DOI: 10.30680/ECO0131-7652-2017-7-20-33

Urbanization in Siberia. A glimpse from satellite[1]

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Abstract. Based on nightlight and Landsat satellite images, the authors studied urbanization in Siberia from 1992 to 2012. Changes in illuminated urban areas correspond to declines and booms of economic development. Despite significant reduction in population of Siberia in that period, large administrative centers – Novosibirsk, Krasnoyarsk, Omsk and Irkutsk – are getting an influx of population in the last decade and are growing in size at the expense of adjacent rural areas. The paper identifies major environmental issues facing these Siberian cities and correlation between indicators of urbanization and economic development.
Keywords: *urbanization; urban built-up area; ecology; air pollution; Siberia; satellite survey systems*

Cities and towns in Siberia have been long associated with the resource extraction in the region, serving as the transportation and industrial hubs for related activities since the early days when the Trans-Siberian Railway constructed 120 years ago. However, these human dwelling centers in Siberia (>70% of the populations) have been experiencing new challenges since the collapse of the USSA in 1989, including the chaotic emigration that was responsible for the 8,7% decrease in overall population of the Siberian Federal District from the 1990 to 2014, as compared with 1,4% decrease of the overall population of Russia. This change in population, coupled with volatile

[1] We would like to acknowledge the financial support from the National Aeronautics and Space Administration (NASA)'s Land Cover and Land Use Program through its grant to Michigan State University (NNX15AD51G) and the Center for Global Connections (CGC) at Michigan State University (MSU) for funding Peilei Fan's field trip in Siberia in May 2015. We thank all interviewees we have met for taking time to talk with us and provide insights on cities in Siberia. We are particularly thankful to our local collaborator who helped us to arrange all the interviews and the field visits to various parts of these cities. We also thank Dr. Lihua Xu for processing data on land use of Siberian cities. We appreciate the constructive comments provided by several colleagues on earlier versions of this paper. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of NASA of CGC of MSU.

economy, hinders sound landscape and urban planning toward the long-term sustainability for the region. Meanwhile, it provides us a great experiment opportunity to study the unique dynamics of the urban systems in a transitional economy.

Despite their importance, current literature on the human systems of these agglomerations in Siberia is far from adequate, with a limited number of publications on urban systems [e.g., Suspitsyn, 2012; Bashalkhanova et al., 2012; Grigor'ev, 2009; Becker et al., 2014]. In this paper, we focus on studying urbanization and the changing urban environment in Siberia from 1990 to the 2010s. Urbanization here refers to both the demographic perspective and land perspective [Fan et al., 2016]. Urbanization is the increase in the ratio between urban population and the total population and the expansion of the urban built-up area (i.e., the conversion from non-urban land into urban built-up area). The reverse direction can be denoted as "de-urbanization". Our specific research questions are.

1. What is the current status of urbanization? How did it evolve since the economic transition? What are the spatial variations?

2. How has the urban environment changed over time for major cities in Siberia? What are the major challenges facing the Siberian cities?

3. What is the relationship between economic development and urban changes in Siberia?

Study Area

A broader definition of Siberian refers to a vast territory that extends from the east of the Ural Mountains to the Pacific coast, from the Arctic Ocean in the north to Russia's border with former USSR Central Asian countries, China, and Mongolia in the south. In this paper, we used a narrower definition of Siberia that includes only the Siberian Federal District of the Russian Federation (Figure 1 and Table 1) due to the ease of data analysis of using the same administrative hierarchy as the statistical system of the Russian Federation. The Siberian Federal Subject contains 30% of the territory of Russia, settled 19 million people (13% of the total population of Russia), and included 30% of Russian cities that have >100,000 people in 2016. This immense terrain covers a wide range of biomes, from the tropical/subtropical moist broadleaf forest in the southern edge, to boreal forest (*taiga* in Russian) in the vast middle area, to the tundra belt in the north. Most cities with more than 100,000 people are located in the various types of forest areas in the southwest part of the federal district. Within the Siberian Federal District, there are a total of 12 federal subjects, with the top six most populous ones as Krasnoyarsk Krai, Novosibirsk Oblast, Kemerovo Oblast, Irkutsk Oblast, Altai Krai, and Omsk Oblast, in a decreasing order. In addition to examining all 12 federal subjects of the Siberian Federal District, we also chose four major administrative centers as our case cities: Krasnoyarsk, Omsk, Novosibirsk, Irkutsk. Krasnoyarsk, Omsk, and Novosibirsk are the three most populous cities in Siberia, with over 1 million residents and important economic centers of their respective federal subjects. Though Irkutsk is the fifth populous city with slight less population than Barnal, it serves as an important node on the Trans-Siberian Railway and has been historically an important trading center in the eastern part of Siberia. We therefore chose Irkutsk as one of four cases. Among the four case cities, we visited three (i.e., Krasnoyarsk, Novosibirsk, and Irkutsk).

Table 1. **Basic socioeconomic characteristics of Siberian Federal District, Russia (2016)**

Geographic Area	Siberia	Total North Asia	Total Russia	% of Russia
Land area (km^2)	5 114 800	13 132 800	17 075 400	30
Population (2016)	19 324 031	37 630 081	144 221 341	13
# of federal subjects	12	27	85	14
# of municipalities	4,082	6,781	22,923	18
# of cities > 100000	21	47	165	30
Urbanization (2014),%	72,7	75,5	74,0	

Data and Analysis

We used a range of methods and data sources to approach our research questions, relying on a variety of satellite imageries, statistical data on socio-economic variables, and field visits for validation of image interpretation and interviews with local experts.

Land cover and changes

At the regional level, we examine the spatiotemporal variation of urbanization through the analysis of DMSP/OLS nighttime light data. We chose this product because it has the longest data record to cover our study period and strong correlations with population density, economic activity and impervious area (Elvidge, 2010; Lu, 2008), implying that the NTL brightness is an empirical indicator of the economic status and built-up density. In order to reduce the variations and differences among sensors, an inter-calibration of NTL data was first performed following Elvidge et al., 2013 (Table 2). Also, some bright area in NTL images might be gas fares that are fake urban information. We excluded gas flares using the gas flares layer produced by Elvidge, et al. (2009). When there were multiple annual DMSP/OLS NTL composites of a year, we chose the one with the largest number of could-free observations (Table 2). Threshold-based methods are commonly used to convert NTL data into unban built-up area class (Imhoff et al., 1997), but a proper threshold vary among different urban clusters and different period due to social-economic differences, sensor sensitivity difference, and other factors (Li, 2016; Liu, 2012; Ouyang et al. 2016). To avoid complexity, we used a single threshold for the whole regions among all years. Base on a previous study that mapping China's urban dynamics (Liu, 2012), the threshold for mapping urban land through NTL for those provinces neighboring to Russia/Siberia is roughly 40 on average though out 1990s to 2000s, we therefore used 40 as the threshold to classify lighted area with NTL >40 as urban land. For each federal subject, we calculated the lighted area with NTT > 40 from 1992 to 2012. The form of the calculation is:

$$Y= C_0+C_1X+C_2X^2,$$

where Y is the DN of the year needs calibration, and X is the F12–1999 DN. Please see details from Elvidge et al. [2013].

At the city level, urban built-up area was classified from Landsat TM images in three periods (i.e., the 1988, 2000, and 2010) to examine spatiotemporal changes for the five cities. All Landsat TM images were downloaded from USGS (https://www.usgs.gov/) Level-1geo-referenced product, which were then converted to reflectance using the calibration function built-in ENVI 4.8. For each image, we classified it using EARDAS IMAGINE9.3 into urban built-up area, forestry, water surface, farmland, and bare soil. First, we classified and masked forests using a normalized difference vegetation index (NDVI) threshold. We then classified and masked water surface using the modified normalized difference water index (MNDWI) (Xu, 2007) threshold. The remaining image area were then classified into urban built-up and farmland, and bare soil through supervised classification. Post classification processes, including clumping, sieving, and combining classes, were conducted to eliminate patches that are smaller than six TM/ETM+ pixels. Finally, additional manual corrections were applied to rectify some misclassification to improve the overall accuracy. The overall accuracy is ca. 85% for year 2011 when validated by 90 points per city that is interpreted by experts based on Google earth high-resolution images.

Table 2. **DMSP/OLS data used in this study and the coefficients for the inter-calibration applied to the digital values in time series (1992–2012)**

Satellite	Year	C_0	C_1	C_2
F10	1992	-2.0570	1.5903	-0.0090
F10	1993	-1.0582	1.5983	-0.0093
F10	1994	-0.3458	1.4864	-0.0079
F12	1995	-0.0515	1.2293	-0.0038
F12	1996	-0.0959	1.2727	-0.0040
F12	1997	-0.3321	1.1782	-0.0026
F12	1998	0.1535	1.0451	-0.0009
F14	1999	-0.1557	1.5055	-0.0078
F15	2000	0.1029	1.0845	-0.0010
F15	2001	-0.7024	1.1081	-0.0012
F15	2002	0.0491	0.9568	0.0010
F15	2003	0.2217	1.5122	-0.0080
F15	2004	0.5751	1.3335	-0.0051
F15	2005	0.6367	1.2838	-0.0041
F15	2006	0.8261	1.2790	-0.0041
F16	2007	0.3210	0.9216	0.0013
F16	2008	0.5564	0.9931	0.0000
F16	2009	0.9492	1.0683	-0.0016
F18	2010	2.3430	0.5102	0.0065
F18	2011	1.8956	0.7345	0.0030
F18	2012	1.8750	0.6203	0.0052

Air pollution data

We extracted the areal mean air pollutant concentration within each city administrative boundary of the surface air pollution data of fine particulate matter ($PM_{2.5}$) and NO_2 from remotes sensing products. Both $PM_{2.5}$and NO_2 products were produced by the Atmospheric Composition Analysis Group (http://fizz.phys.dal.ca/~atmos/martin/). Annual ground-level $PM_{2.5}$ were estimated by combining aerosol optical depth retrievals from the NASA MODIS, MISR, and SeaWIFS instruments with the GEOS-Chem chemical transport model at 0.01×0.01 degree resolution (Van Donkelaar et al, 2016). Annual ground-level NO_2 were produced at 0.1×0.1 degree resolution with observations of NO_2 tropospheric column densities from three satellite instruments (i.e., Global Ozone Monitoring Experiment (GOME), Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), and GOME-2 satellite instruments) in combination with a chemical transport model [Geddes et al., 2015].

Socioeconomic, population, and other statistical data and processing

To understand the driving forces for the urbanization in Siberia, we collected data on demography and economic development for federal subjects and population data for all cities over 100,000 people. The main data sources include various years (2004–2015) of Socioeconomic Indicator of Russian Regions and Census data of the Federal State Statistics Service of Russian Federation. We also conducted field trips in Novosibirsk, Krasnoyarsk, and Irkutsk in May 2015. For each city, we conducted five to six semi-structured interviews with local experts in urbanization, economic development, and urban environment. Each interview lasted about one to two hours, with local experts being asked to describe the urban development stages and main driving forces of each stage, to draw an illustrative map of the city's spatial structure, and to enumerate the main environmental problems and social challenges.

Results

Urban land changes

Siberia has experienced an interesting dynamics of urban landscapes (Fig. 1 is on the cover). An overall snap shot of 1992 and 2012 shows that while some non-urban land were converted to urban land during the period, the reverse direction also existed (Figure 2a). A more subtle study of urban built-up land area of each district shows that during the first decade from 1992 to 2002 most federal subjects experienced a volatile and decreasing urban built-up land, while urban built up land after 2002 started to increase, but none of the federal subject were able to recover to the level of 1992 (Figure 2).

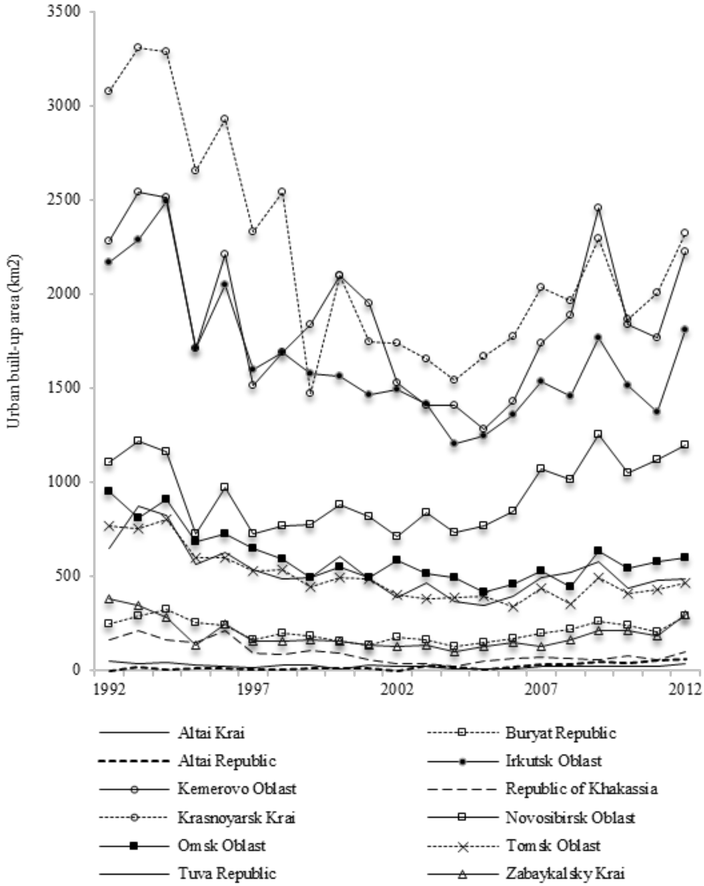

Figure 2. Urban built-up area in 12 federal subjects in Siberian Federal District from 1992 to 2012

An examination of urban built-up areas of the four largest cities in Siberia illustrates that although the urban built-up area the Siberia region declined, all cities have experienced an overall urban expansion, but their spatial extent and expansion rate varied distinctively (Figure 3). For example, Novosibirsk started with the largest urban built-up area of 14.72 km^2 in 1988 and expanded rapidly to 19.59 km^2 in 2000, but then contracted its urban built-up area to 18.1 km^2 in 2014. Krasnoyarsk followed a similar trend, although it started with a much smaller urban built-up area of 5.14 km^2. Omsk and Irkutsk expanded continuously, with Omsk experiencing a much faster expansion from 5.07 km^2 in 2000 to 12.02 km^2 in 2014.

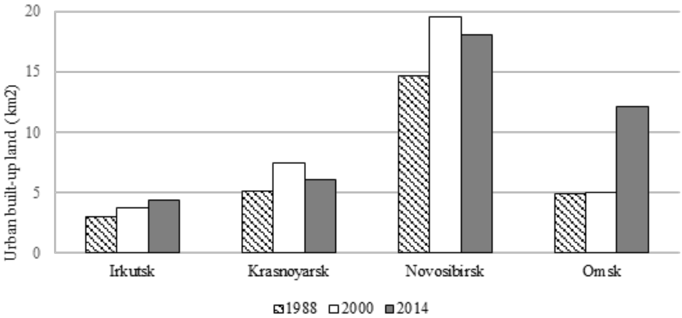

Figure 3. Urban land expansion of Irkutsk, Krasnoyarsk, Novosibirsk, and Omsk in 1998, 2000, 2014

Population dynamics

An examination of the population dynamics of Siberian Federal District revealed that the region decreased its population by 8.7% from 1990 to 2014, although the Russian Federation only decreased its population 1.4%. Each of the twelve federal subjects illustrates a similar trend as the region, although some recovered a little in recent years (Figure 4). It is, however, interesting to note that when we examined the urban population of large administrative centers, these cities experienced first a decrease from the 1989 to 2002 but then an increase of population in the following decade, despite the loss or stagnant growth of the population of their respective federal subjects. This trend become more distinguished as the percentage of the population of these cities vis-à-vis their respective federal subjects all increased over time (Table 3).

Table 3. **% of population of Administrative Center of the Federal Subject from 1998 to 2016**

	1998	2002	2010	2016
Irkutsk	22	23	24	26
Krasnoyarsk	30	31	34	37
Novosibirsk	52	53	55	57
Omsk		56	58	60

Urban environmental changes

Irkutsk fared the best among the four major administrative centers in Siberia in terms of urban air pollution (i.e., $PM_{2.5}$ and NO_2). Novosibirsk, Omsk, and Krasnoyarsk are in the similar situation. While Omsk had the highest concentration of $PM_{2.5}$, Novosibirsk had the highest NO_2 concentration. All four cities had a general increasing concentration of $PM_{2.5}$ and NO_2, with $PM_{2.5}$ in Irkutsk as an exception (Figure 4). It is also interesting to note that $PM_{2.5}$ increased for all four cities quickly from 1999 to 2003 but then started to diverge into different directions among the cities. In contrast, while Irkutsk kept a relative stable level of NO_2, three other cities experienced a slight decreasing trend before increasing in the early 2000s.

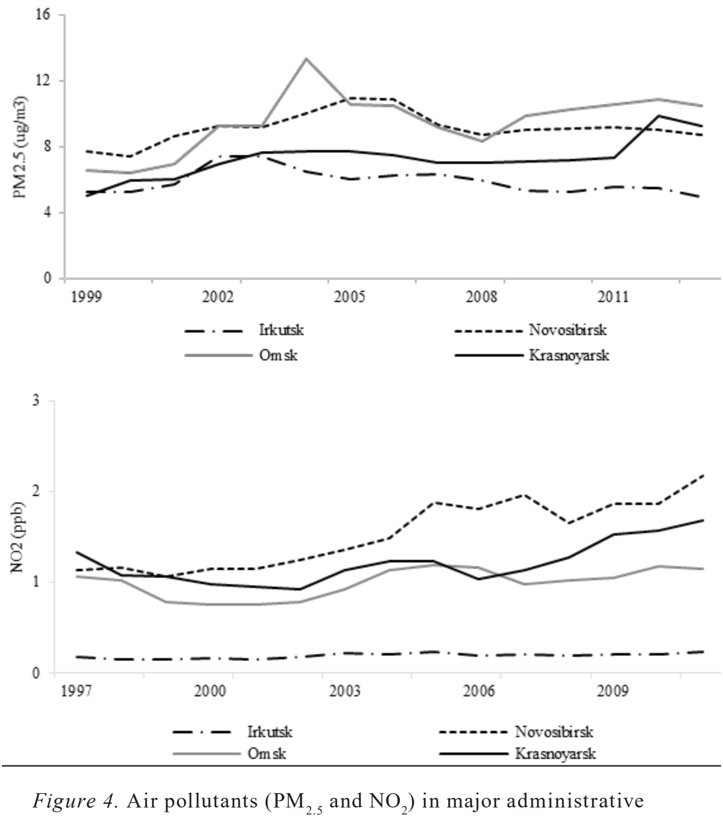

Figure 4. Air pollutants ($PM_{2.5}$ and NO_2) in major administrative centers in Siberia from 1997 to 2011

It is more revealing when local experts identified the most challenging environmental problems of their cities and discussed possible causes and solutions. Here we summarized their opinions, particularly in aspects of urban green space, air pollution, and garbage and recycling. First, it is surprising that quite a few local experts mentioned that the urban green space has become an emerging environmental concern for Siberian cities although Siberian cities are stereotyped to have more open spaces and are greener than other parts of Russia. Lack of sufficient urban green space and declining green space has been identified as the major environmental problem for all three cities. For instance, residents commented that few urban parks exist in Krasnoyarsk. In Irkutsk, intensive construction has filled out open space with very little open space remaining across the urban landscapes.

Second, air pollution was recognized as an aggravating issue for some cities in some seasons, with complicated causes. For example, air pollution became serious in winter although some consider that Novosibirsk has a generally good air quality due to its relative high position and strong wind due to its location at the western edge of Siberia. On one hand, closure of some industrial plants in cities may alleviate air pollution; on the other hand, increasing traffic due to more usage of private vehicles have increased the emission of pollutants. Novosibirsk experienced significant change in its economic structure, with its service sector starting to play a larger role in its economy. Meanwhile, some factories were relocated or closed in the 1990s (e.g., the tin plant which used to be its main ecologic problem), thus alleviating the pollution problem. In Krasnoyarsk, main sources of air pollution were from the emission of transportation and the metal processing sector (e.g., aluminum factories). Similarly in Krasnoyarsk, the coal-electricity power stations and aluminum factories have long been the major sources of pollution. Some interviewees mentioned that air pollution from traffic increased, counter-balancing the effect of decreased pollution from the factories although the manufacturing sector managed to decrease the emission.

Third, garbage and recycling have been mentioned as one of the issues gradually gaining citizen’s attention, as it is for the entire Russia. People started to be concerned of garbage dumping in landfills that leads to loss of land and the need to build recycling facilities in the cities.

It should also be noted that urban environmental problems also illustrate spatial dimension for each city. For example, academic towns in both Novosibirsk and Krasnoyarsk are called towns in the forest due to the full integration of the academic facilities in the forest landscape. At the other extreme, the most polluted area in Novosibirsk is the old city core started building up in the 1940s whereas for Krasnoyarsk, it is the northeast part of the city where power factories and chemical factories are located, along with many supermarkets due to the low land prices.

Discussion

What have been the key driving forces for the urban dynamics in Siberian cities? It has long been considered that urbanization is tightly connected with economic development (Davis, 1966). Quite a few scholars have already reported that urban land expansion was closely associated with economic development, as well as policy and extreme events [Acemoglu et al., 2002; Fan et al., 2016; Tian et al., 2014]. Have Siberian cities followed the same suite? To reveal the complicated relationship between urbanization and economic development, we conducted a simple Pearson correlation analysis among urban built-up area, urban population, and Gross Regional Product per capita (GRPpc) that represents the level of economic development (Table 4). We examine not only the region of Siberia, but also two major federal subjects whose administrative centers that are the first and third most populated cities in the region: Krasnoyarsk Krai and Novosibirsk Oblast. We found that the co-evolved relationship between urban built-up area and urban population, usually seen in other parts of the world, did not occur in Siberia for the period from 1992 to 2012. Further more, urbanization propelled by economic development did not really hold for Siberia as there is no clear relationship between either (1) urban built-up area and GRPpc, or (2) urban population and GRPpc, except for Novosibirsk where there is a significant correlation (0.82) between urban built-up area and GRPpc. However, when we examine only the last ten years, we found that the region seems to conform to the expected relationships (Table 4). Correlation coefficients between urban built-up area and GRPpc are above 0.73 for Siberia, Krasnoyarsk and Novosibirsk, whereas for Novosibirsk, urban population and GRPpc also appear high (0.62).

Table 4. **Coefficients of Correlation in Siberian Federal District, Krasnoyarsk Krai, and Novosibirsk Oblast from 1992 to 2012**

	1992–2002			2003–2012		
	Urban Built-up	Urban population	GRPpc	Urban Built-up	Urban population	GRPpc
Siberian Federal District						
Urban Built-up	1.000	0.228	0.110	1.000	-0.653	0.767
Urban population	-	1.000	-0.878	-	1.000	-0.819
GRPpc	-	-	1.000	-	-	1.000
Krasnoyarsk Krai						
Urban Built-up	1.000	0.433	-0.142	1.000	-0.686	0.732
Urban population	-	1.000	-0.873	-	1.000	-0.748
GRPpc	-	-	1.000	-	-	1.000
Novosibirsk Oblast						
Urban Built-up	1.000	-0.331	0.817	1.000	0.407	0.825
Urban population	-	1.000	-0.548	-	1.000	0.621
GRPpc	-	-	1.000	-	-	1.000

Conclusions

We evaluated the urbanization trend of Siberia from 1992 to 2012 through examining the changes in urban population and urban land use in Siberia. Based on nightlight and Landsat satellite images, we derived the urban built-up land in Siberia with high-resolution of urban built up areas for Novosibirsk, Krasnoyarsk, Omsk, and Irkutsk. We found that there was a significant amount of conversion in the reverse direction (i.e., de-urbanization) as some non-urban lands were converted to urban land from 1992 to 2012. Urban built-up land experienced first decrease before an increasing trend, but none of the federal subjects recovered to its level of 1992. Nevertheless, major cities have experienced an overall urban built-up area expansion despite the regional trend. Meanwhile, large administrative centers experienced first a decrease then an increase in their population regardless that the region experienced significant reduction in population.

We found that Irkutsk fared the best among the four major administrative centers in Siberia by the measurements of concentrations of $PM_{2.5}$ and NO_2. All four cities had increasing trends of air pollutants of $PM_{2.5}$ and NO_2, with $PM_{2.5}$ concentration in Irkutsk as an exception. Our semi-structured interviews revealed that urban green space, air pollution, and garbage and recycling are major environmental challenges faced by Siberian cities.

Finally, we found that the co-evolving relationship between urban built-up area and urban population did not exist in Siberia for the period from 1992 to 2012; and the urbanization was not tightly related with economic development. However, there was closer association between urbanization and economic development during 2003–2012.

This paper serves as an initial effort in examining the urbanization in Siberia. There remain many questions remain unanswered, including What role did or can planning play in the process of urbanization/de-urbanization? How did urban environment relate to urban economic development and urban expansion? Did Siberia's urban development converge with the trend of Russia? Within Siberia, did different federal subjects take the diverging paths for urbanization and what exactly caused these divergences? What intellectual contribution can we make to the field of urban studies by studying Siberian cities? We hope this paper serves as stimulating action toward a long-term urban sustainability in Siberia.

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