Knowledge Geography for Measuring the Divergence in Intellectual Capital of Russia

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Abstract: Knowledge is becoming a paramount resource of innovation economies. The efficient management of generation, use, accumulation and transfer of knowledge within a non-linear innovation process plays a critical role in economic growth. Knowledge geography registers the uneven landscape of the national innovation system and captures the key excellence clusters at different hierarchical levels – from local nodes to cities and regions. While the spatial patterns of knowledge commercialization are primarily considered via production processes at the regional level (regional innovation systems, regional innovation clusters), knowledge generation has to be monitored and assessed at the level of cities. Urban settlements accommodate communities of people and a population of firms that form unique configurations of innovation ecosystems that sculpture the intellectual capital of regions and states. This paper presents the distribution of knowledge-generating centres in Russia by undertaking an in-depth evaluation of bibliometric data for 440 settlements across the country for a period of 2013-2017. Methods of spatial scientometrics enable to register the intellectual capital accumulated in a certain locality and analyse development trajectories of urban settlements. Russia is an interesting case of studying the spatial patterns of knowledge generation. The large territorial extent of the country, the remoteness of individual cities from each other, their heterogeneity in size, level of development, and knowledge specialization makes it a highly diverse context. Research results suggest that knowledge domain characteristics are formed irrespective of the population figures, whereas the development dynamics of small and medium-sized cities are specific. Smaller cities strive to be integrated into inter-regional and international collaboration in order to overcome the shortage of local resources. A limited gross volume of research output generated by small and medium-sized cities creates extreme indicator values as compared to the major cities and the national average. The study concludes with a typology of cities taking into account the specific features of knowledge generation dynamics.

Keywords: knowledge geography, innovation geography, spatial scientometrics, regional innovation system, knowledge management, intellectual capital, Russia

1. Introduction

Spatial patterns in knowledge distribution is a prominent topic within a new dimension of human geography discipline – the knowledge geography. Despite being often defined as elusive, tacit and impalpable, knowledge has a clear impact on framing the intellectual capital of territories and their development trajectories (Balland et al., 2013; Crescenzi et al., 2012; Doloreux and Shearmur, 2012; Howells, 2012). Knowledge continuously found to be the major source of regional competitiveness and growth (Navarro et al., 2015). By concentrating in cities, the knowledge-intensive, high-technology and innovative institutions form a new competitive realm, a knowledge-driven ecosystem.

Considering the density and the diversity of stakeholders, cities are seen as knowledge hubs (OECD 2011) offering an inventive-enabling environment that attracts talents, entrepreneurs, and capital (Edvardsson et al., 2016; Goffe, 2016; Yigitcanlar et al., 2015; Penco et al., 2020). However, not all cities have transformed into innovative milieus, creative spaces, and innovation ecosystems (Oksanen and Hautamäki, 2014; Romano et al., 2014; Ölschläger, 2012). Scholars register the uneven distribution of intellectual capital within and between regions (Ilic et al., 2016; Krušinskas and Bruneckienė, 2015; Maltseva et al., 2019). Deviation from national or global values by a set of key performance indicators perceived as a threat to national innovation security and an impetus to drastic action for levelling out the discrepancies. However, the overall quality increase should not disregard local specificity. Recent findings on what is lately titled as knowledge or innovation geography argue for focusing on strengthen the strength perspective by considering the predisposition of the locus, i.e. the territorial capital (Camagni, 2017; Cojanu and Robu, 2019).

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National innovation systems constitute of a complex set of innovative milieus – locations that exhibit a variety of advanced capabilities, skills, ideas, practices, resources, etc. embedded in locations. We advocate that knowledge landscape need not and should not be even nor equal. The knowledge diversity is mutually reinforcing, creating a holistic mosaic of competences in an innovation system. Innovative development implies disruption as opposed to path-dependency, thus, it is not something to be made uniform or standardized. Knowledge hubs are not to be replicated, but rather combined in a complex of multiple knowledge constellations based on interdependence and complementarity. Therefore, managing the diversity of knowledge in a sense of matchmaking and offering place-adaptive policies is a challenging and a prominent issue of the knowledge-based economy.

The article studies the diversity of capabilities in knowledge generation domain accumulated by cities across Russia – the rapidly changing but highly divergent country. The spatial scientometric techniques enable to identify the territorial distribution of intellectual capital using a multidimensional set of indicators covering the aspects of productivity, quality, demand, impact, networking, and internationalization. The hypothesis to be tested is that knowledge geography is more complex than a straightforward delimitation of cities by size. The study is expected to provide a typology of cities that would capture the patterns of knowledge generation dynamics. Results will increase the efficiency of knowledge management initiatives by acknowledging the heterogeneity of local innovation systems.

2. Literature review

The spatial perspective over studying innovation processes is traditionally set at the regional level, where production and technological value chains are registered. However, this approach is increasingly criticized due to the excessive focus on the stages of commercialization, which are evaluated using output indicators of innovative products, patenting, and the costs of creating innovations, while neglecting the preceding stages, including knowledge generation (Garud et al., 2013; Van de Ven, 1999; 2017). Long pre-market preparation drops out of most studies, including interaction on knowledge co-creation, creative problem solving, testing, prototyping, etc. These important activities left undefined within the framework of existing innovation statistics (Tanner, 2018). Early studies on the patterns in the distribution of scientific activity date back to the 1970s. However, the development of information technologies and the creation of scientometric and bibliometric databases became the defining impetus for the emergence of studies on spatial analysis of the generation, accumulation and transfer of knowledge (Frenken and Hoekman, 2014; Maisonobe et al., 2016; van Noorden, 2010).

First scientometric studies focused on comparative analysis at the level of countries and regions by individual indicators (Aksnes et al., 2014). Research on cities was less common due to high complexity and labour intensity of collecting, processing and analysing data. At the same time, cities as urban centres of the scientific space are of increasing interest for studying the specifics of the formation of intellectual capital and its management for concentrating a critical mass of organizations involved in the process of creating and disseminating knowledge (Blakely and Hu, 2019). Research in the field of geospatial assessment of the scientific output of cities began to appear in the late 1990s. The growing prominence of these studies is due to a number of factors. Firstly, cities, including small and medium-sized, play a leading role in technology development and knowledge creation (Börsch, 2019). Secondly, the increasing role of cities is associated with the growth of urban agglomerations and increased functional subordination of the central and adjacent territories, which led to the unification of their intellectual and territorial capital (Lamorgese and Petrella, 2019). Thirdly, according to the latest research results (Zhang and Wu, 2019), cities are increasingly seen as platforms for the exchange of knowledge due to the growing importance of not only the diversity of participants, but also the environment in which knowledge reproduction and exchange takes place.

To date, the scholarly literature has covered a variety of certain aspects of the distribution and operation of knowledge generation centres related to defining the patterns of publication and citation of articles, the formation of scientific specialization and networks of international research cooperation. Research held by Matthiessen and Schwarz (1999), Van Noorden (2010), Zhou et al., 2009) emphasise on assessing the effectiveness of cities and regions as nodal points of the scientific system using the volume of publications indexed in Scopus, Web of Science Core Collection, in Nature and Science journals. In recent studies, the quantitative approach is supplemented by the qualitative one to identify centres of excellence through citation assessment, including highlighting the proportion of highly cited publications (Andersson et al., 2014;

Bornmann and Leydesdorff, 2011; 2012; Bornmann and Waltman, 2011; Bornmann et al., 2011; Csomós, 2018; Matthiessen and Schwarz, 1999).

Golichenko and Malkova (2017) use the citation index to measure the demand for scientific knowledge generated. Scholars note that the consumption of knowledge codified in a scientific article is determined by the perception of its quality and is reflected in the number of citations. The effectiveness of the local system of knowledge reproduction is an integral characteristic of the cumulative result of publications cited. This approach is consistent with studies by Csomós (2018) and Wuestman et al. (2019), who identified additional factors influencing the publication efficiency of cities from the standpoint of research output quality, and not its volume. The main ones include: geographical location of the knowledge-generating centre and its academic reputation (scientific recognition determines confidence in the results of the studies published); research profile and field of scientific knowledge (medicine and basic sciences are the most cited disciplines); used model of interregional and international cooperation. While only a small part of spatial scientometric studies, for example, focusing on mapping co-authorship networks (Ma et al., 2014; Maisonobe et al., 2016), examine the forms of urban cooperation, the aspect of international research collaboration has been widely considered (Csomós and Tóth, 2016; Gui et al., 2019; Shashnov and Kotsemir, 2018).

According to (Csomós, 2018; Csomós and Lengyel, 2019), the international cooperation of cities is primarily determined by their scientific profile, geographical proximity, historical, cultural and linguistic ties. The analysis of data on joint publications is used to assess the impact of geographical, technological, social and cultural proximity on the diversity of cross-country cooperation in science (Gui et al., 2018). Interesting results are obtained in a study by Wuestman et al. (2019), according to which the decisive factor for citation is the interdependence of knowledge areas, and not their similarity. Moreover, the specialization of the territory in a particular field of knowledge is quite stable over time, which sets long-term scientific ties for cities with complementary scientific profiles (Abramo et al., 2014). Einem (2011) notes that in the modern world no single company, research institute or city is capable of independently generate the knowledge of the highest level in each scientific field without a complete set of all the relevant elements, including implicit knowledge. A similar statement is argued by Cantwell and Zaman (2018), pointing to the importance of both the international and local networks between cities.

Thus, earlier studies suggest that a comprehensive assessment of the spatial distribution of excellence centres and the examination of their ability to generate knowledge should include not only quantitative but also qualitative indicators of scholarly output. The evaluation methodology has to capture the quality, efficiency, prominence of the results of an intellectual activity, as well as outline the ties and integration of the knowledge cities into the national and global knowledge domain.

3. Methodology

Bibliometrics is a relatively new source of data on territorial distribution of intellectual capital. It enables to form comparable data series in a single template for heterogeneous entities – organizations, urban and rural settlements, regions, countries, which is unattainable for general statistics. It further quantifies the new knowledge expressed in articles, books, conference proceedings and other publications. Spatial scientometrics is a new methodological perspective on bibliometric and science related data analytics. It is associated with the projection of best practices and knowledge on a territorial context, giving an idea of the local milieu, network collaboration, specialization, other properties and dynamics.

The initial analysis covered 1118 settlements located in 85 regions of the Russian Federation. The Arkhangelsk and Tyumen regions are evaluated separately from their autonomous districts. Two regions are excluded from the assessment process – the Republic of Crimea and Sevastopol. This is due to the inconsistency of country affiliation indicated in publications metadata, causing interference with data assessment. Thus, the final sample includes cities in 83 regions of Russia, featuring a list of publications for a five-year period (2013-2017) indexed in Scopus, the largest international abstract citation database of scholarly literature.

The choice of this database is due to the following reasons:

- the overall high quality of published documents (database includes only peer-reviewed publications in sources selected by independent board);

- an extensive coverage of publications affiliated with Russia, in comparison with other databases (348 thousand documents are indexed in Scopus versus 296 thousand documents in indexed Web of Science, as of July 30, 2019);
- the availability of advanced search and analytical tools to separate publications by city and obtain generalized indicators;
- the opportunity to highlight scientific results published in high-quality international journals (under 10% of all Russian publications; see: www.elibrary.ru).

The list of publications by city is compiled and subsequently uploaded in April 2019. The Scopus advanced search form used focusing on affiliation city name (field code – AFFILCITY). The list of all Russian cities is available at the Russian Federation Federal State Statistics Service (Rosstat. Doklady "Ob itogakh Vserossiyskoy perepisi naseleniya 2010 goda" [Reports "On the Results of the All-Russian Population Census 2010"]. URL: http://www.gks.ru/free_doc/new_site/perepis2010/croc/perepis_itogi1612.htm [*In Russian*]). Since not all publications contain information about cities (or other settlements), the search is supplemented by profiles of organizations using identification numbers (field code – AF-ID). Each search is configured individually per settlement.

Example of Omsk: *AFFILCOUNTRY (russia*) AND AFFILCITY ("Omsk") OR (AF-ID ("Omsk State Technical University" 60075514) OR AF-ID ("Omskij Gosudarstvennyj Universitet" 60031116) OR AF-ID ("Institute of Hydrocarbons Processing of the Siberian Branch of the RAS" 60103858) OR AF-ID ("Omsk State Medical University" 60069087) OR AF-ID ("Omsk State Transport University" 60104566) OR AF-ID ("Omsk State Pedagogical University" 60015090) OR AF-ID ("P.A. Stolypin Omsk State Agrarian University" 60004961) OR AF-ID ("Siberian State Automobile and Highway University" 60109647) OR AF-ID ("Omsk Scientific Center of the Siberian Branch of the Russian Academy of Sciences" 60112471) OR AF-ID ("Siberian Research Institute of Agriculture" 60110502)) AND (LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013))*

Variation in spellings is taken into account, for example, *Nizhni Novgorod State University OR Lobachevsky State University Of Nizhni Novgorod OR Nizhny Novgorod State University OR Lobachevsky State University Of Nizhny Novgorod OR University Of Nizhny Novgorod OR Lobachevsky State University OR Nizhnii Novgorod State University OR Lobachevskii State University N. I. Lobachevsky OR State University Of Nizhny Novgorod OR Radiophysical Research Institute*. Affiliation is defined for each author, including non-academic organizations, thus, taking into account the diversity of organizations, and not just universities and academic institutes.

After raw data sourcing, the metadata exported to the SciVal analytical tool. Data with missing city or organization information does not exceed 3%. Cities with zero articles are excluded from further analysis. The final sample constitutes of 440 cities from 83 regions. The classification of Lappo (1997) is used to differentiate cities by size: millionaire cities with over 1 million inhabitants, largest cities – 0.5 to 1 million people, large cities – 250-500 thousand people, big cities – 100-250 thousand people, medium-sized cities – 50-100 thousand people, small cities – up to 50 thousand people.
Assessment of knowledge generating capabilities of cities to is done using 6 indicators (Table 1):

- *Overall citation rate* indicates the demand for intellectual activity results published, and the number of users attracted. It also reflects the performance, interest of scientific community in the research results and topic prominence. Self-citations and intra-institutional citations have potential impact. Significant differences in citations found between different subject areas: from minimum in humanities to maximum in physics and medicine.
- *Field-Weighted Citation Impact* (FWCI) reflects the global research impact within a specific field of research. FWCI equals 1.0 means that the amount of contribution made is at the global average level. Studies carried out at the intersection of humanities and natural sciences will naturally outperform the "pure" humanities by FWCI indicator.
- *International collaboration* reflects the integration of local knowledge-generating institutions into international networks, their compliance with international research agenda, the availability of significant competencies that contribute to building international relations, i.e. a competitive knowledge base.
- *National collaboration* reflects the intensity of intra- and inter-regional networking, the role of a 'hub' or a 'spoke' in the framework of the national innovation system.

- *Publications in Top-10% journals* reflects the level of ongoing research, its compliance with high international standards. It is measured by CiteScore indicator, which is calculated as the average number of citations per calendar year for all articles published in this journal over the previous three years.
- *Research productivity* reflects efficiency and the volume of research activities held. This indicator should be considered in relative terms; otherwise, large cities will always outperform small and medium-sized cities. The problem of "predatory journals" can influence this indicator, however, only in regions with a small number of publications. Moreover, these anomalies are visible when compared with other indicators, largely decreasing the demand and impact.

Table 1: The key indicators characterizing knowledge-generating capabilities of cities

Indicator	**Focus**	**Value intervals**		
		Below average	**Average**	**Above average**
I. The overall citation rate – the ratio of citations to research output in 2013-2017	Demand for research results	[0 – 5.2]	(5.2 – 8.6]	(8.6 –83.0]
II. FWCI – the ratio of citations to the average expected citation rate by subject area	Impact strength and research quality	[0 – 0.74]	(0.74 – 1.0]	(1.0 – 6.89]
III. Share of publications written in international co-authorship	International integration	[0 – 18.8]	(18.8 – 24.9]	(24.9 – 100]
IV. Share of publications written in national co-authorship	National involvement	[0 – 29.5]	(29.5 – 29.8]	(29.8 – 100]
V. Share of publications in Top-10% journals by CiteScore	Global competitiveness	[0 – 10.1]	(10.1 – 24.8]	(24.8 – 100]
VI. The ratio of total scholarly output to the average annual population	Research productivity	[0 – 1.96]	(1.96 – 2.4]	(2.4 – 1248.13]

A benchmark for each indicator selected are national and global average values obtained in the SciVal (Table 1). All cities are divided into groups by indicator into 'below average', 'average', and 'above average' performers. The 'average performers' attribution means that the indicator values are in the interval between the national and global average values. For indicators I, II, IV, V, the lower limit is the national average value, while the upper limit is the global average value. For indicators III and VI it is vice versa. The study results in a typology of cities by knowledge-generating capabilities based on a combination of values for all 6 indicators.

4. Research results

The research demand indicator shows strong heterogeneity in the spatial distribution of excellence centres across the country (Figure. 1).

Almost 20% of all the cities included in the sample showed no demand for their research results – zero citations per paper. Generally, these are small cities – an average of 41.2 thousand people, lacking large scientific organizations. Of the 87 cities with zero citation rate, only 5 are classified as large: Bataysk, Khasavyurt, Kopeysk, Novokuybyshevsk and Novy Urengoy. Most of the remaining cities are small with up to 50 thousand people (66 cities), and average with a population of 50-100 thousand people (16 cities).

Another 104 cities barely reach an average value of 1 citation per article. This includes 1 large city – Nizhnevartovsk with a population of over 275 thousand people, 22 big cities (including Pskov – the administrative centre of the Pskov region), 40 medium and 41 small cities. Figures indicate a very low level of international demand for R&D generated in these cities. There are numerous possible causes to this pattern, including insufficient research quality, publications in unreliable sources that lack credibility, outdated topics or studies of local value, lack of journal visibility ("standalone journals"), etc.

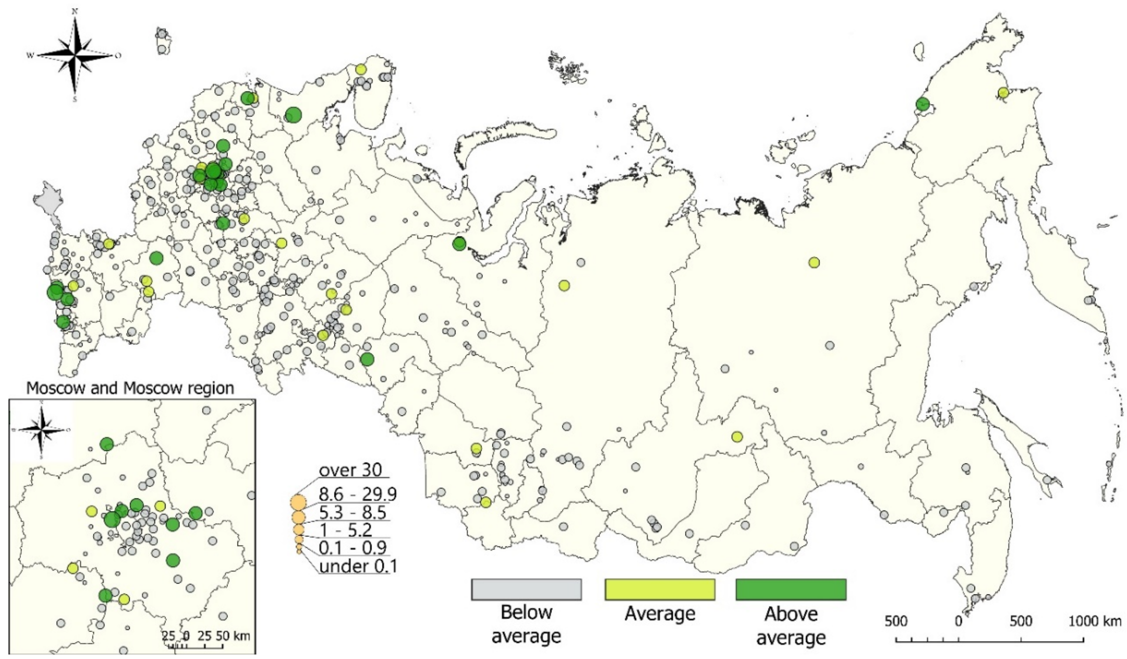

Figure 1: The volume of demand to the knowledge disclosed, 2013–2017.

About 47% of all the cities that excel "one citation to paper" barrier showed are cited below the national average value of 5.3. The composition of these cities is heterogeneous: 12 millionaire cities – the administrative centres regions (Ekaterinburg, Kazan, Chelyabinsk, Omsk, Samara, Rostov-on-Don, Ufa, Krasnoyarsk, Perm, Voronezh, Volgograd) and Moscow – the country's capital, 22 largest, 37 large, 56 big, 37 medium and 43 small cities. Almost half of all science cities ("naukogrady") fell into this category: the new and actively developing Innopolis – a satellite city of Kazan; Biysk in Altai Krai; Korolyov, Fryazino and Reutov in Moscow region; Obninsk in Kaluga region. The existing territorial distribution by the level of demand for knowledge generated follows two general patterns. The first is characterized by sustainable generation of a large volume of research of different quality, wide coverage of sources and subject areas. In this case, the level of demand blurs due to scale and averages between highly cited and undemanded. In other words, these predominantly large excellence centres generate knowledge of both high and low demand. Moreover, due to the significant number of the latter, the overall citation rate is moderate. The second pattern involves cities with a small number of research published with low citation rates.

Cities with the citation interval fluctuating between the national and global average values (between 5.3 to 8.6) are identified separately. This group of average performing cities is composed of 22 settlements, including 3 millionaire cities (St. Petersburg, Novosibirsk, Nizhny Novgorod), 1 large (Volzhsky), 2 big (Nevinnomyssk, Novoshakhtinsk), 3 medium (Gorno-Altaysk, Lysva, Ozyorsk) and 13 small ones, including 2 science cities – Chernogolovka and Pushchino in Moscow region. Most of these cities have world-class excellence centres and demonstrate fairly high citation rates.

There are only 20 cities of Russia featuring an overall high demand for their research, including on a global scale. The group of leaders includes 4 big (Dolgoprudny, Kislovodsk, Krasnogorsk, Pushkino), 6 medium (Dubna, Gatchina, Mikhaylovka, Pavlovsky Posad, Sarov, Voskresensk) and 10 small (Alagir, Kondopoga, Nizhnij Arkhyz, Pevek, Pokrov, Protvino, Salekhard, Teberda, Torzhok, Zavodoukovsk) cities. Overall, there is a limited number of research indexed in Scopus, but their studies are in demand.

The second highly important indicator of assessing knowledge generation is FWCI. The spatial distribution of excellence centres displays similar pattern with the indicator of demand (Figure. 2).

Almost 82% of all cities in the sample showed a FWCI level below the national average – 0.74, incl. zero value for 88 cities. Comparison of the list of cities with a zero level of demand and zero impact showed their almost complete intersection. In the latter case, a small town Kasimov in Ryazan region is added. It has 1 citation per article, but it is insignificant in comparison with global citation pattern for this subject area. The most numerous is the group of cities with FWCI falling below both international and national level of impact – 271 in total. It includes 148 small and medium-sized cities, 67 big, 34 large, 15 largest and 7 millionaire cities (Ekaterinburg, Omsk, Ufa, Krasnoyarsk, Perm, Voronezh, Volgograd). An interesting observation is the absence relationship between the city size and FWCI indicator: the correlation coefficient is 0.46. This shows that higher research impact values can be obtained in small cities having a strong research group.

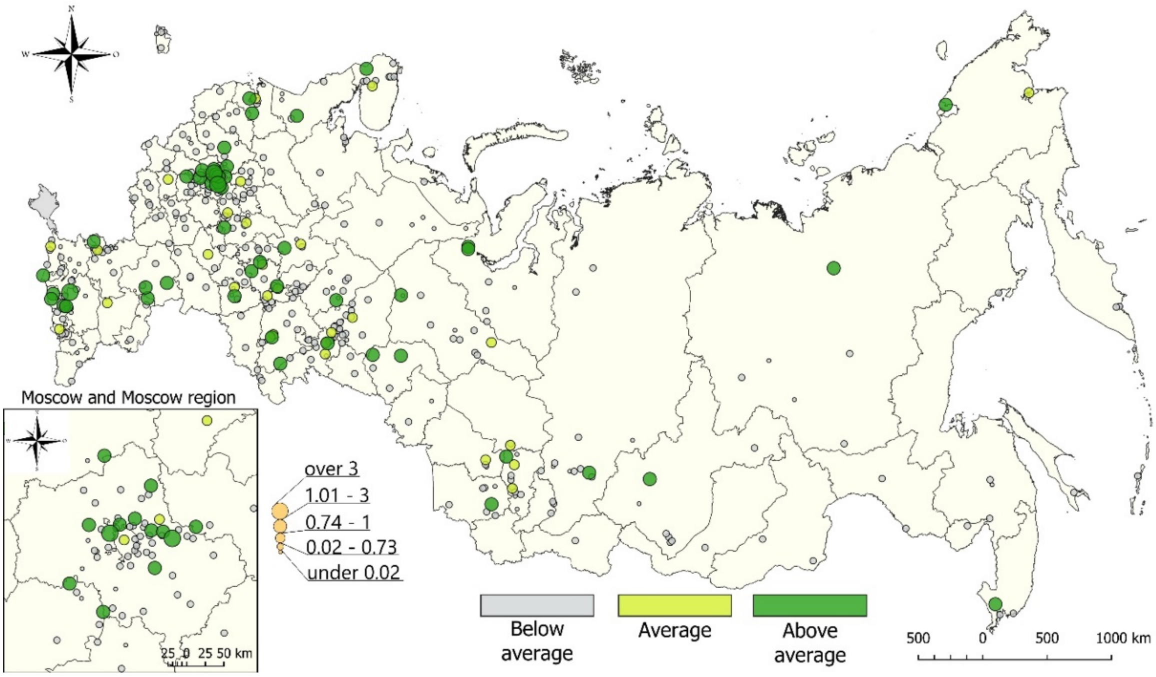

Figure 2: Spatial distribution of cities by knowledge impact, 2013-2017.

Another 30 cities are in an intermediate position, having crossed the line of national average FWCI, however, not having overstepped the global average. This group includes large national knowledge centres (Moscow, St. Petersburg, Novosibirsk, Kazan, Tomsk, etc.), and numerous average ones of regional scale. Three cities have FWCI from 0.99 to 1: Tomsk – group of largest cities, and 2 small ones – Alagir and Anadyr.

For 51 cities, the FWCI indicator turned out to be more than the global average value, incl. in 33 cities, the excess ranged from 1 to 90%, and in 18 – from 117 to 589%. The top-10 cities whose research show the highest FWCI values are Pavlovsky Posad – 6.89; Krasnogorsk – 4.99; Nevinnomyssk – 3.96; Teberda – 2.98; Znamensk – 2.97; Protvino – 2.96; Yurga – 2.85; Losino-Petrovsky – 2.81; Ishimbai – 2.73; Peresvet – 2.65. Most of these cities are small and medium-sized, and half of them have a metropolitan location, acting as satellites of Moscow.

Figure 3 presents an overview of cities by their integration into the global research space, featuring the share of research held in international collaboration.

It should be noted that Russia demonstrates higher rates of R&D internationalization than the global average: 24.9 versus 18.8%. However, almost 77% of all Russian cities studied have extremely low values for the percentage of publications written in international co-authorship. As many as 196 cities have no cooperative ties with scientists from other countries. In 59 cities the share of studies held in international collaboration is under 10%; another 88 cities are at 10-18.8% range, which is also below average. Results identified a transition group of 27 cities that demonstrate a higher level of internationalization than the world average but not yet reaching the national average values of 24.9%. This group includes 2 millionaire cities (Rostov-on-Don, Krasnoyarsk), 5 largest (Barnaul, Irkutsk, Krasnodar, Ulyanovsk, Vladivostok), 5 large (Khimki, Murmansk, Petrozavodsk, Sochi, Tver), 7 big (Blagoveshchensk, Kyzyl, Miass, Neftekamsk, Obninsk, Reutov. Yessentuki), 4 medium (Azov, Belovo, Gorno-Altaysk, Kropotkin) and 2 small ones (Tashtagol and Yelizovo). As can be seen from the data presented, the distribution of cities by the share of publications with international co-authorship is quite uniform and does not depend on the city size.

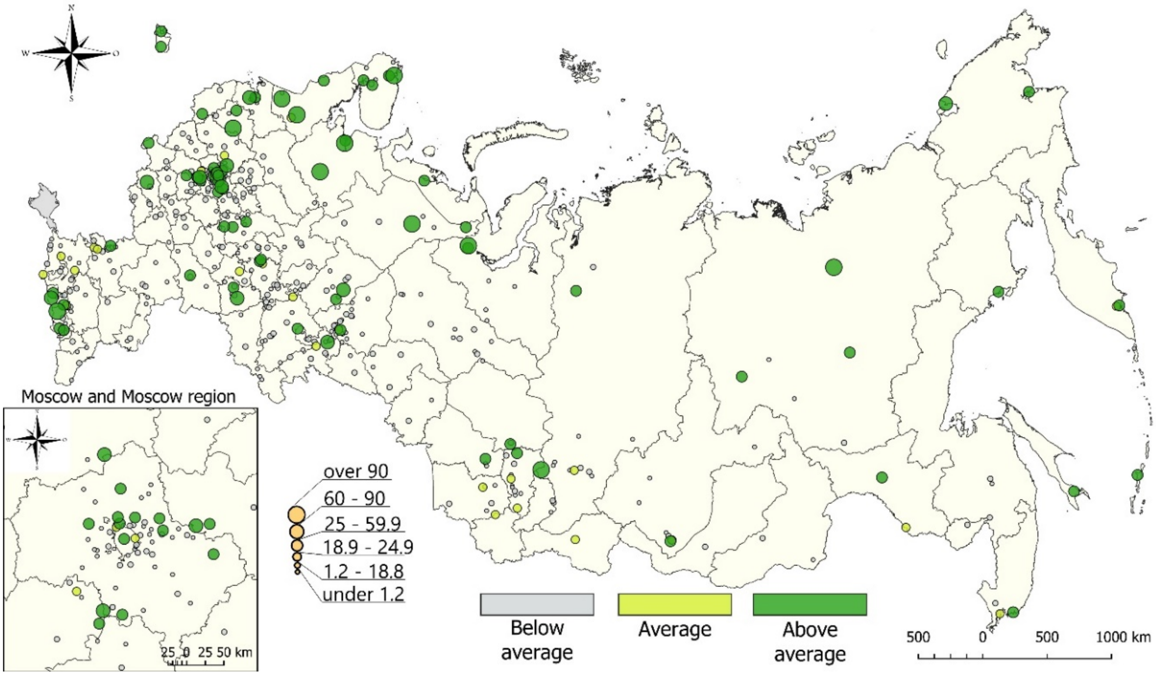

Figure 3: Integration of Russian cities into international research networks, 2013-2017.

Leaders by integration into international research cooperation are 77 cities. Interestingly, the correlation coefficient for this group between the intensity of international collaboration and the city size is of negative value (-0.17), i.e. the larger the city, the less internationalization it has. Among the 11 cities with all published research held in international collaboration, there are only small towns with a population of up to 40 thousand people (Arkhoy, Kondopoga, Labytnangi, Novodvinsk, Pechora, Pitkyarantur, Sharypovo, Snezhnogorsk, Tyrnyauz, Valday). For comparison, the large scientific centres of Russia, such as Moscow, St. Petersburg, Tomsk, Novosibirsk, have an internationalization level of 26 to 35%, i.e. less than a third of all publications held in collaboration with foreign scientists.

The large territorial distribution and remoteness of excellence centres in Russia increases the importance of their inter-regional networking. Figure 4 shows the differentiation of the cities according to the share of publications written by authors from various institutions of the country.

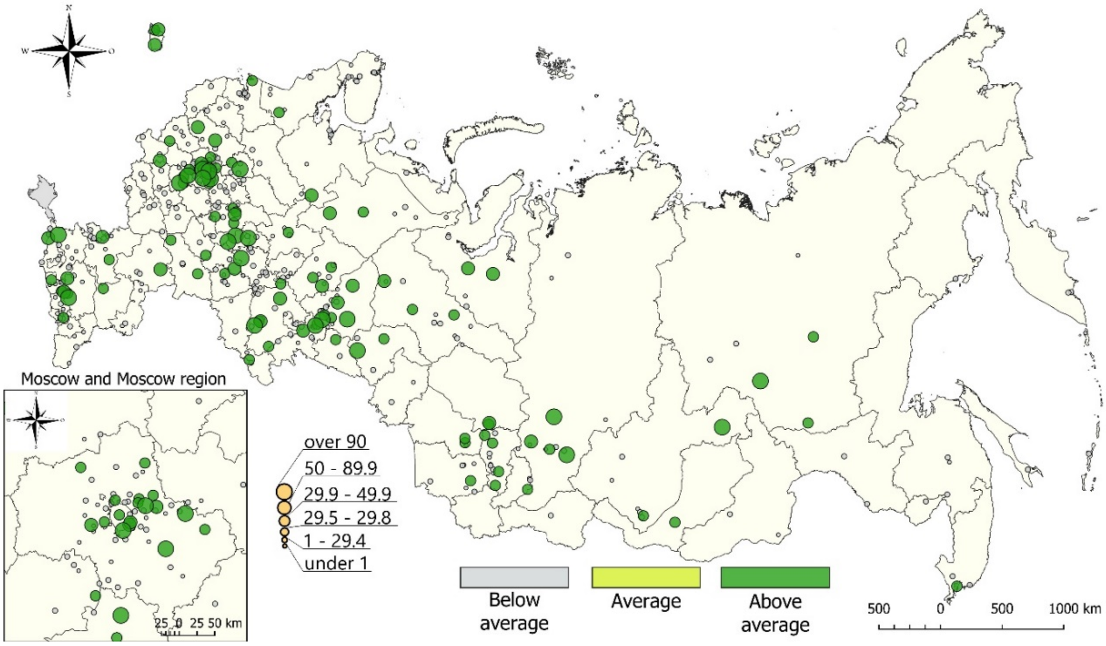

Figure 4: Involvement in national research networks, 2013-2017.

Despite the considerable length of the country, there is practically no lag between the average Russian and global average levels of involvement of research groups in national networking: 29.5 and 29.8%, respectively. Research centres of 31.8% of the studied cities operate in a closed mode, i.e. they do not network with other researchers within the country. This value is slightly less than the share of cities with zero publications in international co-authorship (44.5%), which indicates greater accessibility to national research networks than international ones for Russian research organizations. Another 186 cities have weak involvement to national research cooperation: less than a third of their publications are result of collaboration with researchers from other organizations. Thus, 74.4% of all cities studied have relatively weak research ties. Only 1 city has an average level of national involvement: Pyatigorsk in Stavropol Krai, having 29.6% of Scopus publications written jointly with authors from various scientific organizations of the country.

Over a quarter of all cities in the sample – 112 cities, have relatively high inter-organizational engagement values. In 22 cities, all of the research output produced in a cooperative from; another 29 cities display a range of 50-85.7%. Most of these cities are small and medium-sized, less often large. As in the case of international integration, the correlation coefficient between the city size and the share of publications co-authored with other institutions is negative (-0.17). For the largest scientific centres of Russia (Moscow, St. Petersburg, Kazan, Novosibirsk, Tomsk, etc.), the level of integration into national networking ranges from 20 to 45.5%.

Figure 5 presents the distribution of cities by global research competitiveness, featuring notable differences from the indicators stated above.

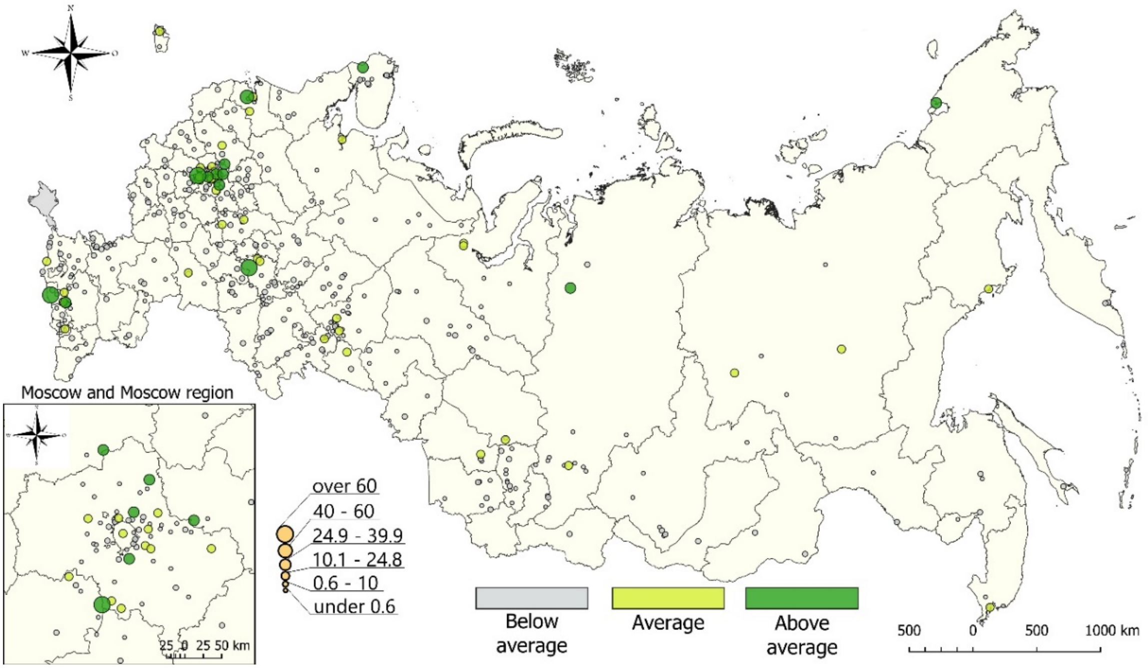

Figure 5: Global research competitiveness by city, 2013-2017.

The level of publication activity in top-10% Scopus-indexed journals is twice below the global average: 10.1 versus 24.8%. Over 88% of all Russian cities had none (266) or below the average Russian value (123). The transition group includes 38 cities (8.6%), whose researchers excel the national average value, but do not reach global indicators. These are 6 millionaire cities (Moscow, St. Petersburg, Novosibirsk, Nizhny Novgorod, Kazan, Krasnoyarsk), 3 largest cities (Saratov, Tomsk, Vladivostok) and 3 large cities (Arkhangelsk, Kaliningrad, Yakutsk), 7 big and medium-sized cities, 12 small cities, incl. 3 science cities.

Only 3% of cities have a high (over 25%) share of publications in the top-10% journals. These are 3 large (Domodedovo, Pushkino, Yessentuki), 2 medium (Dubna, Gatchina) and 8 small (Bolgar, Igarka, Kovdor, Peresvet, Pevek, Pokrov, Protvino, Teberda) cities. Note that 38% of all cities in the group of leaders are located in the Moscow region and are characterized by a metropolitan position.

The five indicators presented above should be considered in the context of publication performance of excellence centres. Figure 6 shows the distribution of cities by the volume of scholarly output generated per 1,000 population.

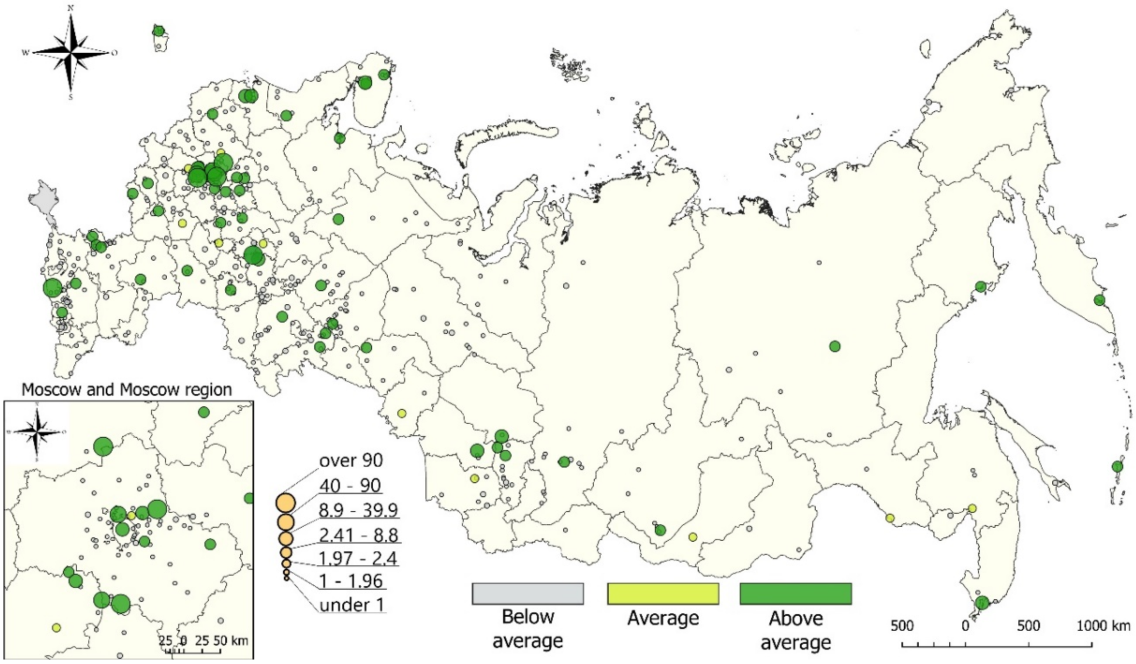

Figure 6: Scholarly output per 1,000 population, 2013-2017

In 2013-2017, Russia accounted for 2.4% of the global volume of Scopus documents with a higher national level of publication productivity: 2.4 versus 1.96 documents per 1,000 inhabitants. In absolute terms, the three largest knowledge nodes generate over 76% of research: Moscow (50.8%), St. Petersburg (15.5%) and Novosibirsk (9.9%). Another 20% of studies are produced in 6 cities: Tomsk, Kazan, Ekaterinburg, Nizhny Novgorod, Vladivostok, Dubna. Thus, 96% of all articles in the Scopus database over 2013-2017 are affiliated to 9 cities, which accounted for 2% of cities included in the sample. Considering Moscow as part of Moscow agglomeration, the capital and its satellite cities accounted for slightly under 60% of the total volume of scholarly output. The data presented indicates a high degree of polarization of the Russian knowledge landscape.

Distribution of Russian cities by the relative number of publications, adjusted by population figures, shows that the majority (84.5%) has extremely low productivity in knowledge generation: 76 cities had only 1 publication in 5 years. The average performing group includes 11 cities with publication productivity values ranging between 1.96-2.4 articles per 1,000 inhabitants (Barnaul, Blagoveshchensk, Kaluga, Khabarovsk, Korolyov, Omsk, Saransk, Tambov, Tver, Ulan-Ude, Yoshkar-Ola). The group of leaders includes 58 cities, including 41 with productivity of 2.4-8.8 articles per 1,000 people (e.g. Yekaterinburg and Nizhny Novgorod). The highest research productivity is found in 17 cities: Moscow and 6 of its satellite cities (Chernogolovka, Pushchino, Dubna, Protvino, Dolgoprudny, Fryazino), St. Petersburg and its satellite city Gatchina, large scientific centres – Tomsk, Novosibirsk, Kazan, and Vladivostok, as well as 1 big (Obninsk), 1 medium (Apatity) and small (Innopolis) cities and 1 village (Nizhnij Arkhyz).

5. Discussion

The study revealed numerous variations of excellence centres generalized into three groups: 1) Advanced, 2) Transitional, and 3) Local. Groups 1 and 3 have subcategories due to highly divergent composition (Figure. 7).

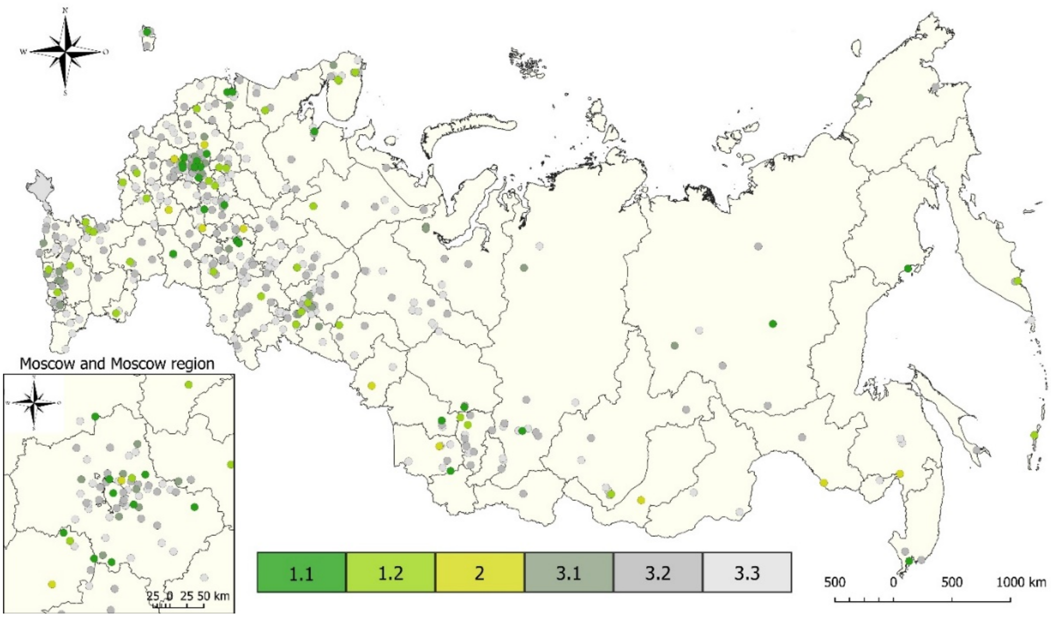

Figure 7: Typology of excellence centres by capabilities to generate knowledge

Group 1 includes 58 cities – 13% of the total sample. These are highly productive cities in the knowledge generation domain, producing over 2.4 articles per 1,000 people. *Subgroup 1.1.* has 24 cities – the largest national knowledge agglomerations: Moscow and its 7 satellite cities (Chernogolovka, Dolgoprudny, Dubna, Protvino, Pushchino, Shatura, Zhukovsky), St. Petersburg and its satellite city (Gatchina), Novosibirsk, Tomsk, Kazan, Nizhny Novgorod, Vladivostok, Krasnoyarsk, Saratov. Results suggest that the size of the city does not define leadership per se. The subgroup also includes a number of highly productive cities of average (Arkhangelsk, Kaliningrad, Magadan, Sarov, Yakutsk) and small (Borovsk, Innopolis) population against high research productivity. These are cities with globally competitive knowledge-generating institutions characterized by a combination of high research productivity (VI), global competitiveness (V), and quality research (II). Large cities however tend to be more research self-sufficient generating most output internally, while the cooperative ties dominate by international cooperation. Cities of subgroup 1.1 lead in the national knowledge generation domain, which is largely consistent with observations based on patents and innovation activity. Subgroup 1.1. is the strategic core that ensures frontier research and international presence, thus, knowledge management should foster hub-and-spoke ties for knowledge diffusion across the country.

Subgroup 1.2. includes 34 cities that are diverse in size and geography: the largest national (Ekaterinburg) and inter-regional (Chelyabinsk, Irkutsk, Perm, Rostov-on-Don, Samara, Ufa) scientific centres of Russia, the strong excellence centres with focused research (e.g. Belgorod, Fryazino, Nizhnij Arkhyz, Petrozavodsk, Tyumen, Vladimir, Volgograd, Voronezh, Yurga, etc.), as well as small excellence centres with high research productivity against low population figures (e.g. Kholm, Kirovsk, Kurilsk, Rostov). The defining feature of these cities are strong asymmetries for either external or internal cooperative ties, and limited performance by research quality and demand despite high research productivity.

Group 2 – incorporates 11 transitional cities (2.5% of the total: Barnaul, Blagoveshchensk, Kaluga, Khabarovsk, Korolyov, Omsk, Saransk, Tambov, Tver, Ulan-Ude, Yoshkar-Ola), whose knowledge-generating institutions demonstrate a higher level of publication productivity than the global average (1.96-2.4 articles per 1,000 people), and have accumulated some global expertise. However, the average quality of and demand for their research is generally below average. Integration of these cities into national and international research networks is weak, while most cooperative ties are in the status of “followers”. These cities have the capacity for becoming competitive on a global arena, yet strategic planning is required for building ‘glo-cal’ networks and prominent topics.

Group 3 is the largest group of all, including 371 cities (84.5% of the total). It is characterized by low research productivity in comparison with other cities: 0.03-1.96 articles per 1,000 people. *Subgroup 3.1.* includes 27 cities (8 large – Cherkessk, Domodedovo, Kislovodsk, Nazran, Pushkino, Ramenskoye, Serpukhov, Yessentuki; 5 medium – Kirishi, Novouralsk, Ozyorsk, Shadrinsk, Tuapse; and 14 small – Bolgar, Igarka, Istra, Kovdor, Labytnangi, Mirny, Peresvet, Pevek, Pokrov, Salekhard, Staraya Kupavna, Teberda, Torzhok, Zarechny) publishing an average of 1-2 articles per year (less often 10-12), while a number of articles are published in top journal percentiles receiving many citations. These cities exhibit an example of a distributed network of excellence centres – the local nodes of the national innovation system. Generally, these are small but efficient research teams that require assistance to strengthening extra-regional intergration and knowledge transfer to local industries.

Subgroup 3.2. includes 156 cities, including 6 largest cities (Kirov, Krasnodar, Naberezhnye Chelny, Penza, Tolyatti, Ulyanovsk) generating an average of 200 articles per year; 7 large cities (Khimki, Novorossiysk, Oryol, Sochi, Sterlitamak, Tula, Volzhsky) – 50 articles per year; 36 big cities – 14 articles per year; 44 medium cities with 4 articles per year; and 63 small cities with an average of 1 article per year. Despite the low research productivity and a very small number of articles in leading journals, nevertheless, some cities have formed collaborative ties with other national or foreign organizations, and there is a gap between the overall and filed-weighted citation index in favour of the latter. These cities require further investigation over a longer research period, while their research seems to be driven by local industry demand.

Subgroup 3.3. – the largest subgroup of cities. It includes 188 cities, of which about 250 articles a year come from the largest city of Izhevsk, 20-200 articles a year from 29 cities, 2-20 articles a year from 45 cities, and 113 cities with under 10 articles over 5 years. These cities are close to invisible in the scope of national innovation system. These cities are "silent" by all indicators considered. The values of all 6 indicators in this subgroup of cities is below the minimum average level.

6. Conclusion

This study focuses on the geography of knowledge across the cities of Russia. The country has launched the "5-100" Russian academic excellence project in 2012 for boosting research quality and internationalization (see: https://www.5top100.ru/en). Competitive selection process for project membership has revealed great distribution of excellence centres across the country – from the westernmost exclave of Kaliningrad to the far-eastern city of Vladivostok, thus, indicating geographical spread of intellectual capital.

Given the great diversity of cities by their size, socio-economic development and innovation dynamics, we produce a typology of cities by their ability to generate knowledge for the national innovation system. A sample of 440 cities are given an in-depth assessment, including: 173 small cities – under 50,000 people, 102 medium-sized cities – 50-100,000 people, 89 big cities – 100-250,000 people, 39 large cities – 250-500,000 people, 22 largest cities – 500,000 to 1 million people, and 15 millionaire cities. Each city is analysed using 6 indicators showing the research productivity, demand, quality and impact of research, integration into national and international research networks.

It is revealed that the smaller the city, the higher are its needs for integration into research networks. Generally, the share of collaborative research at inter-organisational and international level is greater than that of larger cities. Achieving maximum values for individual indicators (for example, 100% of publications are internationally co-authored) is possible for small cities with a low volume of scholarly output. In the case of large cities, it is not only impossible due to the wide variety of topics, authors, articles, but also unnecessary. For example, cities with over 500 thousand people, generally, have a large number of articles, of which less than a third are co-authored with researches from other countries.

By acknowledging the diversity of the knowledge landscape, knowledge management should account for the differences between excellence centres. A typology of cities resulted from this study is to be applied for managing the related variety of knowledge generating institutions for achieving synergies. The research results reveal the following patterns.

A list of 24 cities if defined as major national knowledge centres with high research quality and productivity. Subgroup 1.1 includes cities both leading in the absolute number of scholarly output, and those, having a significant volume of publications relative to their size. Being integrated into national and international research collaboration this subgroup of cities plays the role of a hub in the 'hub-and-spoke' scheme of networking. These cities are competitive growth nodes of the research and innovation space, its locomotives. The cities of this subgroup are self-sufficient knowledge generating centres. However, their research ties in the national projection should be strengthened in order to develop the intellectual capital of cities assigned to the second and third groups. Another 34 cities are defined as subgroup 1.2, which require overall improvement of research quality. This includes focusing on more prominent topics that would generate global demand; selection of top journals with a large impact factor to disclose research results; increasing the share of interdisciplinary research by using city's internal capacity.

Of particular interest are 27 cities assigned to subgroup 3.1, which are moderate in terms of knowledge generative capacity. Despite publishing a small number of research output, the knowledge generating institutions of these cities are focusing their efforts on high-ranking journals with a high level of citations, which indicates a good scientific level of their research. With proper government support and strategic knowledge management, these centres may grow. Yet today, most of them are followers rather than leaders.

The smallest number of cities (11) took a transitional position (Group 2), reaching average values for many indicators. They require impetus for further growth in order to move into a group of leaders by improving the quality of publications and increasing research productivity.

The most numerous groups are 3.2 and 3.3, including 156 and 188 cities respectively. These cities fall below average for all 6 indicators or score well only on individual indicators. The subgroups include research centres of regional and municipal importance, poorly integrated into the national and global knowledge space. Their development should be based on understanding their competitive research specialization and local benefits from developing the ability to generate knowledge, inter-organizational and interdisciplinary research cooperation. The researchers of these cities need to gain publication experience, predominantly by collaborating with advanced research centres. Knowledge management for these cities should be place-specific by incorporating the existing institutional environment, rather than adopting a "catching up" policy using the same key performance indicators as for the group of leaders.

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