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# Economic Growth and Environmental Pollution in the USA and Russia: Comparative Spatial-Econometric Analysis

**Aleksei N.**
**KURBATSKIY**
Moscow School of Economics, Lomonosov Moscow State University
Moscow, Russian Federation
e-mail: akurbatskiy@gmail.com
ORCID: 0000-0001-6478-8034; ResearcherID: K-4309-2013

**Ekaterina I.**
**SHAKLEINA**
Moscow School of Economics, Lomonosov Moscow State University
Moscow, Russian Federation
e-mail: kateshkln99@gmail.com
ORCID: 0000-0001-5872-6179

**Abstract.** One of the vital problems of the 21st century is environmental pollution, unfavorable both locally and globally. Contaminants released into the soil, air, and water runoff pollute drinking water which leads to an increase in the number of epidemic outbreaks. Moreover, pollutants affect local ecosystems. And when the ecosystem dynamics change, the balance of organisms that provide us with clean air is disrupted. The main cause of the pollution problem is economic growth. It encourages intensive energy use which leads to an increase in $CO_2$ emissions. It is important to understand how to reduce emissions while maintaining the pace of economic growth. To date, the emission-leading countries have fundamentally different economic structures, and therefore it seems necessary to conduct a comparative analysis of the economic growth impact on pollutant emissions for them. The paper considers the situation typical of the Russian regions and American states for the period from 2004 to 2018. We have used spatial

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econometric models to identify dependencies. The paper proves the existence of spatial correlation in the level of pollutant emissions in Russia's regions and American states. We have confirmed the hypothesis that the dependence of emissions on economic growth in Russia's regions has the form of an inverted U-shaped curve. The value of the GRP turning point, after reaching which the level of pollutant emissions will decrease, has shown that only in ten Russia's regions, with GRP growth, emissions are reduced, and most regions are on the increasing part of the curve. For the United States, the estimates obtained are not significant, which proves the paramount importance of the structure of the country's economy in the issue of the relationship between environmental pollution and economic growth.

**Key words:** pollutant emissions into the atmosphere, economic growth, Kuznets ecological curve, spatial econometrics, Moran's index.

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## Introduction

Economic growth is one of the most important characteristics of social production in any economic system. After the industrial revolution, the countries of the world are striving to achieve ever higher rates of economic growth through the use of existing including non-renewable, natural resources (Jian et al., 2019). This leads to forest destruction, disappearance of rivers, sea pollution, decrease in drinking water quality, large-scale changes in land use, increase in greenhouse gas emissions, especially carbon dioxide ($CO_2$), which plays an important role in global warming and ozone layer destruction[1]. It is worth noting that the saturation of carbon dioxide in the Earth's atmosphere over the previous 150 years has increased from 280 to 400 ppm (particles per million), such a high level has not been observed over the previous 400 thousand years[2]. During the 20th century, the average global surface temperature increased by 0.6 °C, sea level rose by 10–20 cm, snow cover and ice extent decreased by 10% (Canas et al., 2003). Thus, at present, humanity faces two most important tasks – sustainable economic development and environmental conservation.

Economic progress, carried out through progressive economic development, is one of the factors in the country's development and represents economic growth, characterized by the following indicators: growth of gross domestic product and per capita income, growth of industrial production and labor productivity, changes in the social structure and the economy as a whole, the availability of sales markets and others (Zhuravleva et al., 2017). At the same time, carbon monoxide emissions into the atmosphere have an impact on economic growth. Accordingly, in order to achieve sustainable development, we should take into account the relationship between economic activity and environmental quality (Shikwambana et al., 2021).

The most widely used method of analyzing the relationship between economic growth and environmental pollution is the environmental Kuznets curve, an inverted U–shaped dependence of emissions on economic growth, considered in the work (Grossman, Krueger, 1991).

[1] Intergovernmental Panel on Climate Change (IPCC). AR5 synthesis report: Climate change 2014.

[2] Intergovernmental Panel on Climate Change (IPCC). AR5 synthesis report: Climate change 2015.

The environmental Kuznets curve (EKC) was presented in the World Development Report (1992) as a relationship between the concentration of sulfur dioxide in the environment and GDP per capita in 47 cities, located in 31 countries[3]. The EKC corresponds to an inverted U-shape of the relationship between income and concentration of sulfur dioxide.

The theory of the environmental Kuznets curve is based on the effect of the transition from agricultural to industrial production. As industrial production in urban areas becomes more intense, environmental pollution increases. With an increase in the income level, heavy industry is gradually being phased out in favor of more high-tech production. This transition should reduce environmental pollution. Thanks to high-tech and efficient production, emissions are reduced and the demand for a clean environment from consumers increases, and there is also a high political interest in the environment well-being (Dinda, 2004).

In the work, we will carry out a comparative analysis of the issue of the relationship between emissions and economic growth on the example of the USA and Russia. According to the World Bank, the United States and Russia occupy the leading places in terms of pollutant emissions per capita, ahead of China, the European Union and India[4]. The USA is one of the most developed economies in the world, Russia is an emerging market country, and therefore, the economic model of their GDP formation is different. However, at the same time, according to the level of pollutant emissions per capita, the countries are located in neighboring positions. Thus, due to the urgency of the environmental pollution problem for Russia and the USA, the purpose of the study is to conduct a comparative analysis of the relationship between emissions and economic growth on the regional data of Russia and the USA.

To achieve this purpose, we have solved the following research tasks: we have carried out a comparative analysis of environmental problems in Russia and the United States, estimated spatial correlation in terms of pollutant emissions on regional data for the United States and Russia, tested the hypotheses about the existence of the Environmental Kuznets Curve in the two countries at the regional level, identified factors of reducing the environmental burden, and noted development trends environmental politics in the USA and Russia.

Further, it is necessary to note the works that served as a starting point for our research.

**Literature review**

Quite a lot of books and articles have been devoted to the topic of the relationship between the pollution level and economic growth. For example, the hypothesis of this relationship was tested in 217 countries for the period from 1990 to 2014 (Kudryavtseva et al., 2017). The problem of carbon dioxide emissions is one of the most urgent, which is also reflected in the Kyoto Protocol (1997). That is why the level of carbon dioxide ($CO_2$) emissions was taken as a measure of environmental pollution. The researchers have confirmed the hypothesis of the existence of an inverted U-shaped dependence of economic growth on emissions. Thus, there is a critical turning point between the positive and negative nature of the economic growth dependence on the $CO_2$ emissions level. At the same time, the hypothesis is accepted for developing countries, for developed countries the dependence is linear negative. To test the hypothesis, we have used the following equation specification:

$$\mathrm{Ln}\, y_{it} = \alpha + \rho \times \ln y_{i,t-1} + x'_{it} \times \beta + y_1 \times CO_{2it} + y_2 \times {CO_2}^2_{it} + h_i + \varepsilon_{it}, \quad (1)$$

where $y_{it}$ – GDP per capita,

$x_{it}$ – matrix of regressors,

$CO_{2it}$ – carbon dioxide emissions,

$h_i$ – individual country effects.

[3] World Bank. World development report 1992: Development and the environment.

[4] Available at: https://data.worldbank.org/

It is also worth noting that the generalized moment method, proposed by (Arellano, Bond, 1991) and used to evaluate dynamic panel data models, was chosen as a method for econometric analysis. We should note that the method allows obtaining reliable and consistent estimates of the coefficients. Based on the results obtained, the authors of the article (Kudryavtseva et al., 2017) established the existence of relationship between the pollution level and economic growth.

There are works that investigate the hypothesis of the existence of the environmental Kuznets curve and its turning point on the data for Russia. For instance, the hypothesis was tested for the period from 1998 to 2013 in the work (Yang et al., 2017). The pollutant was the volume of greenhouse gas emissions. In this paper, the authors considered emissions from energy consumption, industrial production, agricultural production and inorganic emissions, and also estimated specific emissions from ferrous metallurgy, primary aluminum production and cement production. The presence of an inverted U-shaped relationship between GDP per capita and economy-related greenhouse gas emissions per capita has been verified. The EKC model, used in this study, looks like:

$$Y = \alpha + \beta X + \gamma X^2 + \varepsilon , \quad (2)$$

where Y – environmental change indicator, X – indicator of economic development (GDP per capita in USD in 2005), $\alpha$, $\beta$, $\gamma$ – X coefficients.

We have noted that from 1998 to 2008, the total volume of greenhouse gas emissions gradually increased from 2,230 to 2,605 million tons of $CO_2$, annually by 1.6%. The obtained results have confirmed the hypothesis of the environmental Kuznets curve. Based on the calculations, we assume that Russia will reach a turning point in 10 years with the stability of economic growth rate.

The problem of the relationship between carbon dioxide emissions and energy consumption, real income, international trade, level of education and urbanization was considered on the basis of Russian data from 1991 to 2016. An empirical dependence of the volume of $CO_2$ emissions on other factors is constructed (Ketenci, 2018). The paper confirmed the hypothesis of the environmental Kuznets curve, according to which environmental pollution decreases after reaching a certain income level.

We have used an autoregressive model with a distributed lag to assess short-term and long-term relationships. It is worth noting that this model allows analyzing the impact of shocks of independent variables on the dependent one using dynamic coefficients (analogy with the functions of impulsive response in VAR models). Based on the results obtained, we have concluded that real incomes, energy consumption, level of education and urbanization affect the carbon emissions level, and trade openness is an insignificant factor.

Also, the economic impact issue on the environment was considered in the work (Druzhinin et al., 2018). The authors have analyzed the relationship between emissions and economic development in the case of Russia and Finland for the period 1990–2017. At the same time, the $SO_2$ indicator was taken into account. The paper used a multiplicative function linking economic and environmental indicators:

$$E(t) = A(t) \times X_1^{\mu}(t) \times X_2^{-\eta}(t) \times X_3^{\nu}(t) , \quad (3)$$

where $E(t)$ – environmental indicator under study (environmental impact – ratio of $SO_2$ emissions to GDP); $X_j(t)$ – factors, $A(t)$ – neutral environmental progress (it shows a decrease in the pollution rate due to factors, not included in the equation, primarily structural shifts); $\mu$, $\eta$, $\nu$ – constant parameters (factorial elasticities); $t$ – year.

It is worth noting that the indicators of the dynamics of investments in fixed assets, new construction, modernization, air protection, machinery and equipment and the share of industry in GDP were used as independent variables in relation to the Russian Federation. As a result, we have revealed that an increase in the share of industry in GDP by 1% leads to an increase in the ratio of $SO_2$ emissions to GDP by 0.15%, an increase in cumulative investments in atmospheric air protection by 1% leads to a decrease in the ratio of $SO_2$ emissions to GDP by 0.15%, an increase in investments in machinery and equipment by 1% has an impact on reducing the ratio of $SO_2$ emissions to GDP by 0.32%.

As independent variables in the model for Finland, the indicators of the dynamics of industrial production, investment in the economy, air protection, machinery and equipment, and the share of industry in GDP in the pre-crisis (1996–2008) and post-crisis (2009–2015) periods are taken. We have found that an increase in the share of industry in GDP by 1% leads to an increase in the ratio of $SO_2$ emissions to GDP by 2.35%, an increase in cumulative investments in atmospheric air protection by 1% leads to a decrease in the ratio of $SO_2$ emissions to GDP by 0.39%, in the first period, an increase in investments in the economy by 1% led to a decrease in the ratio of emissions $SO_2$ and GDP by 1.08%, in the second period, an increase in investment in machinery and equipment by 1% contributed to a decrease in the ratio of $SO_2$ emissions to GDP by 1.07%.

The environmental impact on economic growth has recently attracted the researchers' attention. Environmental pollution has a negative impact on labor productivity. Accordingly, some works consider the following problems: the consequences of economic development for the environment and climate change impact on the development of certain economic sectors. For example, one of the articles studied the problem of the relationship between emissions of harmful substances from stationary sources and economic growth on the example of Russia and its regions for the period 2000–2011 (Druzhinin, Shkiperova, 2014). The authors have concluded that economic growth leads to an increase in greenhouse gas emissions, while modernization and structural shifts in the economy reduce them by 4.9% annually.

For the regions, calculations were carried out using linear and multiplicative functions. The results showed that the EKC hypothesis on greenhouse gas emissions and harmful substances coming from stationary sources is not confirmed for most Russia's regions. The authors conclude that most of the regions, according to the main indicators of environmental load, are far from the maximum position on the EKC and potential economic growth may be accompanied by increased environmental degradation.

Next, we will consider the problem of the relationship between pollutant emissions, energy consumption and economic development on the example of the BRICS countries for the period 1971–2005 (for Russia it is 1990–2005) (Pao, 2010). The article has revealed that in the long term there is a relationship between emissions, energy consumption and output for the BRICS countries. In the long term, the elasticity of energy consumption is statistically significant and is estimated higher for each of the four countries. This elasticity means that energy consumption is highly sensitive to changes in emissions. The results obtained confirm the hypothesis of the environmental Kuznets curve, according to which emissions increase along with the actual production volume, stabilize and then decrease. Consequently, after reaching a critical production level, an increase in output can lead to a reduction in emissions and a growth in demand for environmental quality. The authors have shown that energy consumption and real production complement each other, and environmental degradation has only an accidental impact on economic growth. Thus, the best environmental policy is to raise investments in energy supply, increase energy efficiency, and activate energy conservation policies to reduce unnecessary energy losses.

It is also worth noting that this problem has been investigated on the example of the United States of America taking into account energy consumption. For instance, the article (Soytas, et al., 2007) studied the impact of energy consumption and output on $CO_2$ emissions for the period from 1960 to 2004. We should emphasize that earlier studies mainly focused on verifying the existence of the Kuznets curve without taking into account energy consumption. The work (Motrenko, 2011) considered the Granger causality between income, energy consumption and $CO_2$ emissions including labor and gross fixed capital accumulation.

The researchers conclude that income is not the cause of $CO_2$ emissions in the USA in the long run, unlike energy consumption, so America should not reduce income to decrease emissions. It is worth emphasizing that an important aspect is the reduction of energy consumption. The authors note the absence of causal relationship between energy consumption and income and conclude that in the United States, reducing energy consumption can be considered as a serious environmental policy that does not harm long-term prospects for economic growth (Soytas et al., 2007).

The problem of the relationship between environmental pollution and economic growth in the case of Russian data taking into account three different types of pollutants ($CO_2$, $SO_2$, $NO_2$) was carried out in the work (Mihalishchev, Raskina, 2016). The research has reviewed the information database of 79 entities of the Russian Federation from 2000 to 2013, and tested the hypothesis of the EKC existence.

Attention was paid to the indicator characterizing the socio-economic situation, GRP per capita, indicators of nitrogen dioxide, sulfur dioxide, carbon oxides were considered as characteristics of the ecological level. In order to assess the impact of external factors and the variability of the economic environment, the Gini coefficient and the share of the contribution of the industry's added value to the total GRP are integrated into the model. As a result, the econometric model has the following form:

$$Y_{it} = \alpha_i + \beta_1 X_{it} + \beta_2 X_{it}^2 + \beta_3 X_{it}^3 + \beta_4 GINI_{it} + \beta_5 STRUCT_{it} + \varepsilon_{it}, \quad (4)$$

where $i = 1, ..., N$ – regions,

$t = 1, ..., T$ – years, $GINI$ – Gini coefficient,

$STRUCT$ – vector of variables responsible for the GRP structure.

The results obtained through modeling allowed formulating the following conclusions:

– only a small part of Russia's entities is outside the area of the ascending Kuznets curve;

– reduction of emissions is accompanied by an increase in inequality (Gini coefficient)

– econometric insignificance of the unproductive GRP sector is fixed.

Summarizing, we can note that the socio-economic situation of Russia's entities is characterized by low stability in the long term and does not significantly contribute to reducing the environmental pressure exerted.

Thus, we understand that the work on the relationship between $CO_2$ emissions and economic growth is relatively controversial and contradictory. They do not consider the spatial autocorrelation of factors at the regional level including environmental pollution factors and regional incomes.

Most studies have used panel data to analyze the relationship between economic development and environmental pollution in relation to a group of developed and/or developing countries. But for a correct assessment, it is necessary to take into account spatial correlations, especially for large countries.

There are several works which use spatial-econometric models. So, in the article (Xu et al., 2018), the problem was investigated on the example of 30 provinces of China for the period 2000–2012. To test the EKC hypothesis, the following equation was used:

$$\ln CE_{it} = \alpha_0 + \alpha_1 \ln EG_{it} + \alpha_2 \ln EG_{it}^2 + \\ + \alpha_3 \ln PSI_{it} + \alpha_4 \ln UR_{it} + \varepsilon_{it}\,, \quad (5)$$

where CE – carbon emissions expressed in tons, UR – urbanization level, expressed as a percentage, EG – gross domestic product per capita, expressed in 100 000 Yuan/km$^2$, PSI – share of secondary industry, expressed as a percentage.

In the article, to analyze the relationship between economic growth and $CO_2$ emissions, the authors have used the following models:

- spatial autoregression model (SAR) of fixed effects:

$$\ln CE_{it} = \alpha_0 + \alpha_1 \ln EG_{it} + \alpha_2 \ln EG_{it}^2 + \\ + \alpha_3 \ln PSI_{it} + \alpha_4 \ln UR_{it} + \rho W \ln CE_{it} + \varepsilon_{it}\,, \quad (6)$$

where W – spatial matrix, ρ – spatial autocorrelation coefficient which reflects the magnitude and direction of spatial correlation;

- spatial error regression model (SER) of fixed effects:

$$\ln CE_{it} = \alpha_0 + \alpha_1 \ln EG_{it} + \alpha_2 \ln EG_{it}^2 + \\ + \alpha_3 \ln PSI_{it} + \alpha_4 \ln UR_{it} + \varepsilon_{it}\,, \quad (7) \\ \varepsilon_{it} = \lambda W \varepsilon_{it} + \gamma_{it}\,,$$

where $\lambda$ reflects the spatial dependence of the estimated region on neighboring,

$\varepsilon_{it}$ – the remainder obeying the normal distribution.

Based on the results obtained, the researchers have showed that the EKC has an inverted U-shape of the relationship between $CO_2$ emissions and economic growth in China. Moreover, there is a significant spatial correlation between carbon emissions and economic growth, it means that carbon emissions in a province are influenced by emissions from neighboring provinces. The authors note that a 1% increase in carbon emissions in a neighboring province could lead to a 0.028% increase in carbon emissions in the local province. When economic growth reaches 279.91 million yuan per unit of GDP, the contradiction between economic growth and carbon emissions will be gradually eliminated. We should note that currently in China, only a few well-developed provinces or provincial-level cities, such as Tianjin, Beijing, Shanghai and Jiangsu, have reached this inflection point (Xu et al., 2018).

V. Ivanova in her article has carried out the analysis taking into account the spatial relationship of the Russian regions. The article examines the dependence of the environmental pollution level on the indicator characterizing the socio-economic situation in Russia's entities – the level of disposable income per capita (Ivanova, 2019).

An econometric model with a time trend and individual effects is used as the main equation:

$$Y = \alpha + \beta_1 \ln GRP + \\ + \beta_2 \ln GRP^2 + X'\delta + \gamma t + \varepsilon\,, \quad (8)$$

where $Y$ – pollutant emissions into the atmospheric air from stationary sources in terms of per capita (kg),

lnGRP – gross regional product per capita (rub.), logarithm,

$\alpha$ – individual effects of regions,

$X'$ – vectors-strings of explanatory variables,

$\delta$ – vector of coefficients,

$t$ – temporary trend, $e \sim i.i.d.\ N(0, \sigma^2)$.

In order to quantify the closeness of the relationship between the values of indicator $x$ for closely located regions, the global index of Moran's spatial autocorrelation $I$ was used.

The obtained Moran's indices for logarithms of average per capita pollutant emissions into the atmosphere emanating from stationary sources are statistically significant. Hence, the dependent variable in the equation is spatially autocorrelated. The assumption was confirmed that the regions' pollution is due to their location relative to each other.

The work of V. Ivanova has considered two regression models:

- Spatial autoregressive model including the spatial lag of the dependent variable (hereafter – SAR):

$$Y = \alpha + \rho WY + \beta_1 \ln GRP + \beta_2 \ln GRP^2 + \\ + X'\delta + \gamma t + \varepsilon, \quad (9)$$

- Spatial error model (hereafter – SEM):

$$Y = \alpha + \beta_1 \ln GRP + \beta_2 \ln GRP^2 + \\ + X'\delta + \gamma t + \epsilon, \quad (10) \\ \epsilon = \lambda W\epsilon + \epsilon,$$

where W – matrix of spatial weights, X – matrix of control variables $\rho$ and $\lambda$. The following control variables were used:

lnGini, lnElc– electricity consumption per capita (thousand kW/hr.),

lnGini, $\ln Gini^2$ – Gini coefficient (income concentration index),

*Manf* – share of manufacturing industries in the sectoral structure of gross value added,

*Ming* – share of mining in the industry structure of value added.

The SAR model based on the spatial Lagrange multiplier test turned out to be preferable.

The research results have confirmed the hypothesis of an inverted U-shaped relationship between environmental emissions and per capita GRP. The significance of the income tipping point demonstrates that most regions are characterized by an increase in the pollutant volume with an increase in income.

Accordingly, the problem of the relationship between economic growth and environmental pollution does exist. Economic development, which affects the depletion of natural resources, cannot be sustainable in the long term. S.N. Bobylev considers new economic models, related to environmental factors: the green economy, the low-carbon economy, the blue economy, the bioeconomy, etc. (Bobylev, 2019). The researcher also points out the long-term objectives of the Russian economy development: the transition to sustainable development, replacement of the export-raw material model with a model with clearly defined environmental priorities, as well as human capital development. The author believes that for the Russian economy development, it is necessary to adopt its own sustainable development strategy, in which a new economic model should take an important place; to develop a system of sustainable development goals with appropriate indicators for the long term taking into account international experience and agreements in which Russia participates.

**Methodology and data**

In the study, we have used panel data. To verify the existence of spatial dependence in the data, we have performed Moran's test. The value of the Moran's index is found by the formula:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}}, \quad (11)$$

where $w_{ij}$ –spatial weights that are (i, j) elements of the spatial matrix W,

$x_i$ and $x_j$ – values of variables in regions i and j,

$\bar{x}$ – average value,

*n* – number of regions.

Spatial weights $w_{ij}$ are a comparative characteristic of regions, with a higher value of the weighting coefficient, there is a greater similarity in the location of territories.

In the case of a positive Moran's index, the spatial dependence for variables is positive, otherwise it is negative, and at zero level it is absent (Zhukova et al., 2016).

Identification of weighting coefficients characterizing the level of spatial impact of indicators of other regions on the values of the region's indicator is one of the main factors of spatial data analysis. The weights are determined by a matrix, based on adjacency or distance. Distances between regions are set as distances between centroids or regional centers (Ivanova, 2019). To construct the spatial matrix, we have used inverse geographical distances.

The study constructed a model with spatial lag and spatial structure in errors (SAC – Spatial Autoregressive Combined):

$$Y = \lambda \times (\mathrm{W} \times \mathrm{y})_{\mathrm{it}} + \mathrm{X}_{\mathrm{it}} \times \beta + \epsilon_{\mathrm{it}}, \quad (12)$$
$$\epsilon_{\mathrm{it}} = p \times (\mathrm{W} \times \epsilon)_{\mathrm{it}} + u_{\mathrm{it}}, \; u_{\mathrm{it}} \sim N(0, \sigma_u^2, \mathrm{I_n}),$$

where $Y = (y_1, \dots y_\mathrm{n})^T$ – vector of dimension n×1 of values of the endogenous variable for each sampling unit,

$\lambda$ – spatial autoregression coefficient,

n – number of sample items (territorial systems),

$\rho$ – autoregression coefficient,

$\epsilon_{\mathrm{it}}$ – error vector (n×1) assuming autocorrelation,

$\mathrm{W} = (\mathrm{w_{ij}})_{\mathrm{i=1,j=1}}^{\mathrm{n,n}}$ – spatial weighing matrix of size n×n, W$Y$– spatial lag of the dependent variable,

$\mathrm{X} = (\mathrm{x_{ij}})_{\mathrm{i=1,j=1}}^{\mathrm{n,k}}$ – matrix of explanatory variables of size n×k, k – number of explanatory variables,

$\beta$ – vector of dimension k×1 of the estimated parameters reflecting the influence of explanatory variables on the dependent variable,

$u_{\mathrm{it}} = (u_1, \dots u_\mathrm{n})^T$ – vector n×1 of the model residuals, with respect to which it is assumed hereafter that they are equally and independently distributed with zero mean and variance $\sigma^2$, it means that $\varepsilon \sim \mathrm{N}(0,\sigma^2,\mathrm{I_n})$, $\mathrm{I_n}$ – a unit matrix of size n×n.

We have carried out calculations using the statistical package R.

The data for the study were taken from the websites of the United States Environmental Protection Agency[5], the U.S. Bureau of Economic Analysis[6] and the Federal State Statistics Service of Russia[7].

**Research results and their analysis**

Before building the models, we have analyzed the regions of Russia and the USA with the highest and lowest pollution levels.

In 2018, $CO_2$ emissions in Wyoming amounted to 110 tons per capita, which is the highest in the United States. According to the Energy Information Administration (EIA), the state is a major producer of coal, natural gas and crude oil. Also, one of the most polluted states is North Dakota. In 2018, its emissions amounted to 77 tons per capita. It is one of the ten largest coal-producing states in the United States and provides almost 4% of coal production in the country[8].

In Russia, the highest level of pollutant emissions was 1.6 tons per capita (Yamalo-Nenets Autonomous Okrug). According to the report "On the environmental situation in the Yamalo-Nenets Autonomous Okrug in 2017", the main pollution sources were oil and gas producing enterprises[9].

Thus, both in the US states and in Russia's regions, the main reason for the high emission level is the mining industry.

As for the regions with the lowest level of $CO_2$ emissions per capita, in 2018 in the United States, those were the states of Maryland and New York with indicators of 7.7 and 7.8 tons, respectively. According to the Energy Information Administration (EIA), New York City, with a population of almost 20 million people, has one of the lowest $CO_2$ emissions per capita – about 8 tons per capita. It is important to notice that the New York economy is focused on activities with low energy consumption (for example, financial markets)[10].

[5] United States Environmental Protection Agency. Available at: https://www.epa.gov/

[6] The Bureau of Economic Analysis (BEA). Available at: https://www.bea.gov/

[7] Available at: https://rosstat.gov.ru/

[8] Energy Information Administration (EIA). Available at: https://www.eia.gov

[9] On the environmental situation in the Yamalo-Nenets Autonomous Okrug in 2017: State Report. Salekhard, 2018.

[10] Energy Information Administration (EIA). Available at: https://www.eia.gov

Table 1. Moran's index and p-value for the dependent variable "pollutant emissions" in the USA and Russia (by year)

| Year | US Inverse Distance Matrix | | Russia's Inverse Distance Matrix | |
|---|---|---|---|---|
| | Moran's Index | P-value | Moran's Index | P-value |
| 2004 | -0.017 | 0.740 | -0.011 | 0.802 |
| 2005 | -0.016 | 0.66 | -0.01 | 0.748 |
| 2006 | -0.017 | 0.703 | -0.011 | 0.771 |
| 2007 | -0.016 | 0.675 | -0.011 | 0.783 |
| 2008 | -0.015 | 0.612 | -0.009 | 0.649 |
| 2009 | -0.013 | 0.455 | -0.009 | 0.646 |
| 2010 | -0.013 | 0.489 | -0.007 | 0.505 |
| 2011 | -0.013 | 0.49 | -0.007 | 0.506 |
| 2012 | -0.014 | 0.516 | -0.008 | 0.587 |
| 2013 | -0.012 | 0.439 | -0.007 | 0.488 |
| 2014 | -0.012 | 0.432 | -0.007 | 0.463 |
| 2015 | -0.014 | 0.518 | -0.007 | 0.485 |
| 2016 | -0.014 | 0.561 | -0.007 | 0.492 |
| 2017 | -0.014 | 0.561 | -0.009 | 0.605 |
| 2018 | -0.015 | 0.595 | -0.010 | 0.731 |

Source: Own compilation according to data of Energy Information Administration (https://www.eia.gov), U.S. Bureau of Economic Analysis (https://www.bea.gov), and Federal State Statistics Service of Russia (https://rosstat.gov.ru/).

In Russia, the lowest value was observed in 2018 in the Republic of Ingushetia – 0.002 tons per capita. We have noted that most of the regions with low pollutant emissions are located in the south of Russia (North Caucasian Federal District) and are the least economically developed. Also, low rates were recorded in Moscow and Saint Petersburg. This is not surprising, since these cities have the highest population density: in Moscow, it is 4,925.9 people per 1 sq. km, and in Saint-Petersburg – 3,741.5 people per 1 sq. km.

The next step for analyzing the spatial dependence between regions on the pollutant emission level is to find the Moran's spatial autocorrelation index *(Tab.1)*.

We can see that in Russia and the USA there is a spatial correlation according to the dependent variable, which means that the pollutant emissions are significant (at a significance level of 0.1). Accordingly, the emission level in one region is closely related to the emission level in another, so spatial models for the environmental Kuznets curve are constructed further:

1) for the USA:

$$Y = \lambda \times \mathrm{W} \times \mathrm{y} + \\ + \beta_1 \times \ln\mathrm{GDP} + \beta_2 \times \ln\mathrm{GDP}^2 + \beta_3 \times (Min) + \\ + \beta_4 \times (Man) + \beta_5 \times \ln\mathrm{In} + \beta_6 \times \ln\mathrm{El} + \mathrm{u}, \quad (13) \\ \mathrm{u} = p\mathrm{Wu} + \varepsilon,$$

where $Y$ – dependent variable (energy-related carbon dioxide emissions per capita (metric tons), W – matrix of spatial weights,

$\lambda$ and $p$ – spatial parameters.

We have used the following variables as explanatory variables:

lnGDP – real GDP by state per capita (in 2012 prices, million US dollars);

(*Min*) – share of mining in the sectoral structure of GDP by state;

(*Man*) – share of manufacturing industries in the structure of GDP by state;

lnIn – disposable income per capita (US dollars);

lnEl – energy consumption per capita (million BTU);

2) for Russia's regions:

$$\begin{gathered} Y = \lambda \times \mathrm{W} \times \mathrm{y} + \\ + \beta_1 \times \mathrm{lnGRP} + \beta_2 \times \mathrm{lnGRP}^2 + \beta_3 \times (Min) + \\ + \beta_4 \times (Man) + \beta_5 \times \mathrm{lnIn} + \beta_6 \times \mathrm{lnEl} + \mathrm{u}, \\ \mathrm{u} = pW\mathrm{u} + \varepsilon, \end{gathered} \quad (14)$$

where $Y$ – dependent variable (pollutant emissions into the atmospheric air from stationary sources per capita (t)), W – matrix of spatial weights, $\lambda$ and $p$ – spatial parameters. We have used the following variables as explanatory variables:

lnGRP – gross regional product per capita (in 2012 prices, million rubles);

$(Min)$ – share of mineral extraction in the sectoral structure of GRP;

$(Man)$ – share of manufacturing industries in the structure of GRP;

lnIn – average per capita monetary income (thousand rubles);

lnEl – electricity consumption per capita (thousand kWh).

It is worth noting that the dependent variables in the USA and Russia are different. For the US data, an indicator of $CO_2$ emissions, related to energy, was taken. They arise as a result of the consumption of fossil fuels in all sectors including residential, commercial, industrial, as well as during electricity consumption for production. We have taken the indicator "air pollutant emissions from stationary sources" as a dependent variable for analyzing regional data for Russia. It includes the following pollutants: sulfur dioxide, nitrogen oxides, carbon monoxide, hydrocarbons taking into account volatile organic compounds. The differences in the dependent variables, taken for analysis, are due to the fact that the methodologies for accounting for pollutant emissions in the USA and Russia differ.

*Table 2* shows the results of the obtained models.

Spatial autoregression coefficients are significant in both models; therefore, there is an interdependence of the pollution levels of neighboring regions both in Russia and in the USA.

In the model, based on the data from Russia's regions, the coefficients for all variables except *Min* and *Man* are statistically significant. In the USA, the coefficients for the variables *Min, Man*, lnEl are statistically significant. The estimates in *Table 2* cannot be interpreted directly because the spatial regression specification should be taken into account for the coefficients obtained. If there are lags of a dependent variable or independent variables in the models, then the dependent variable in *i*-th region (state) is influenced not only by its regressors, but also by indicators of other regions (states).

Table 2. SAC-FE model estimates

| | Coefficient | | Standard error | |
|---|---|---|---|---|
| | USA | Russia | USA | Russia |
| Spatial coefficient | 0.18 | -0.56 | - | |
| **Spatial autoregression coefficient** | **-0.66**** | **1.18**** | **(0.09)** | **(-0.35)** |
| **Regressors** | | | | |
| *Share of mining* | 0.00** | 0.00 | (0.00) | (0.00) |
| *Share of manufacturing industries* | 0.01*** | 0.00 | (0.00) | (0.00) |
| Ln (*Gross regional product*) | -0.69 | -1.43*** | (-2.71) | (-0.35) |
| (ln (*Gross regional product*))$^2$ | -0.02 | 0.05*** | (-0.12) | (-0.01) |
| Ln (*Average per capita income*) | 0.11 | 0.21** | (-0.07) | (-0.06) |
| Ln (*Electricity consumption*) | 0.85*** | -0.46** | (-0.04) | (-0.14) |

Note: *** – p < 0.001; **– p < 0.01; * – p < 0.05; . – p < 0.1.
Source: Own compilation according to data of Energy Information Administration (https://www.eia.gov), U.S. Bureau of Economic Analysis (https://www.bea.gov), and Federal State Statistics Service of Russia (https://rosstat.gov.ru/).

Direct and indirect effects are used for the correct interpretation of the coefficients. The direct effect is the influence of exogenous variables that relate to *i*-th state on the explained variable λ of *i*-th state. It is worth noting that in the simplest models, this is the coefficient $\beta$ before the variable. If there are $X$ and $Y$ lags in the equations, then the direct effect is calculated as the average value of the diagonal elements of the matrix $(I - p\times W)^{-1}\text{-}\beta_i$, where $I$ is a unit matrix of size $N$ (number of states), and $W$ is a matrix of weights (matrix of inverse distances). The indirect effect is the effect of independent variables that relate to *i*-th state on the dependent variable of *j*-th state. This effect is calculated as the average value of the non-diagonal elements of the matrix $(I - p\times W)^{-1}\text{-}\beta_i$.

The specificity of this model is that the right side of the equation includes the spatial lag of the endogenous variable ($\lambda\times W\times y$). Coefficients for independent variables cannot be interpreted directly; this requires direct and indirect effects which we have calculated at the next step.

According to *Table 3*, the coefficient for the variable "Share of mining" in both countries is significant. Accordingly, both in Russia and in the USA, this economic branch has an impact on pollutant emissions.

Indeed, the extractive industry makes a big contribution to the amount of pollutant emissions (Addison, 2018). When burning oil and gas, large amounts of $CH_4$ (methane), $C_2H_6$ (ethane), and $CO_2$ (carbon dioxide) are released into the atmosphere.

Also, in both countries, the coefficient for the variable "Share of manufacturing industries" is significant. Accordingly, manufacturing has a significant impact on emissions in both the US and Russia.

Moreover, this industry affects emissions not only in a particular state, but also in neighboring ones. For instance, a sharp increase in the cost of natural gas in one state may lead to the introduction of new energy-efficient technologies, which, in turn, will have an impact on reducing emissions and improving living standards. In the long term, this may affect production facilities, located in neighboring states. They can follow suit and also introduce more energy-efficient technologies to reduce energy consumption and decrease emissions. Accordingly, changes in the manufacturing industry in this state will affect emissions changes in others.

As for the region's GRP variable (or state GDP), this variable is not significant in the USA. We can assume that the lack of impact of this indicator on emissions is due to the fact that the main industries that influence carbon dioxide emissions (mining and manufacturing) do not make a significant contribution to the state's GDP. Thus, the hypothesis of the existence of the environmental Kuznets curve on the data of the US states has not been confirmed. It means that the

Table 3. Magnitude of direct and indirect effects

| | Direct effect | | Indirect effect | |
|---|---|---|---|---|
| | USA | Russia | USA | Russia |
| *Share of mining* | 0.005* | 0.03*** | 0.01 | 0.00 |
| *Share of manufacturing industries* | 0.01*** | 0.01* | 0.01. | 0.00 |
| *ln(Gross regional product)* | -0.71 | 2.85*** | -1.31 | -0.35 |
| *(ln(Gross regional product))$_2$* | **0.02** | **-0.11*** ** | 0.04 | 0.01 |
| *ln(Average per capita income)* | 0.11 | -0.54*** | 0.2 | 0.07 |
| *ln(Electricity consumption)* | 0.88*** | 1.28*** | 1.62. | -0.16 |

Note: *** – p < 0.001; **– p < 0.01; * – p < 0.05; . – p < 0.1.
Source: Own compilation according to data of Energy Information Administration (https://www.eia.gov), U.S. Bureau of Economic Analysis (https://www.bea.gov), and Federal State Statistics Service of Russia (https://rosstat.gov.ru/).

level of carbon dioxide emissions does not depend on the state's economic growth. Consequently, changing the economic structure by reducing the share of manufacturing and extractive industries does not have a significant impact on the economic development rate, but at the same time entails a reduction in emissions in the United States.

However, for Russia, the GRP variable turned out to be significant. The results of the model's evaluation confirmed the presence of EKC, which means that there is an inverted U-shaped dependence of pollutant emissions on GRP in Russia's regions. Variable $(\ln GDP)^2$ is significant, therefore, the change in this indicator has an impact on the change in carbon dioxide emissions. Next, we have found GRP turning point, after which the pollutant emissions level will decrease. To calculate the turning point, the found values of the direct effects (lnGREP) and $(\ln GRP)^2$ were taken. The result was 581,602 (in 2012 prices, rubles).

Accordingly, in 10 regions out of 75, the average annual GRP per capita for the period 2004–2018 exceeds this value. Large indicator values are typical for Moscow and regions with a raw material export-oriented economy. Most of them are characterized by a high share of mining in the GRP structure. For example, in the Magadan Oblast in 2018, the share of the extractive industry in the GRP structure was 37%.

Thus, the value of the GRP turning point, obtained over a given period, cannot be considered easily achievable for many Russia's regions.

Accordingly, Russia's continued dependence on energy-intensive types of production not only poses a problem for the Russian economy in the future, but is also expected to exacerbate the consequences it faces as a result of climate change. Therefore, it is necessary to take measures to reduce greenhouse gas emissions and preserve the environment. Let us try to highlight the main measures.

First of all, it is necessary to revise the goal of reducing emissions by 2030. For instance, we can try to take into account the experience of the EU countries, which have committed to reduce air emissions by 55% by 2030. Also, in many countries there is a quota trading policy, which means that a limit on carbon dioxide emissions is set. A government agency sets a "limit" on the emissions that can be produced in its jurisdiction, and companies are given carbon emission quotas. These quotas can be used or sold to other companies. It is possible to raise the question of setting more stringent requirements for greenhouse gas emissions. So, for example, it is possible to make a decision on a carbon tax, and to introduce a fee for burning carbon-based fuels. It is worth noting that this tax is taken into account in the policies of many developed countries in order to reduce the use of fossil fuels, the burning of which harms the environment. The Government of the Russian Federation started discussing this issue at the end of 2021.

Second, it is important to gradually reduce emissions of coal-fired electricity. Instead, it is necessary to develop other sources of energy, such as solar, wind, tidal, geothermal. Investment from the state is essential part for the development of alternative sources.

Third, measures should be taken in the field of agriculture and forestry, which is to increase the amount of $CO_2$ absorption due to new forest plantations and to reduce $N_2O$ emissions by reducing the amount of fertilizers used.

Fourth, it is necessary to increase the number of landfill gas capture plants for reducing emissions. Landfill gas is a renewable energy source. So that the gas does not dissipate in the atmosphere, it can be captured, processed and used.

**Conclusion**

Global warming is one of the most serious problems in the world today. It is believed that the cause of environmental problems is economic growth: an increase in production leads to emission growth.

The article assesses the impact of mining, manufacturing, monetary income per capita, electricity consumption on air pollution (pollutant emissions) in the two countries. There is no doubt that air pollution, even at the regional level, is also influenced by the policies of States including neighboring countries. The obvious difficulty lies in the fact that it is difficult for countries to agree on common approaches to solving the problem of environmental pollution, in particular air. The situation is aggravated by the difficult international situation, when many agreements are being revised, and countries are withdrawing from the treaties. The Paris Agreement is an example. It is impossible to ignore the positive fact that the current positions of the Presidents of the Russian Federation and the United States on this issue do not contradict each other in general.

As a result of the analysis, we have revealed that economic growth may not have an impact on the pollution level (for example, in the USA). As policy measures in the United States, we can consider the reduction of the manufacturing and extractive industries, since it will not affect the development rate of the US economy. It is also worth noting that the use of energy-efficient technologies and renewable energy sources will lead to a reduction in the pollutant emissions level.

In Russia's regions, we have obtained a U-shaped dependence of pollutant emissions on the region's GRP for the period from 2004 to 2018. But the calculated value of the GRP turning point, upon reaching which emissions of pollutants should begin decreasing, turned out to be quite high for Russia's entities, and only in 10 of them the emission level decreases when this value is reached. Thus, the confirmation of the hypothesis of the existence of the environmental Kuznets curve on Russian data is conditional. Regions with a high GRP level correspond to a high emission level, since they have a significant raw material base.

Consequently, the economic growth of Russia's regions cannot be defined as stable in the long term and contributing to reducing the pressure exerted on the environment. The main reason is the raw material dependence of the Russian economy. Decarbonization measures are quite obvious: the use of highly efficient, "clean" technologies in the extractive sector of the economy, energy-saving technologies in the manufacturing sector, as well as the implementation of economic diversification. Nevertheless, their intensive implementation remains an extremely difficult task.

In conclusion, we would like to note that the research results can help in modeling regional economic growth taking into account trends in environmental policy. The more accurate the estimates of the coefficients of the factors considered in the model are, the more concrete it is possible to formulate assumptions about the necessary regional policy measures and their impact on economic growth, as well as predict pollution levels. The approach to this issue in the United States is also useful for Russia, despite the fundamental differences in the economies of the two countries. The findings may be useful for a coordinated environmental policy at the federal and regional levels.

## References

Addison T. (2018). Climate change and the extractives sector. *Extractive Industries*, 460.

Arellano M., Bond S. (1991). Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *The Review of Economic Studies*, 58(2), 277–297.

Bobylev S.N. (2019). New economic models and sustainable development. *Ekonomicheskoe vozrozhdenie Rossii=The Economic Revival of Russia*, 3, 23–29 (in Russian).

Canas A., Ferrao P., Conceicao P. (2003). A new environmental Kuznets curve? Relationship between direct material input and income per capita: Evidence from industrialized countries. *Ecological Economics*, 46(2), 217–229.

Dinda S. (2004). Environmental Kuznets curve hypothesis: A survey. *Ecological Economics*, 49(4), 431–455.

Druzhinin P.V., Shkiperova G.T. (2014). Assessment of mutual influence of economic and ecological processes. *Ekonomicheskie i sotsial'nye peremeny: fakty, tendentsii, prognoz=Economic and Social Changes: Facts, Trends, Forecast,* 2(32), 213–224 (in Russian).

Druzhinin P.V., Shkiperova G.T., Potasheva O.V. (2018). Environmental Kuznets curve: The case of Russian and Finland. *Ekonomika: vchera, segodnya, zavtra=Economics: Yesterday, Today and Tomorrow*, 8(11a), 83–97 (in Russian).

Grossman G.M., Krueger A.B. (1991). Environmental impacts of a North American free trade agreement. *National Bureau of Economic Research, Working Paper Series,* 3914.

Ivanova V. (2019). GRP and environmental pollution in Russian regions: Spatial econometric analysis. *Kvantil'=Quantile,* 14, 53–62 (in Russian).

Jian J., Fan X., He P. et al. (2019). The effects of energy consumption, economic growth, and financial development on $CO_2$ emissions in China: A VECM Approach. *Sustainability*, 11(18), 4850.

Ketenci N. (2018). The environmental Kuznets curve in the case of Russia. *Russian Journal of Economics*, 4, 249–265.

Kudryavtseva O.V., Ivanov E.V., Kolesnik D.P. et al. (2017). Assessment of the impact of environmental pollution on economic growth. *Nauchnye issledovaniya ekonomicheskogo fakul'teta. Elektronnyi zhurnal=Scientific Research of Faculty of Economics. Electronical Journal*, 9(3), 68–80 (in Russian).

Mihalishchev S., Raskina Yu. (2016). Environmental Kuznets Curve: A case of Russia. *Finansy i biznes=Finance and Business*, 1, 17–39 (in Russian).

Motrenko A.P. (2011). Using the Granger test when predicting time series. *Mashinnoe obuchenie i analiz dannykh=Machinery Learning and Data Analysis*, 1(1), 51–60 (in Russian).

Pao H.T., Tsai C.M. (2010). $CO_2$ emissions, energy consumption and economic growth in BRIC countries. *Energy Policy*, 38(12), 7850–7860.

Shikwambana L., Mhangara P., Kganyago M. (2021). Assessing the relationship between economic growth and emissions levels in South Africa between 1994 and 2019. *Sustainability*, 13(5), 2645.

Soytas U., Sari R., Ewing B.T. (2007). Energy consumption, income, and carbon emissions in the United States. *Ecological Economics*, 62(3–4), 482–489.

Xu H., Zhang C., Li W., Zhang W., Yin H. (2018). Economic growth and carbon emission in China: A spatial econometric Kuznets curve? *Zbornik radova Ekonomskog fakulteta u Rijeci: časopis za ekonomsku teoriju i praksu*, 36(1), 11–28.

Yang X., Lou F., Sun M. et al. (2017). Study of the relationship between greenhouse gas emissions and the economic growth of Russia based on the Environmental Kuznets Curve. *Applied Energy*, 193, 162–173.

Zhukova A.K., Silaev A.M., Silaeva M.V. (2016). Spatial analysis of life expectancy in Russian regions. *Prostranstvennaya ekonomika=Spatial Economics*, 4, 112–128 (in Russian).

Zhuravleva T.A., Semenova E.M., Pavlov K.V. (2017). Economic growth and problems ecology in Russia. *Izvestiya Tul'skogo gosudarstvennogo universiteta. Ekonomicheskie i yuridicheskie nauki=News of the Tula State University. Economic and Legal Sciences*, 2(1), 188–195 (in Russian).

## Information about the Authors

Aleksei N. Kurbatskiy – Candidate of Sciences (Physics and Mathematics), Associate Professor, head of department, Moscow School of Economics, Lomonosov Moscow State University (1, Leninskie Gory, building 61, Moscow, 119234, Russian Federation; e-mail: akurbatskiy@gmail.com)

Ekaterina I. Shakleina – master's degree student, Moscow School of Economics, Lomonosov Moscow State University (1, Leninskie Gory, building 61, Moscow, 119234, Russian Federation; e-mail: kateshkln99@gmail.com)

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