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a synthesis for Asian Russia

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Urbanization and sustainability under transitional economies: a synthesis for Asian Russia

Peilei Fan[1,11], Jiquan Chen[2], Zutao Ouyang[3], Pavel Groisman[4], Tatiana Loboda[5], Garik Gutman[6], Alexander V Prishchepov[7,8], Anna Kvashnina[9], Joseph Messina[2], Nathan Moore[2], Soe W Myint[10] and Jiaguo Qi[2]

1 School of Planning, Design, and Construction and Center for Global Change and Earth Observations, Michigan State University, East Lansing, MI 48824, United States of America
2 Department of Geography, Environment, and Spatial Sciences and Center for Global Change and Earth Observations, Michigan State University, East Lansing, MI 48824, United States of America
3 Center for Global Change and Earth Observations, Michigan State University, East Lansing, MI 48824, United States of America
4 North Carolina State University at National Centers for Environment Information, Federal Building, 151 Patton Avenue, Asheville, NC 28801, United States of America
5 Department of Geographical Sciences, University of Maryland, College Park, MD 02742, United States of America
6 NASA Headquarters, 300 E Street, SW, Washington, DC 20546, United States of America
7 Department of Geosciences and Natural Resource Management (IGN), University of Copenhagen, Øster Voldgade 10, DK-1350 København K, Denmark
8 Institute of Environmental Sciences, Kazan Federal, Russia
9 Russian Federal Nature Preserve (Zapovednik) 'Denezhkin Kamen', 6 Lenin Street, Severouralsk, Sverdlovsk region, Russia
10 School of Geographical Sciences and Urban Planning, Arizona State University, Tempe, AZ 85287-5302, United States of America
11 Author to whom any correspondence should be addressed.

E-mail: fanpeile@msu.edu, jqchen@msu.edu, yangzuta@msu.edu, pasha.groisman@noaa.gov, loboda@umd.edu, garik.gutman@nasa.gov, alpr@ign.ku.dk, akvaanna@gmail.com, jpm@msu.edu, moorena@msu.edu, soe.myint@asu.edu and qi@msu.edu

Keywords: urbanization, sustainability, economic development, environmental condition, social development, Asian Russia

Abstract

Spanning a vast territory of approximately 13 million km^2, Asian Russia was home to 38 million people in 2016. In an effort to synthesize data and knowledge regarding urbanization and sustainable development in Asian Russia in the context of socioeconomic transformation following the breakup of the Soviet Union in 1990, we quantified the spatiotemporal changes of urban dynamics using satellite imagery and explored the interrelationships between urbanization and sustainability. We then developed a sustainability index, complemented with structural equation modeling, for a comprehensive analysis of their dynamics. We chose six case cities, i.e., Yekaterinburg, Novosibirsk, Krasnoyarsk, Omsk, Irkutsk, and Khabarovsk, as representatives of large cities to investigate whether large cities are in sync with the region in terms of population dynamics, urbanization, and sustainability. Our major findings include the following. First, Asian Russia experienced enhanced economic growth despite the declining population. Furthermore, our case cities showed a general positive trend for population dynamics and urbanization as all except Irkutsk experienced population increases and all expanded their urban built-up areas, ranging from 13% to 16% from 1990 to 2014. Second, Asian Russia and its three federal districts have improved their sustainability and levels of economic development, environmental conditions, and social development. Although both regional sustainability and economic development experienced a serious dip in the 1990s, environmental conditions and social development continuously improved from 1990 to 2014, with social development particularly improving after 1995. Third, in terms of the relationships between urbanization and sustainability, economic development appeared as an important driver of urbanization, social development, and environmental degradation in Asian Russia, with economic development having a stronger influence on urbanization than on social development or environmental degradation.

Abbreviations

ECI	Economic index
EVI	Environment index
FD	Federal district
FS	Federal subject
GHS	Global human settlement
NTL	Nighttime light
RSI	Regional sustainability index
SDI	Social development index
SEM	Structural equation model

1. Introduction

Integrated assessments of urbanization and sustainability in transitional economies are necessary to address the particular challenges facing those regions. With more than half of the global population already living in cities, the world is entering the urban era (United Nations 2014). Although many have examined the extent and spatial patterns of urban transformations around the globe (Seto *et al* 2011, Zhou *et al* 2015, Reba *et al* 2016), assessments of whether urbanized areas are evolving in a sustainable manner are rare (Nassauer *et al* 2014, Fan *et al* 2016). This assessment is particularly relevant for countries with transitional economies, i.e., countries that have transitioned from central planning-based economies to market-based economic systems in Southeast and East Asia, Eastern Europe, and Russia, in the past several decades. In these countries, both the state and the market can affect the urbanization process, and their interplay may lead to a different pattern of urbanization from that of industrialized countries or non-transitional economies in the developing world. Furthermore, the differences in land use and institutions governing urban land use may lead to a variety of trajectories of urbanization and sustainability among transitional economies (Shatkin 1998, Leaf 2002, Sýkora and Bouzarovski 2012, Tian *et al* 2013). Yet, few comprehensive efforts have been made to explore the processes and consequences of the transformations of transitional economies, including post-Soviet countries, to understand how economic transition may have affected urbanization and sustainability (Fan *et al* 2016, Fan *et al* 2017a, Park *et al* 2017).

Asian Russia stands out as a unique system to help us understand the processes and challenges of urbanization under transitional economies due to the unusual changes that occurred in the region following the collapse of the former Soviet Union. Comprised of the eastern part of Russia, Asian Russia spans a vast territory of approximately 13 million km^2 from the Ural Mountains in the west to the Pacific Ocean in the east and was home to 38 million people in 2016. Here, we focus on Asian Russia in contrast to the smaller but more densely populated European Russia due to its very different economic and societal development over the 20th century (Forsyth 1994). While Asian Russia has a lower population density (2.9 people km^{-2} in 2016) compared to European Russia (27 people km^{-2} in 2016), 75.5% of the population in Asian Russia is concentrated in cities, primarily consisting of large cities spread over the southern edge of Asian Russia (figure 1). In contrast to European Russia, cities and towns in Asian Russia have long been associated with resource extraction and have served as transportation and industrial hubs for related activities since the start of the construction of the Trans-Siberian Railway in 1891. However, these human dwelling centers in Asian Russia (>70% of the population) have been experiencing new challenges since the collapse of the Soviet Union in 1990. For example, the population in Asian Russia decreased by 10.3% from 1990 to 2016, whereas the total population in Russia declined by only 2.7% during the same period. This change in population, coupled with a volatile economy, may hinder landscape change and urban planning toward the long-term sustainability of the region. Meanwhile, it provides us with a unique opportunity to study their dynamics. Despite the environmental vulnerability and the challenging conditions of human systems, current literature on urban systems and sustainable development in Asian Russia is very scarce, with the exceptions of works by Becker *et al* (2014) and Fan *et al* (2017b) on urbanization in Russia and Siberia, and a few on regional sustainability (e.g., Grigor'ev 2009, Bashalkhanova *et al* 2012, Suspitsyn 2012, Slepneva *et al* 2016, Zabelina and Klevakina 2016) (please see details of related key literature in appendix A).

To address the knowledge gap about changing urbanization patterns and their relationship with sustainability in Asian Russia following the collapse of the Soviet Union, our objective was set to synthesize the data and knowledge on urbanization and sustainable development in the context of socioeconomic transformation. Specifically, we aimed to answer the following research questions: (1) What are the trends in the spatiotemporal distributions of economic activity and urban built-up lands in Asian Russia after 1990? (2) What are the spatiotemporal changes of regional sustainability, including its three pillars: economic development, environmental conditions, and social development? (3) What are the interrelationships between urbanization and different measures of sustainability?

2. Methods

2.1. Study area

Representing 77% of the Russian territory, Asian Russia is a large landmass of Northern Eurasia that has

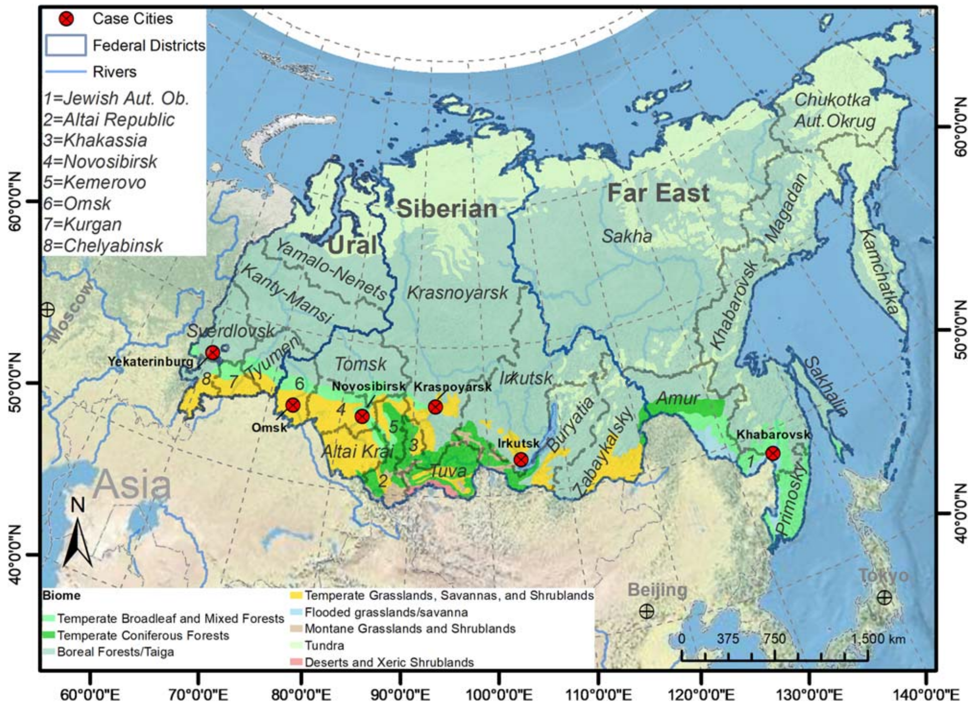

Figure 1. Asian Russia and the spatial distribution of three federal districts, twenty seven federal subjects, and six case cities. The map is projected into north Albert equal area conic projection.

been endowed with extraordinary natural resources and plays a critical role in the wellbeing of the global environment. We define Asian Russia as an area that includes three federal districts (FDs, administrative level-1 units) of Russia: Ural, Siberia, and Far East (figure 1), with FD as an official division of Russia's regions. If Asian Russia were an independent country, it would be the largest country in the world. The elevation of Asian Russia varies greatly, with a relatively flat landscape below 100 m over hundreds of kilometers—the West Siberian Plain—and with more rugged terrain in the Central Siberian Plateau (a.s. l = 1700 m) and 3100 m toward the eastern edges and in southern Siberia's Sayan Mountains (Afonin *et al* 2008). Similarly, the climate also varies considerably across Asian Russia. Asian Russia is an earthly gem because of its rich natural resources (e.g., minerals, oil, gas, soil, etc) and partially intact boreal forests—the largest terrestrial biome on Earth—which are home to some close-to-extinction species (e.g., the Siberian tiger, *Panthera tigris tigri*) and provide the necessary livelihoods for indigenous people who rely on the forests for their daily needs. In addition, Asian Russia, as the main terrestrial part of the arctic region, plays a vital role in the global ecosystem dynamics and biogeochemical cycles (World Wide Fund for Nature (WWF) 2007, Groisman *et al* 2017). However, the natural environment in Asian Russia currently faces many pressing challenges caused by intensified logging, mining, and construction, as well as rapid warming that is responsible for large and intense wild fires (Roshydromet 2014, Groisman *et al* 2017). The increasing global demands for wood products, gas, and natural gases have particularly escalated the land use intensity across the region.

Although human activities took place in the region as early as the 11th century, Asian Russia did not become an important economic unit of Russia until after the construction of the Trans-Siberian Railway. Until the mid 19th century, Asian Russia presented little economic interest to Imperial Russia. The region centered its main economic activities on fur trading from the 11th to the 18th century, with a few spots of agricultural production in the Far East (Okladnikov 1968). Mining in the region started in the 17th century, with silver, lead, and copper mining taking place in the 1700s and gold mining beginning in the 1830s. Due to its long and severe winters, the largest part of Asian Russia is not suitable for agricultural production, which also reflects the concentration of settlements in the southern belt of Asian Russia (e.g., populated in Yakutia and the Russian Far East, table 1) (Rosstat 2016). However, the land scarcity and low agricultural productivity in European Russia forced the Imperial Russian government to implement the Stolypin agrarian reform in the early 20th century, which was labeled as the Great Siberian migration of Russians towards Asian Russia (Treadgold 1957). The operation of the Trans-Siberian Railway facilitated the transport of agricultural commodities and goods (e.g., wheat and butter) from West Siberia to European Russia and Western Europe. After the 1917 revolution, Asian Russia experienced rapid industrialization and urbanization with forced labor in coal mining and the iron-steel complexes before World War II (WWII) (Blinnikov 2011).

Table 1. Profiles of Ural, Siberia, and Far East in Asian Russia. Data are from the Russian Federation Federal State Statistics Service (http://gks.ru/wps/wcm/connect/rosstat_main/rosstat/ru/). All data refer to the estimates on 1 January 2016 unless specified.

Federal district	Ural	Siberia	Far East	Asian Russia	Russia	% of Russia
Land area (km^2)	1788 400	5114 800	6179 900	13 132 800	17 075 400	77%
Population in 2016	12 308 103	19 324 031	6194 969	37 630 081	144 221 341	26%
# of federal subjects	6	12	9	27	85	32%
# of municipalities	1344	4082	1355	6781	22 923	30%
# of cities >10 0000	16	21	10	47	165	28%
Urbanization (%) in 2014	79.9	72.7	75.4	75.5	74.0	
Capital city	Yekaterinburg	Novosibirsk	Khabarovsk			

During WWII, some industries from western USSR regions were relocated to the east of the Ural Mountains. To meet the growing domestic food demand and improve national food security from 1954 to 1963, a Virgin Lands Campaign was implemented, resulting in ~20 Mha of virgin steppes being ploughed to support immigration to Siberia from European Russia. After WWII, construction of large thermo- and hydro-electric power plants continued in Asian Russia (Prishchepov *et al* 2018).

The dissolution of the Soviet Union had a significant impact on the population dynamics of the region. From 1990 to 2014, Asian Russia experienced a substantial population decrease of 9.9%, in contrast to a population decrease of 1.4% across the entirety of Russia. While the Far East witnessed the highest population decrease of 23% followed by Siberia with a decrease of 8.7%, Ural experienced the least decrease of 3.7%. At the federal subject (FS) level, i.e., an administrative level-II unit that is equivalent to the state level in the USA or provinces in many countries, 23 FSs in Asian Russia experienced a similar declining trend with the exception of only four, i.e., Tyumen (Ural FD), Altai Republic, Tuva, and Novosibirsk (Siberia FD). Despite the decrease or stagnation of the population within their respective FDs, all 6 major cities studied in this paper, except Irkutsk, experienced an increase in population from 1989 to 2016 (figure 2(b)). In 2016 less than 26% of Russia's population resided in Asian Russia (population density = 7.8 persons km^{-2}). The urbanization ratio (i.e., percentage of urban population) in the region was 75.5% in 2014, which was slightly higher than the Russian average of 74.0%.

Under this natural/historic background and in this particular socioeconomic context following the collapse of the Soviet Union, we conducted this study on urbanization and sustainability at three hierarchical levels: Asian Russia, FD, and federal subject (FS). Asian Russia includes three out of eight FDs and 27 out of 85 FSs of Russia and most of Russia's socioeconomic data are collected at the FD and FS level. We additionally incorporated six major cities as case cities to illustrate the dynamics of urban built-up area and population at the city level. Out of 47 cities with population over 100 000 inhabitants by 2016 in Asia Russia, thirteen cities have >500 000 inhabitants (figure 1, table A1). We acknowledge that large cities may not fully represent the region-wide urbanization trajectory because they tend to be the most resilient to change, due partially to their strong economic resources and large demographic bases. Nevertheless, cities rather than nations have become the centers of the global economy (Beeverstock *et al* 1999, Hall and Pfeiffer 2013, Sassen 2013); large cities can serve as important nodes and connect their vast hinterland with the increasingly globalized economy. Becker *et al* (2014) argued that large cities, particularly those in the southern and western parts of Russia, seem to attract migrants from the far north and east. In this study, we focused on examining whether large cities in Asian Russian share similar fates as the large cities in Russia in general. This knowledge allows us to understand if they are in sync with the region in terms of population loss, and whether similar challenges in urbanization and sustainability exist in Asian Russia. The six cities were chosen due to their large sizes and importance in economic development, political administration, and cultural and educational structures. They are: Yekaterinburg in Ural, Novosibirsk, Krasnoyarsk, Omsk, and Irkutsk in Siberia, and Khabarovsk in the Russian Far East (figure 1). All of the cities are the capitals of their administrative level-II provinces. Additionally, Yekaterinburg, Novosibirsk, and Khabarovsk are the capitals of administrative level-1 FDs. Though Irkutsk is the fifth populous city in Siberia with a slightly lower population than Barnaul, it serves as an important node on the Trans-Siberian Railway and historically was an important trading hub in the eastern part of Siberia and its administrative capital during the Russian Empire epoch. We also conducted field trips to four of these cities, Yekaterinburg, Novosibirsk, Krasnoyarsk, and Irkutsk, in the summer of 2015.

2.2. Data and analysis

We relied on several data sources for this study, including remote sensing products (table A2), socioeconomic statistics, and on-site interviews with local experts. We examined the changes of economic statistics at the FD and FS scales through the analysis of 1 km resolution DMSP/OLS nighttime light (NTL) data from 1992 to 2012. To quantify the changes in built-up land for the six cities, we used data from the

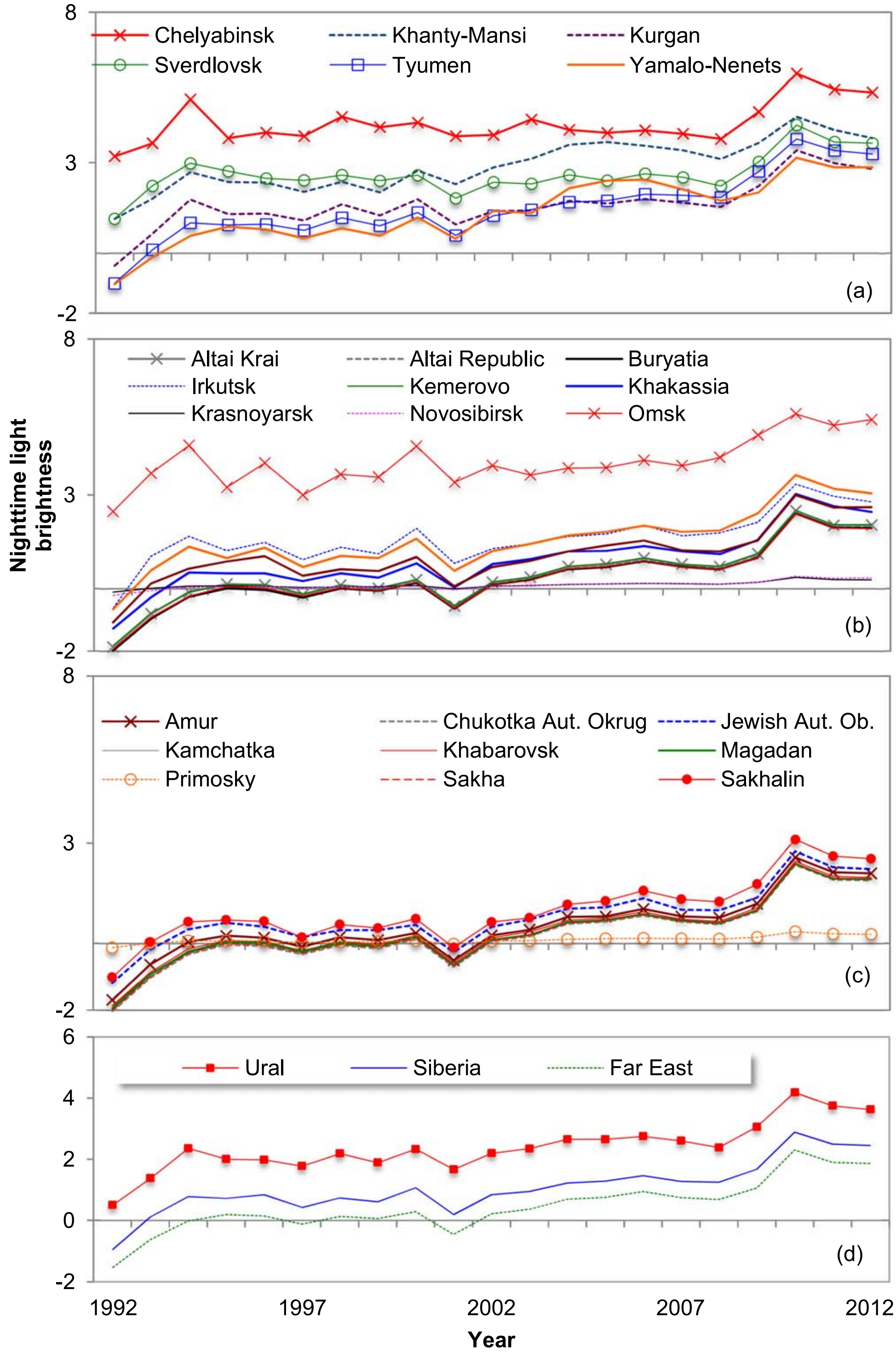

Figure 2. Average nighttime light brightness from 1992 through 2012. (a) Six federal subjects in Ural FD; (b) 12 federal subjects in Siberia FD; (c) nine federal subjects in the Far East FD; and (d) three federal districts in Asian Russia.

38 m resolution global human settlement (GHS) built-up grid (http://ghsl.jrc.ec.europa.eu/datasets.php). We performed geospatial analysis to explore the change of air pollutants of case cities. To understand the driving forces for the urbanization in Asian Russia, we collected data on demography, economic development, environmental conditions, and social conditions for FSs and population data for all cities with >100 000 people and conducted interviews with local experts of the case cities during our field trip (please see details in appendix B).

We developed and calculated sustainability indexes of the socioeconomic-environmental systems for all 27 FSs in the three FDs to explore the interdependent dynamics of multiple dimensions from social, economic and environmental aspects. Based on our literature review, we constructed a regional sustainability index (RSI) that incorporated conditions of economic development (i.e., employment rate), environment condition (i.e., air pollution), and social wellbeing in regard to housing (i.e., living space per capita) and health services (i.e., number of physicians available per 10 000 people) (see details of calculation of RSI in appendix C.1).

We further studied the interrelationships among urbanization and its potential independent variables through structural equation models (SEM). Economic development (ECO) and urbanization (Urb_p) were directly characterized with the observable variables of employment rate and the ratio of urban population to the total population (Davis 1965, Henderson 2003). Environmental degradation (ENV) was directly modeled by an observable variable of air pollutants per capita from the stationary sources (Seldon and Song 1994), Carson *et al* 1997. Social development was modeled as a latent variable SD by the number of physicians per 10 000 people (PHY_d) and living space per capita (LS_{pc}) (please see appendix C.2 for detailed method).

3. Results

3.1. Economic development and urban built-up area

Economic development, indicated by the average nighttime light brightness, increased for all three FDs, with the Far East experiencing the fastest growth (figure 2). While the increase during 1995–2008 appeared gradual with occasional small dips in 1997, 2001 and 2007, the increase was more substantial before 1995 and after 2007. Similar changing trends were also observed at the FS level for Ural, Siberia, and Far East.

All major cities experienced urban expansion measured by total built-up area, with urban built-up land expanding by 13%–16% from 1990 to 2014. Novosibirsk had the largest urban built-up area of 764.6 km^2 in 1990 and maintained its rank in 2014 (879.6 km^2). Khabarovsk and Irkutsk had relatively small urban built-up areas of 319.8 km^2 and 381.1 km^2 respectively, in 1990, but expanded to 361.8 km^2 and 442.5 km^2 in 2014, respectively. Omsk led the pack in terms of total expansion at 16.3%, whereas Khabarovsk came in last at 13.1% (figure 3). The expansion of the urban built-up area of these cities matched well with the overall increasing trend of the population of these cities.

3.2. Regional sustainability and its three dimensions

The RSI of three FDs in Asian Russia followed closely the national trend, which showed a decrease until 2000 and an increase afterward with a small dip around 2008 (figure 4). While the changing trend of economic index (ECI) followed the dynamics of RSI closely, the environment index (EVI) fluctuated with small changes except for Ural, whereas the social development index (SDI) increased continuously. The three major socioeconomic crises during the study period (i.e., the 1992 'shock', the 1998 default, and the 2008 global financial crisis) appeared to have a major influence on Russia's economy. Temporal changes in the regional RSI and its three components, particularly the ECI, confirmed their influences (figure 4). Russia transitioned from the central planning system to the market economy during 1991–1998 and the region witnessed a dramatic decrease in RSI and ECI from 1993 to 1998. The Russian government and Russian Central Bank devalued the ruble and defaulted on its debt in 1998. As a result, Russia's economy bounced back from 1998 on and continued to grow until 2008. The red line in figure 4 around 2009 indicates a recovery that started in late 2009 after Russia was influenced by the global financial crisis in 2008.

Spatial distributions of all indexes showed large variations at the FS level (figure 5). With the exception of Tuva (Siberia FD), all FSs experienced a positive change in RSI from 1990 to 2014. For ECI, Siberia and Far East experienced an overall decrease from 1990 to 2014 while Ural experienced an increase. At the FS level, all FSs within Ural except Kurgan experienced an increase in ECI. Except Novosibirsk, Krasnoyarsk, Khabarovsk, Magadan, and Sakhalin, all FDs in Siberia and Far East experienced a decrease in ECI from 1990 to 2014. All FDs and subjects exhibited a positive change in their SDIs from 1990 to 2014. For the EVI, only six out of 25 FSs (i.e., Altai Republic, Kemerovo, and Tomsk in Siberia and Sakha, Amur, and Jewish Autonomous Oblast in Far East) experienced declines from 1990 to 2014.

3.3. Coupled relationship between urbanization and sustainability

ECO affected urbanization, social development, and environmental degradation directly with path coefficient values (PCV) (i.e., standardized linear regression weights) of 0.33, 0.28, and 0.22, respectively. Economic development had a stronger influence on urbanization ($PCV = 0.33$) than social development (PCV of 0.28) or environmental degradation ($PCV = 0.22$). Urbanization exerted a stronger influence than economic development on environment degradation and social development. Urbanization had higher PCVs of 0.51 and 0.38 in relation to environmental degradation and social development, respectively, whereas economic development had PCVs of 0.22 and 0.28 (figure 6). Urbanization also affected environmental degradation ($PCV = 0.51$) more than social development ($PCV = 0.38$).

4. Discussion

Asian Russia underwent a drastic socioeconomic change after the collapse of the Soviet Union, reflected by the reverse trends of population dynamics and economic development of the region and the further

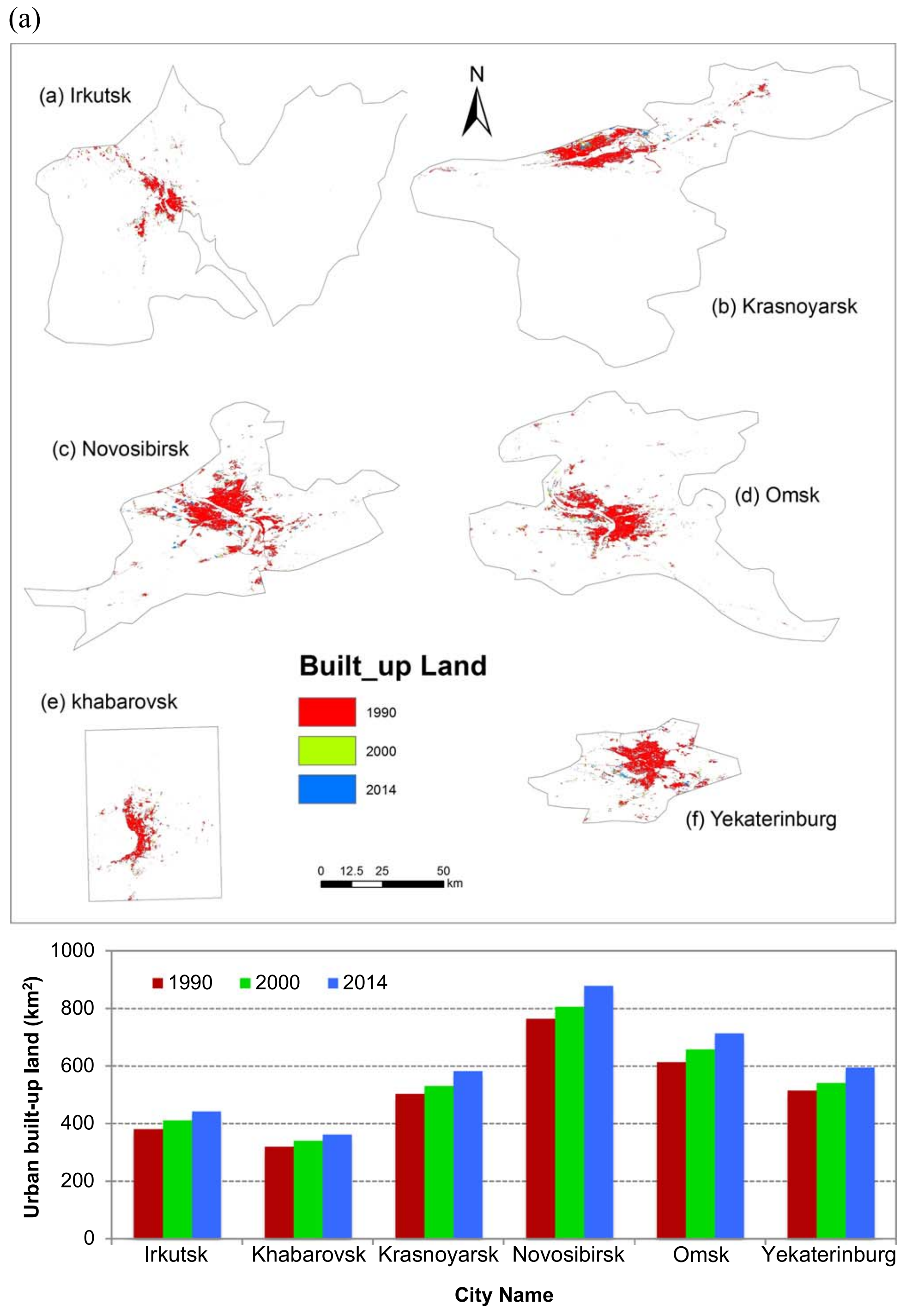

Figure 3. Changes in urban built-up areas (a) and population (b) of Yekaterinburg, Irkutsk, Krasnoyarsk, Khabarovsk, Novosibirsk, Omsk, and Khabarovsk.

enhanced role of large cities, illustrated by their increasing populations and urban built-up land. Despite the generally declining population of Asian Russia, the region has experienced enhanced economic growth as indicated by nighttime light brightness. In particular, the six focal cities experienced a reverse trend of the increased population and expansion of built-up area. These findings imply two parallel processes: (1) the rise of economic growth against the overall decline of the population of the region, and (2) population growth and urban sprawl of large cities to accommodate retail, warehouses, and new economic activities as well as rural–urban migrants. Current literature, however, provides different views on whether or not large cities grow faster than small cities, because the growth of the city depends on various factors, including the trade-off between economies of scale and congestion, which increase as cities grow (Batty 2008). For example, Glaser (2000) argued that large cities grow at a similar rate as small cities. In

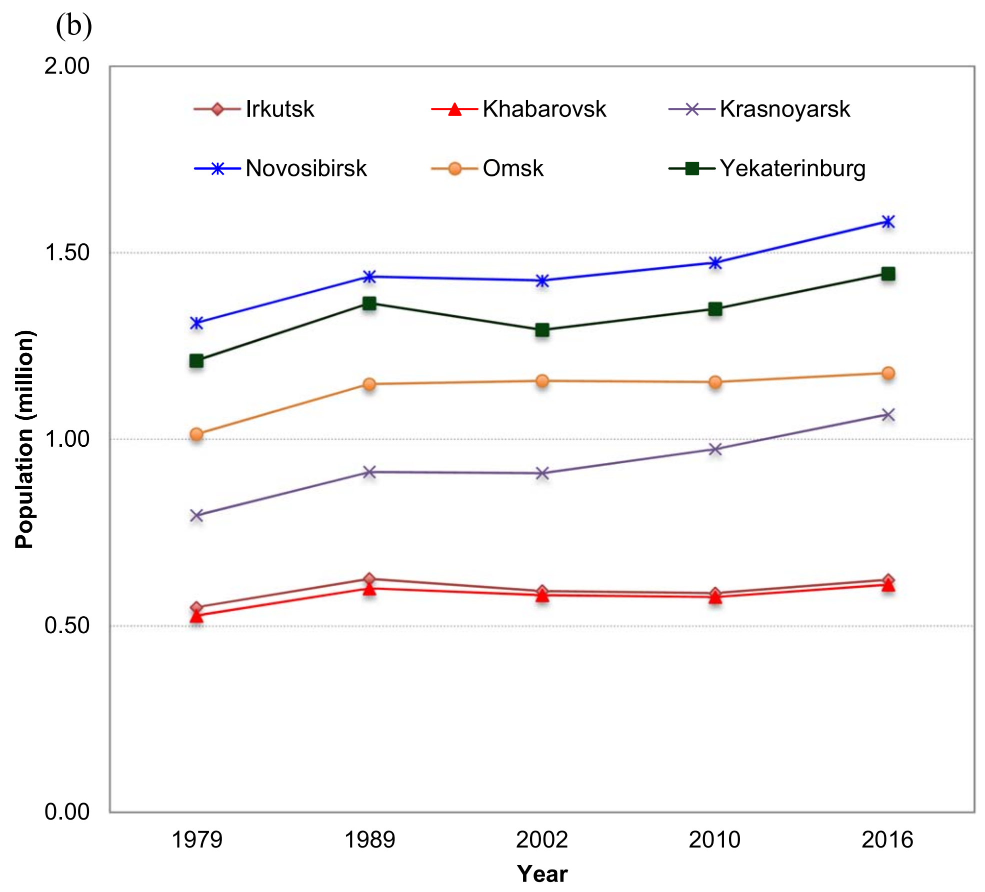

Figure 3. (Continued.)

contrast, Xu and Zhu (2009) found that smaller cities grew faster than large cities in 1990s in China. However, Henderson (2003) pointed out that the urbanization process was much more complicated than initially thought by Glaser (2000). While major cities may not be good representatives of the region, our results indicate the resilience of major cities even during a down time for Asian Russia. We remain unsure about the specific driving forces and mechanisms for this phenomenon, although we believe that large cities may provide better economic prospects and social development (i.e., high resilience) in both prosperous and difficult times (Becker *et al* 2014). In addition, globalization may have augmented the hierarchical structure of cities (Sassen 2013) and exerted more positive impacts on large cities than smaller cities and rural areas of the region.

The trend in regional economies underlines the dramatic impact of domestic institutional change and the global economy, as illustrated by the dynamics of the components of the sustainability index at the federal district level. As presented in section 3.2, three major socioeconomic crises in 1992, 1998, and 2008 had major negative influences on the regional economy, especially the 1992 'shock' and the global financial crisis in 2008 that appeared to cause a prolonged decline of the economy. From a temporal perspective, the declining ECI also reflected a decade of stagnancy and economic hardship after the collapse of the Soviet Union in the 1990s (figure 4), but its overall increase in the 2000s (although some FSs experienced some decline after 2012) revealed that the economy grew remarkably, likely due to the higher domestic demand, greater political stability, and continuous increase in the price of oil until the dramatic drop in prices of oil and gas in 2008 (figure 6). We consider that the bounce-back of the ECI in 2011 may be due to the joining of the World Trade Organization in December 2011 (figure 6). The ECI appeared to exhibit more volatile patterns and thus could lead to a similar change in RSI, whereas the EVI and SDI continuously improved.

The overall increase in the EVI and SDI, especially after 2002, indicates that the region's sustainability on environment conditions and social development did not suffer much despite the economic hardship. This finding may be contradictory to the findings of some researchers who found a decline in social development as indicated by social welfare of some regions of East Siberia (Bezrukov and Bonadysenko 2010). While our findings may be limited due to the selection of variables representing the environmental conditions and social development, we consider that our indicators provide meaningful insights into the sustainability of the region from a different perspective.

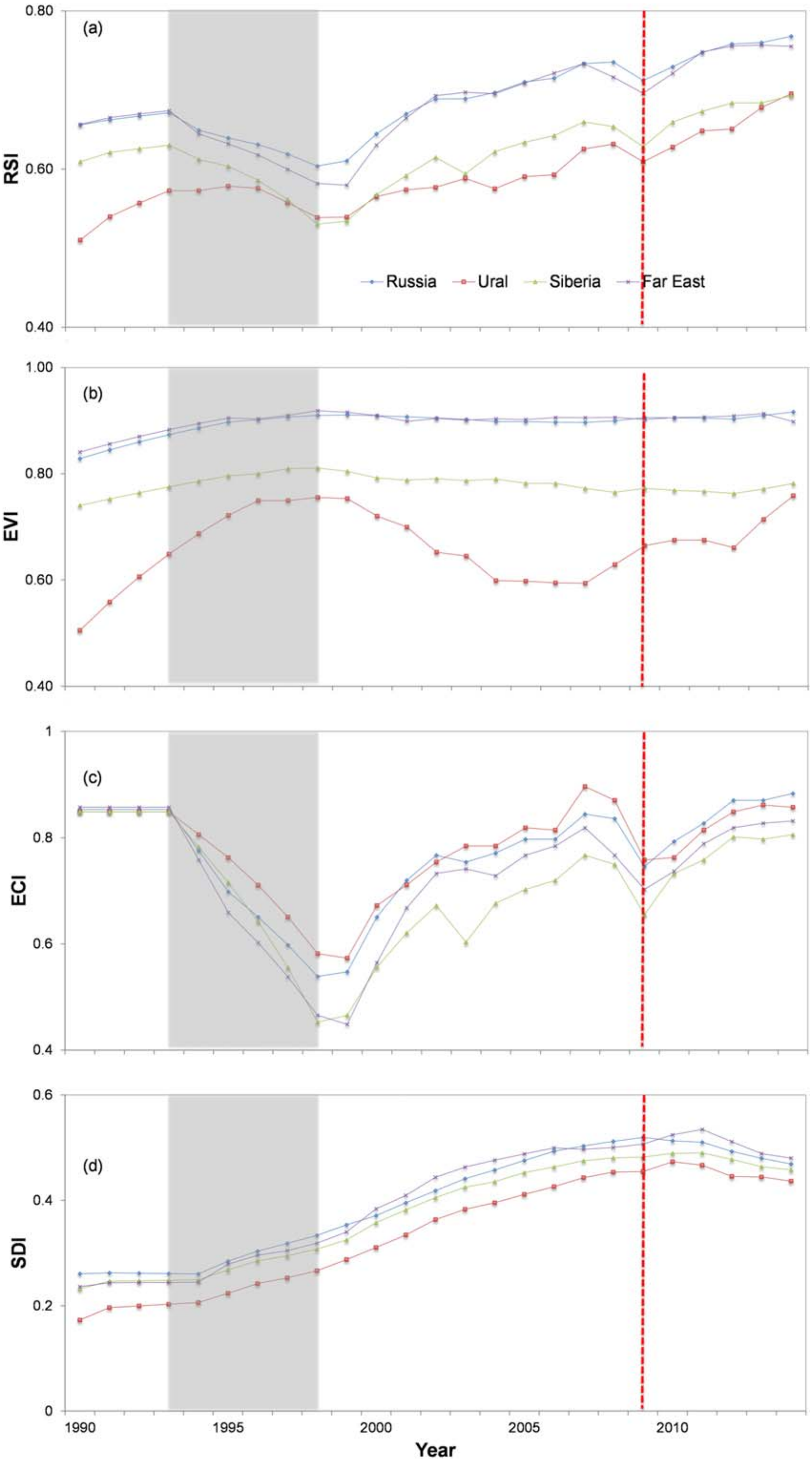

Figure 4. Dynamics of RSI and its three components: ECI, EVI, and SDI. These changes in Asian Russia are illustrated by the influences of three major socioeconomic crises during the period of: the 1992 'shock', the 1998 default, and the 2008 global financial crisis. The shaded area from 1993 to 1998 reflects the dramatic decrease of RSI and ECI corresponding to the shock therapy in 1992 and the default in 1998 in Russia. The red line in 2009 represents the strong economic recovery that started in late 2009 after a decline in the economy when Russia was affected by the global financial crisis in 2008.

The SEM results illustrated that urbanization and sustainability evolved as coupled relationships for Asian Russia. In particular, ECO affected urbanization, social development, and environmental degradation, which further emphasized the economy as the main driver for urban growth and other components of sustainability. Nevertheless, the fact that urbanization exerted a stronger influence than economic development on environment degradation and social development implies that urban population growth may have exerted a large pressure for the urban environment, thus causing environmental degradation. However, urban population

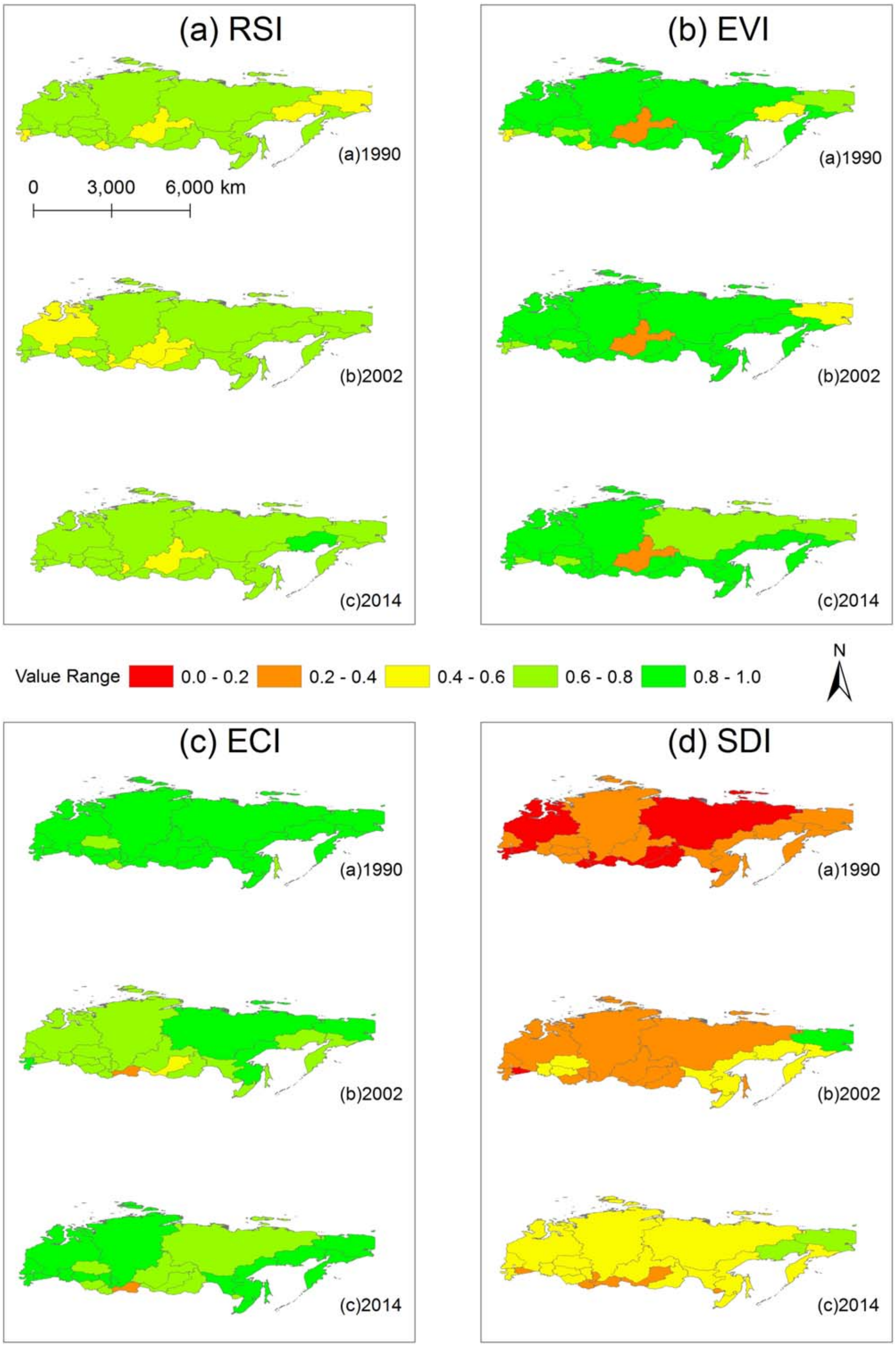

Figure 5. Spatial distribution of RSI and its three components: ECI, EVI, and SDI. Note: in the official statistics, many socioeconomic variables (e.g., population) of Tyumen include FS of Khanty-Mansiy and Yamal-Nenets. Therefore, for RSI, ECS, EVI, and SDI, Tyumen's value represents the values of these three FSs.

growth may also have actually boosted social welfare provision, as cities may gather more necessary resources from the increased population.

While we provide useful insights on urbanization and sustainability of Asian Russia, there is further research that can be conducted to explore the influence of other major drivers, i.e., natural external drivers such as global climate change, and socio-economic drivers such as globalization and regional geopolitics, for urbanization and sustainability of Asian Russia. Broadly speaking, Asian Russia is trending toward a warmer and wetter climate, with many of these trends having been statistically significant over the period of 1950–2010. In response to these changes,

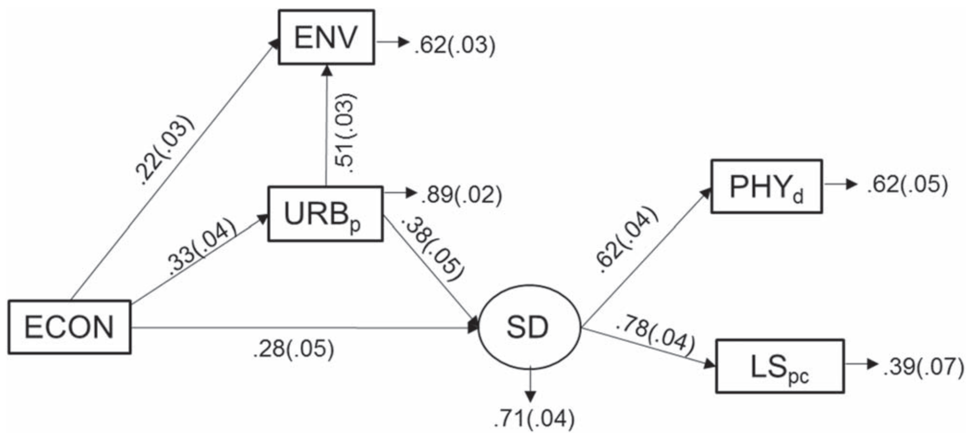

Figure 6. SEM results for Asian Russia during 1990–2014. The latent variables are labeled in the circles and the measured variables are labeled in the squares. The path coefficients describing the relationships between variables are located on the path and their standard errors are shown in parentheses. Only significant relationships are shown on the SEM diagram and all path coefficients are standardized. ECON, ENV, SD, and URB_p stand for economic development, environmental degradation, and social development, and urbanization, respectively. Other abbreviations in the figure are: PHY_d for physician density, i.e., number of physicians per 10 000 people and LS_{pc} for living space per capita (m^2).

there is evidence of earlier spring phenology, later autumn senescence, and community level changes in vegetation (Ovaskainen *et al* 2017). Typical Siberian crops could be grown as far as 500 km further north by the end of the century (Tchebakova *et al* 2011) and there could be a similar expansion of the boreal forest (Tchebakova *et al* 2016). Potentially, these changes could significantly increase agricultural productivity across the region, boosting economic development of the nearby cities and thus attracting a larger population to the region, including the cities. However, some significant negative consequences could arise at the same time, including methane venting from permafrost melting and the disappearance of arctic lakes and alterations of food webs, such as that of Lake Baikal (Hampton *et al* 2008). It remains to be evaluated how these changes as a result of climate may affect economic development and urbanization.

Globalization and regional geopolitics, including foreign direct investment, imports and exports, foreign sanctions, migrations from the former USSR countries, and foreign tourists, can all exert significant impacts on urbanization and sustainability. As discussed, the ECI of each FS reflected the overall trend of national economic development of Russia. Global influence could also have additional influence on regional economic development. For example, Asian Russia includes several leading regions in Russia in terms of the scale of activities of organizations with foreign capital, such as Sverdlovsk, Tyumen, and Chelyabinsk in Ural, Krasnoyarsk in Siberia, Sakhalin in the Far East, measured by number of employed, turnover, and the average three-year volume of fixed capital investments in 2013 (Kuznetsova 2016). Along with the FSs of Moscow and St. Petersburg, Sverdlovsk and Krasnoyarsk are two of the top four Russian FSs that are included in the top ten for all three indicators. Factors such as territory proximity and cultural and historic linkages may have played a significant role in determining each FS's attractiveness for foreign capital of a certain country (Kuznetsova 2016). For example, China's investment has been particularly significant in Asian Russia, accounting for 31% and 32% of the foreign capital in Siberia and Far East, respectively, in 2013 (Kuznetsova 2016). The influence of global investments may be particularly apparent in large cities of the region as cities, especially large cities, serve as important nodes of networks for flows of global capital (Castells 2000). Furthermore, the region has unique natural and cultural assets such as Lake Baikal, the Altai Mountains, valleys and volcanoes in Kamchatka, and cities along the Trans-Siberian Express Railway, that can be of particular interest to foreign tourists. In fact, the Russian authority announced in 2017 that to revive the regional economy through attracting global investment and tourism, free e-visas for fewer than eight days will be issued to visitors from 18 countries who head to the Primorye, Khabarovsk, Sakhalin, Chukotka and Kamchatka regions in Far East. This new rule was expected to increase international tourism by 30% (Russian Times 2017).

5. Conclusions

We examined the spatiotemporal changes of and the interrelationships between urbanization and sustainable societal development of Asian Russia after the collapse of the former Soviet Union. Three major findings are: (1) despite its population decline, Asian Russia experienced an increase in economic activity as reflected by increased nighttime light brightness and most case cities of the region we selected experienced population increases and expansion of urban built-up areas. (2) Asian Russia and its three sub-regions (federal districts) have improved their sustainability and its three major components: economic development, environmental conditions, and social development. While regional sustainability and economic development declined substantially in the 1990s, levels of environmental conditions and social development continuously increased from 1990 to 2014, especially social development after 1995. (3) Economic development was an important driver of urbanization, social development and environmental degradation in Asian Russia, with economic development having a stronger influence on urbanization than on social development or environmental degradation. Nevertheless, urbanization exerted more direct influence than economic development on environmental degradation and social development in Asian Russia. Urbanization also affected environment degradation more than social development.

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Appendix A. Key literature on Asian Russia relating to urbanization and sustainability

There are only a few key literatures on urbanization and sustainability in Asian Russia, providing us a brief background of urbanization, population dynamics, and land transitions in the region, particularly during the transitional economy. Through a comprehensive review on urbanization and urban growth patterns in Russia from 1897 through 2010, Becker *et al* (2014) underlined a significant shift in population within the region following the transition from central planning to the market economy, as people moved away from the far north and east to the south and west: 'from industrial cities with few amenities, towards larger cities and emerging service centers' (pp 100). Historical changes in land use in Asian Russia from the 12th century to 2017 were described by Prishchepov *et al* (2018). Similarly, they highlighted the rapid response of agricultural land use to the major socio-political disruption brought on by the dissolution of the Soviet Union in 1991. Focusing on the transitional period and based on data derived from satellite images of nighttime light from 1992 to 2014, Fan *et al* (2017b) found that urban land with active economic activity in Siberia decreased in the 1990s and then increased in the 2000s. Despite the useful background information provided by the above-mentioned studies, we know very little about urban dynamics and the linkages with different dimensions of sustainability for Asian Russia.

In addition, some studies have focused on the regional economy, such as the level of economic development of the region and sub-regions and possible drivers. For example, using ten indicators, Slepneva *et al* (2016) assessed the level of socioeconomic development of regions in Russia and identified the regions of Krasnoyarsk and Omsk as having high levels of socioeconomic development within the Siberia Federal District in 2013. Furthermore, inequality of income distribution has been found to have a significant impact on Russia's regional economic growth from 2006 to 2010 (Grigor'ev 2009). In addition, the regional economy has been found affected by globalization, both in the past and in near future. For example, foreign investments from China had been found significant in the Asian Russia based on data from 1999 to 2013 (Kuznetsova 2016). After estimating the spatial structure of the economies of Siberia under two different hypothetical scenarios: the entry of Russia into the ranks of developed countries, and a scenario that relies on the potential for self-development of the regions, it was emphasized that the future of Siberia will be determined by how well it is integrated into international economic development (Suspitsyn 2012).

Other studies have focused on non-economic aspect of development by examining the overall quality of life within the regions, and how they have been affected by various natural and socioeconomic shocks (Yaremenko 2005, Rimashevaskava 2010, Bashalkhanova *et al* 2012). For example, from 1990 to 2009, the quality of life in municipal districts of East Siberia declined under conditions of extreme climate severity (coldness) and inadequate infrastructure for transport and services, with a correlation between the low subsistence level of the northern territories and an

Table A1. Cities with more than 100 000 inhabitants in Asian Russia. *Source: Thomas Brinkhoff. 2017. City Population. Available at* http://citypopulation.de.

Name	Native	Adm.	Population	Population	Population	Population	Population
			Census	Census	Census	Census	Estimate
Date of population estimate			1/17/79	1/12/89	10/9/02	10/14/10	1/1/16
Čeljabinsk [Chelyabinsk]	Челябинск	URA	1029 522	1141 777	1104 648	1130 132	1191 994
Jekaterinburg (Sverdlovsk) [Yekaterinburg]	Екатеринбург	URA	1211 172	1364 621	1293 537	1349 772	1444 439
Kamensk-Ural'skij [Kamensk-Uralsky]	Каменск-Уральский	URA	187 401	207 780	186 153	174 689	170 221
Kopejsk [Kopeysk]	Копейск	URA	—	—	140 876	137 601	146 146
Kurgan	Курган	URA	309 863	355 517	345 515	333 606	325 189
Magnitogorsk	Магнитогорск	URA	406 074	440 321	418 545	407 775	417 563
Miass	Миасс	URA	150 179	167 839	158 420	151 751	151 387
Neftejugansk [Nefteyugansk]	Нефтеюганск	URA	52 393	93 930	107 830	122 855	125 368
Nižnevartovsk [Nizhnevartovsk]	Нижневартовск	URA	108 740	241 457	239 044	251 694	270 846
Nižnij Tagil [Nizhny Tagil]	Нижний Тагил	URA	398 146	439 521	390 498	361 811	356 288
Nojabr'sk [Noyabrsk]	Ноябрьск	URA	—	—	102 949	110 620	106 631
Novyj Urengoj [Novy Urengoy]	Новый Уренгой	URA	—	—	104 269	104 107	111 163
Pervoural'sk [Pervouralsk]	Первоуральск	URA	129 189	142 193	132 277	124 528	124 981
Surgut	Сургут	URA	107 343	247 823	285 027	306 675	348 643
Tjumen' [Tyumen]	Тюмень	URA	358 992	476 869	510 719	581 907	720 575
Zlatoust	Златоуст	URA	197 760	207 794	194 551	174 962	169 057
Abakan	Абакан	SIB	128 311	154 092	165 197	165 214	179 163
Ačinsk [Achinsk]	Ачинск	SIB	116 854	121 572	118 744	109 155	105 364
Angarsk	Ангарск	SIB	238 802	265 835	251 176	233 567	226 776
Barnaul	Барнаул	SIB	533 263	601 811	600 749	612 401	635 585
Berdsk	Бердск	SIB	67 336	79 252	88 445	97 296	102 808
Bijsk [Biysk]	Бийск	SIB	211 567	233 238	232 932	210 115	203 826
Bratsk	Братск	SIB	213 725	255 705	259 335	246 319	234 147
Čita [Chita]	Чита	SIB	302 577	365 754	316 643	324 444	343 511
Irkutsk	Иркутск	SIB	549 787	626 135	593 604	587 891	623 424
Kemerovo	Кемерово	SIB	470 640	520 263	529 934	532 981	553 076
Krasnojarsk [Krasnoyarsk]	Красноярск	SIB	796 305	912 629	909 341	973 826	1066 934
Kyzyl	Кызыл	SIB	66 027	84 641	104 105	109 918	115 871
Noril'sk [Norilsk]	Норильск	SIB	—	—	—	175 365	177 428
Novokuzneck [Novokuznetsk]	Новокузнецк	SIB	541 356	599 947	565 680	547 904	551 253
Novosibirsk	Новосибирск	SIB	1312 480	1436 516	1425 508	1473 754	1584 138
Omsk	Омск	SIB	1014 246	1148 418	1156 849	1154 116	1178 079
Prokopjevsk [Prokopyevsk]	Прокопьевск	SIB	266 167	273 838	224 597	210 130	198 438
Rubcovsk [Rubtsovsk]	Рубцовск	SIB	157 082	171 792	163 063	147 002	146 386
Seversk (Tomsk-7)	Северск	SIB	—	—	109 106	108 590	108 134
Tomsk	Томск	SIB	420 730	501 963	487 838	524 669	569 293
Ulan-Udè	Улан-Удэ	SIB	300 370	352 530	359 391	404 426	430 550
Artëm [Artyom]	Артём	DAL	—	—	—	102 603	105 338
Blagoveščensk [Blagoveshchensk]	Благовещенск	DAL	171 997	205 553	219 221	214 390	224 335
Chabarovsk [Khabarovsk]	Хабаровск	DAL	527 848	600 623	583 072	577 441	611 160
Jakutsk [Yakutsk]	Якутск	DAL	152 368	186 626	210 642	269 601	303 836
Južno-Sachalinsk [Yuzhno-Sakhalinsk]	Южно-Сахалинск	DAL	139 861	159 299	175 085	181 728	193 669
Komsomol'sk-na-Amure [Komsomolsk-on-Amur]	Комсомольск-на-Амуре	DAL	263 950	315 325	281 035	263 906	251 283
Nachodka [Nakhodka]	Находка	DAL	133 201	160 056	178 813	159 719	153 581
Petropavlovsk-Kamčatskij [Petropavlovsk-Kamchatsky]	Петропавловск-Камчатский	DAL	214 977	268 747	198 028	179 780	180 963
Ussurijsk [Ussuriysk]	Уссурийск	DAL	146 782	158 016	157 759	158 004	168 598
Vladivostok	Владивосток	DAL	549 789	633 838	594 701	592 034	606 653

Table A2. List of DMSP/OLS data used in this study and the coefficients for the inter-calibration applied to the digital values in the time series. F12-1999 was used as the reference and the data from all other satellite years were adjusted to match the F12-1999 data range. The form of the calculation is: $Y = C_0 + C_1{}^*X + C_2{}^*X_2$, where *Y* is the DN of a satellite year that needs calibration and *X* is the F12-1999 DN. See details from Elvidge *et al* (2013).

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

increase in the ratio of mortality/birthrate indices (Bezrukov and Bonadysenko 2010).

Appendix B. Data and sources

B.1. Mapping economic activity through nighttime light data

We used the DMSP/OLS NTL data to map economic activity because of the strong correlation between DMSP/OLS NTL and economic activity (Elvidge *et al* 1997, Doll *et al* 2006), which means that the NTL brightness is indicative of economic status and activity. We used the DMSP/OLS annual composite time series from 1992 to 2012. When there were multiple annual DMSP/OLS NTL composites of a year, we chose the one with the largest number of cloud-free observations (table A2). In order to reduce the variations and differences among the sensors, an inter-calibration of NTL data was performed following Elvidge *et al* (2014) (table A2). The original DMSP/OLS NTL was recorded at digital numbers (DN) ranging from 0 to 64. Although our inter-calibration introduces negative values and/or values of >64, it also ensures that the same DN in different images represent similar brightness levels of light illumination. The gas flare data produced by Elvidge *et al* (2009) were used to mask gas flares out. We computed the average NTL brightness (i.e., DN) for all pixels in each federal district and subject for all years during 1992–2012.

B.2. Urban built-up land

We used the GHS built-up grid to estimate urban built-up land of the six case cities because of its wide usage as a data source by the scientific community and its accuracy (Pesaresi *et al* 2015). GHS built-up grid was derived from Landsat images that provide multi-temporal coverage (1975, 1990, 2000, and 2014). Using 3826 sample raster tiles collected from cartography data (which covers an area of 133 909 km^2 and a total built-up area of 4656 km^2), the GHS built-up grid was assessed to have an overall accuracy of 0.899 (Pesaresi *et al* 2015). In this study, we extracted the built-up land distribution within the administrative boundary of each city for 1990, 2000, and 2014. An exception is Khabarovsk, for which we extracted the built-up area within a square polygon that incorporated >95% built-up area because the administrative boundaries of Khabarovsk were too large and not comparable with other cities.

B.3. Socioeconomic, demographic, and other statistical data

We relied on the official statistics of Russian government for socioeconomic, demographic, and other statistical data due to widely acknowledged reliability and availability. The main data sources came from the Socioeconomic Indicator of Russian Regions and Census data of the Federal State Statistics Service of Russian Federation for 2004–2015. In addition to secondary data source, we conducted field interviews in Yekaterinburg, Novosibirsk, Krasnoyarsk, and Irkutsk in May 2015 to offer additional insights on drivers, patterns, and impacts and urbanization and sustainability. In each city, we conducted five to six semi-structured interviews of local experts in urbanization, economic development, urban environment, or scholars with relevant expertize. We developed an interview guide for the semi-structured interviews: a list of questions and topics that needed to be covered. The interviewees followed the guidelines, but they were encouraged to expand the discussion during the interviews when appropriate. Each interview lasted 1–2 h, during which time we asked the local experts 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.

Appendix C. Methods

C.1. Development of RSI

Sustainable development can be measured by a variety of sustainability indexes, with some well-known ones such as the Living Planet Index developed by the World Wildlife Foundation, the City Development Index by United Nations Centers for Human Settlements (HABITAT), and the Human Development Index (HDI) by the United Nations Development

Program (Wackernagel *et al* 1999, Böhringer and Jochem 2007). Most of these indexes take into account the three main dimensions of sustainable development: economic development, environment quality, and social wellbeing of a country or region, European countries (Distaso 2007), a city (e.g., Seattle—AtKisson 1996; major cities in China—Fan and Qi 2010, Taipei—Lee and Huang 2007). To evaluate sustainability for all 27 federal subjects in the three federal districts of the Russian Federation (six in Ural, 12 in Siberia, and nine in the Far East), we constructed a RSI by incorporating conditions of economic development (i.e., employment rate), environmental condition (i.e., air pollution), and social wellbeing in regard to housing (i.e., living space per capita) and health services (i.e., number of physicians available per 10 000 people). While more variables can be added toward a more comprehensive evaluation, it is difficult to obtain data for long time periods and for a large number of localities, thus making comparisons across time and space impossible. Based on our literature review, we selected the above four variables that are available for all federal subjects in Russia to construct our RSI. We used a methodology similar to that of the HDI, wherein the index/sub-index is a sum of equally weighed sub-components. This combines normalized measures so that the values of the index or sub-indexes fall between 0 and 1.

First, the RSI is defined as a sum of three equally weighed components:

- Economic index (ECI): determined by the employment rate as an indicator of economic development and standard of living,
- Environment index (EVI): environmental condition of a region, defined as one minus an indicator of air pollutants per capita from the stationary sources,
- Social development index (SDI): social development, determined by health and housing conditions with variables set as number of physicians per 10 000 people and living space per capita (m^2), equally weighed

$$\mathrm{ECI} = \mathrm{EMPI}, \tag{1}$$

$$\mathrm{EVI} = 1 - \mathrm{API}_{pc}, \tag{2}$$

$$\mathrm{SDI} = \frac{1}{2}\mathrm{PHYI}_d + \frac{1}{2}\mathrm{LSI}_{pc}, \tag{3}$$

$$\mathrm{RSI} = \frac{1}{3}\mathrm{ECI} + \frac{1}{3}\mathrm{EVI} + \frac{1}{3}\mathrm{SDI}, \tag{4}$$

where

EMP: Employment rate (%)

AP_{pc}: Air pollutants per capita from the stationary sources

PHY_d: Physician density, i.e., number of physicians per 10 000 people

LS_{pc}: Living space per capita (m^2)

These variables (EMP, AP_{pc}, PHY_d, and LS_{pc}) were normalized into unit-free variables *XI*, i.e., EMPI, API_{pc}, PHYI_d, and LSI_{pc}, so that their respective values would be between 0 and 1, using the following formula:

$$XI = \frac{X - \min(X)}{\max(X) - \min(X)}, \tag{5}$$

where $\min(X)$ and $\max(X)$ are the minimum and maximum values of variable *X*, respectively.

C.2. Structural equation modeling (SEM)

SEM is a statistical method to analyze multiple relationships among variables (Grace 2006). Because of its capacity to include both observable and unobservable variables that represent underlying relationships in the model, it has been widely used in various disciplines such as science, business, and education (Hair *et al* 2014, Fan *et al* 2016). The SEM model in this paper reflects the relationship between urbanization, economic development, environmental degradation, and social development. Our underlying hypothesis is that economic development affects urbanization and social development positively, i.e., urbanization will lead to the improvement of social development (Davis 1965, Ranis *et al* 2000, Deaton 2008) but will also lead to environment degradation (Dinda 2004, Stern *et al* 1996). The SEM has the following structure: economic development is a potential driver affecting urbanization, environmental degradation, and social development, whereas urbanization also exerts its influence on environmental degradation and social development. All the variables used in the SEM were also used in the calculation of RSI and its three subcomponents. In our SEM, ECO and urbanization (Urb) were directly modeled by the observable variables of employment rate and the ratio of urban population to the total population (Davis 1965, Henderson 2003). ENV was directly modeled by an observable variable of air pollutants per capita from the stationary sources (Seldon and Song 1994, Carson *et al* 1997). Social development was modeled as a latent variable SD by the number of physicians per 10 000 people (PHY_d) and living space per capita (LS_{pc}). Education, health care, and quality of life have been recognized as the main areas of social development (Atkinson 1996). Due to data limitations, we chose two indicators to represent health care provision and quality of life, illustrated by the number of physicians per 10 000 people and living space per capita, which have been used frequently by other researchers as indicators of social development (e.g., Wu 2002, Macinko *et al* 2003, Chan *et al* 2002, Park *et al* 2017).

We fit the model with all data during 1992–2014 in Mplus (version 8.11)—computer software designed for SEM. The default maximum likelihood estimator was used for estimating model coefficients, while robust standard errors for these coefficients were computed using the sandwich estimator known as the Taylor expansion of Huber–White (Muthen and Satorra 1995). To test model fit, we used the comparative fit index (CFI), the Tucker–Lewis index (TLI), and root mean square error (RMSE). CFI and TLI measure the improved fitness of a target model relative to the null model (a model in which the variables are assumed to be uncorrelated), while RMSE measures the actual differences between corresponding elements of the observed and predicted covariance matrix. We did not adopt a X^2 test because it is sensitive to sample size (Gerbing and Anderson 1992). Values of CFI and TLI larger than 0.97 and 0.95 were regarded as acceptable fit, respectively (Gerbing and Anderson 1992, Schermelleh-Engel *et al* 2003). RMSE between 0.05 and 0.08 further suggested a good model (Cangur and Ercan 2015). Our model was tested to have CFI of 0.99, TLI of 0.97, and RMSE of 0.06, indicating satisfactory model fitness.

ORCID iDs

Peilei Fan https://orcid.org/0000-0003-4448-4281
Pavel Groisman https://orcid.org/0000-0001-6255-324X
Alexander V Prishchepov https://orcid.org/0000-0003-2375-1651
Soe W Myint https://orcid.org/0000-0001-7809-1211
Jiaguo Qi https://orcid.org/0000-0002-8183-0297

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