaeology of Nadym n.d. Accessed 11 October 2020 http://nadym-museum.ru/expo/ (In Russian)

Nadym district in figures 2020 Accessed 11 October 2020 http://nadymregion.ru/activity/economics/nadym-number.php (In Russian)

NII PG 2017 Documents for territorial planning http://nadymregion.ru/activity/urbanism/dokumenty-territorialnogo-planirovaniya.php (in Russian)

Orttung R (ed.) 2016 *Sustaining Russia's Arctic Cities: Resource Politics, Migration, and Climate Change* (New York: Berghahn Books)

Pechkina *et al* 2016 Green spaces of the city of Nadym as an element of the ecological framework *Geographical studies of Eurasia: history and modernity* **12** 309–313 (In Russian)

Pechkin A S, Pechkina Yu A, Agbalyan E V and Semenyuk I P 2018 Green spaces of the main streets of Nadym *Urboekosystems: problems and development prospects* **6** 117–119 (In Russian)

Pechkina Yu A 2019 *Nadym: green and comfortable* https://goarctic.ru/society/nadym-ozelenyennyy-i-blagoustroennyy/ (In Russian)

Popov A S 2014 Assessment of the state of the cedar-larch woodland park named after E. F. Kozlov in Nadym, Yamalo-Nenets Autonomous Okrug *Forests of Russia and its economy* **49(2)** 24-29 (In Russian)

Pressman N 1996 Sustainable Winter Cities: Future Directions for Planning, Policy and Design *Atmos. Environ.* **30(3)** 521–529

Pincetl S and Gearin E 2005 The Reinvention of Public Green Space *Urban Geogr.* **26(5)** 365–384

Pitt H 2018 Muddying the waters: What urban waterways reveal about bluespaces and wellbeing *Geoforum* **92** 161–70

Pointner G, Bartsch A, Forbes B C and Kumpula T 2019 The role of lake size and local phenomena for monitoring ground-fast lake ice. *Int. J. Remote Sens*. **40** 832–858 https://doi.org/10.1080/01431161.2018.1519281

Riley C B, Perry K I, Ard K and Gardiner M M 2018 Asset or Liability? Ecological and Sociological Tradeoffs of Urban Spontaneous Vegetation on Vacant Land in Shrinking Cities *Sustainability* **10** 2139

Roe J, Barnes L, Napoli, N J and Thibodeaux J 2019 The Restorative Health Benefits of a Tactical Urban Intervention: An Urban Waterfront Study *Frontiers in Built Environment* **5** https://doi.org/10.3389/fbuil.2019.00071

Rupprecht C D D, Byrne J A, Garden J G and Hero J-M 2015 Informal urban green space: A trilingual systematic review of its role for biodiversity and trends in the literature *Urban Forestry & Urban Greening* **14** 883–908

Russo A and Cirella G T 2018 Modern Compact Cities: How Much Greenery Do We Need? *Int. J. Environ. Res. Public Health* **15(10)** https://doi.org/10.3390/ijerph15102180

Sherrouse B C, Clement J M and Semmens D J 2011 A GIS application for assessing, mapping, and quantifying the social values of ecosystem services *Appl. Geogr.* **31** 748-760 https://doi.org/10.1016/j.apgeog.2010.08.002

Spinoni J, Vogt J and Barbosa P 2015 European degree-day climatologies and trends for the period 1951–2011 *Int. J. Climatol.* **35(1)** 25–36 https://doi.org/10.1002/joc.3959

Spinoni *et al* 2018 Changes of heating and cooling degree-days in Europe from 1981 to 2100 *Int. J. Climatol*. **38** e191–e208 https://doi.org/10.1002/joc.5362

Srodnykh T B 2005 State of Settlement Gardening in Towns in the North of Western Siberia *Lesnoj Zurnal (Forest Journal)* **3** 27–34.

Stammler F and Sidorova L 2015 Dachas on permafrost: the creation of nature among Arctic Russian city-dwellers *Polar Rec.* **5**, 576–589 https://doi.org/10.1017/S0032247414000710

Stas' I N 2014 "Naked" urbanization: Greening the cities of oil workers in Western Siberia (1960-1980s) *History and local studies of Western Siberia: problems and prospects of research* **1** 140–145 (In Russian)

Stedman R C 2003 Is It Really Just a Social Construction?: The Contribution of the Physical Environment to Sense of Place *Society and Natural Resources* **16** 671–685 https://doi.org/10.1080/08941920390217627

Steeneveld G J, Koopmans S, Heusinkveld B G and Theeuwes N E 2014 Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect *Landsc. Urban Plan.* **121** 92–6

Streletskiy D A, Shiklomanov N I and Nelson F E 2012 Permafrost, Infrastructure, and Climate Change: A GIS-Based Landscape Approach to Geotechnical Modeling *Arct. Antarct. Alp. Res.* **44** 3

Tunström M, Lidmo J and Bogason Á 2018 The Compact City of the North – functions, challenges and planning strategies *Nordregio Report* **4** (Stockholm: Nordregio) https://doi.org/10.30689/R2018:4.1403-2503

Tyrvainen L, Makinen K and Schipperijn J 2007 Tools for mapping social values of urban woodlands and other green areas Landsc. Urban Plan. **79** 5–19

Walker D A *et al* 2012 Environment, vegetation and greenness (NDVI) along the North America and Eurasia Arctic transects *Environ. Res. Lett*. **7** 015504

Yakubson K I *et al* 2012 Geoindicators of environmental changes in areas of intensive development of oil and gas fields and methods of their estimation *Georesources, geoenergy, geopolitics* **6(2)** 22 (In Russian)

Yu Q, Epstein H E, Engstrom R, Shiklomanov N and Strelestskiy D 2015 Land cover and land use changes in the oil and gas regions of Northwestern Siberia under changing climatic conditions *Environ. Res. Lett.* **10(12)** 124020 https://doi.org/10.1088/1748-9326/10/12/124020