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The Impact of Gross Regional Product Per Capita on the Processes of Convergence between Different Regions of the Country

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ABSTRACT: The purpose of this study was to analyses the dynamics of gross regional product per capita within the regions of Russia from 2005 to 2020, with the objective of examining the presence of convergence among these administrative and territorial units. Beta and sigma convergence methodologies were utilized. Beta convergence refers to the tendency of poorer regions or countries to grow faster than richer ones, leading to income equalization. Sigma convergence indicates a reduction in disparities between regions or countries over time, reflected in decreasing income variance. Those concepts are relevant for Russia as they highlight the potential for reducing regional economic disparities and fostering balanced growth across its diverse regions. The speed of convergence was calculated using both ordinary least squares and nonlinear least squares methods, revealing that eliminating a 50% gap in GRP per capita among Russian regions would take approximately 902 and 821 years, respectively. Thereby, evidence of sigma convergence was not found, implying that the inequality among these regions remained statistically insignificant from 2005 to 2020. The analyzed period was characterized by divergent processes within the economy of the Russian regions. The study fills the gap by highlighting the absence of sigma convergence, indicating persistent inequality in economic results across Russian regions despite globalization trends that typically contribute to convergence. Further research is necessary to understand the underlying reasons for this divergence.

Keywords: beta-convergence, divergence, regional development, regional economic analysis, sigma convergence.

I. INTRODUCTION

Globalization has facilitated the transmission of divergent processes within countries, leading to an increase in the gap between rich, export-oriented regions and regions oriented to the domestic market. This has led to a growing body of academic research on this issue, with several studies providing evidence of both convergence and divergence in regional economic outcomes.

Regional convergence is a concept based on regional growth theory, detailed in a comprehensive study by Barro [1]. It is characterized by a reduction in regional disparities over time. GRP provides a direct measure of the economic output and productivity of individual regions, reflecting their contribution to the national economy. This metric is especially relevant in Russia due to the pronounced economic disparities across its regions, stemming from variations in resource endowments, industrial structures, and access to markets. Bakus and Ferto [2] found evidence of regional divergence in beta, sigma, and unit root convergence. Ceylan and Abiyev [3] employed nonlinear and nonlinear asymmetric unit root tests to detect long-term or deterministic convergence within five European Union countries and stochastic convergence in nine EU countries. Chambers and Dhongde [4] reported that the relative income distributions of developed countries have converged at a more rapid pace.

Fallahi and Voia [5] constructed subsampling confidence intervals to assess the convergence in per capita energy use in OECD countries. They found that the per capita energy use in Australia, Austria, Belgium, Denmark, Finland, Greece, Italy, Japan, Luxembourg, the Netherlands, Norway, Spain, and Switzerland has a convergent pattern; the per capita energy use in Greece, Luxembourg, and Spain appears to be very persistent; and for the remaining countries (i.e., 12 countries), they established a divergent pattern.

The primary objective of our research was to investigate the process of convergence among Russian regions in terms of gross regional product (GRP) per capita from 2005 to 2020. The focal point of our study was the dynamics of the GRP per capita within the analyzed regions of Russia, which reflects the extent of convergence among different areas of the country.

Our hypothesis posits that despite some degree of convergence in terms of the GRP per capita among Russian regions, the equalization of regional development is a gradual and slow process. The originality of our study lies in the fact that instead of utilizing indicators that measure inequality between regions, such as the Gini coefficient, we opted for a more productive approach by employing the concepts of beta and sigma convergence in our methodology. This choice was made because claims of high levels of inequality are often delivered with excessive emotional overtones, resembling journalistic narratives rather than rigorous scientific analysis. In contrast, we conducted an examination of changes in the variance in gross regional product per capita across Russian regions during the specified time frame and rigorously assessed the statistical significance of our findings.

Through our investigation into the presumed presence of convergence among Russian regions, we were able to ascertain the rate at which convergent processes are occurring and determine the timeframe within which the existing (and anticipated) gap in the GRP per capita between the analysed administrative-territorial entities can be narrowed. In the study we employed methodological approach utilizing both beta and sigma convergence metrics to provide a nuanced analysis of regional economic dynamics in Russia. Our results underscore the absence of sigma convergence, highlighting persistent inequalities in economic outcomes despite ongoing globalization. So, it offers valuable insights for policymakers by emphasizing the urgency of addressing regional disparities through targeted economic strategies. This represents the scientific novelty of our research, the practical applications of which we deem appropriate from both the perspective of economic methodology and the formulation of regional economic policies designed to promote economic alignment within the country.

This study was conducted to analyse the dynamics of gross regional product per capita in Russian regions from 2005 to 2020, aiming to examine convergence among these administrative and territorial units.

- The slow convergence rate and absence of convergence signs suggest diverging economic processes across Russian regions.
- The lack of economic equalization (sigma convergence) in regions is driving the migration of the working population to wealthier urban centers.

II. LITERATURE REVIEW

From the standpoint of regional economics, notably within the framework of neoclassical growth theory, it is anticipated that regional disparities will diminish over time. The neoclassical growth model posits that the economic output of a given region, exemplified by metrics such as GDP per capita, hinges upon the accumulation of factors of production, specifically capital and labor, as encapsulated by the aggregate production function. This model operates under the assumptions of constant returns to scale and diminishing marginal productivity of the factor inputs. Consequently, regions endowed with a high initial level of factor inputs tend to experience slower economic growth, while those with lower initial income exhibit faster growth—a phenomenon commonly referred to as beta convergence. It is conventionally hypothesized that all regions ultimately converge toward the same steady-state level of regional output [6, p. R8].

While previous research has extensively studied convergence in other contexts, our study makes a novel contribution by focusing on Russian regions from 2005 to 2020, a period characterized by significant socio-economic transformations. Additionally, unlike prior studies [2, 3] that predominantly use traditional inequality metrics, such as the Gini coefficient, this research employs beta and sigma convergence

methodologies to rigorously assess regional economic disparities. Sigma convergence denotes the progressive reduction of regional disparities concerning regional output over time. Abramovitz [7] called convergence measured by dispersion levels "sigma convergence" and convergence measured by the extent to which poor countries grow faster than rich countries "beta convergence". This concept has been elucidated in works such as those authored by Allington and McCombie [8] and Capello and Nijkamp [9].

Both forms of convergence can be subject to empirical examination. In the case of beta convergence, the natural logarithms of output growth across i regions over a span of T time periods are regressed against the natural logarithms of the initial output values at time t. The initial formulation of the convergence equation was introduced by Barro and Sala-i-Martin [10], employing a nonlinear least squares (NLS) estimation approach. However, in numerous instances, researchers opt for a linear transformation, which enables the utilization of ordinary least squares (OLS) estimation methods, as demonstrated in studies such as those by Allington and McCombie [8], Dapena et al. [11], Schmidt [12], and Young et al. [13]. In economic studies, ordinary least squares (OLS) are commonly used for estimating relationships in linear models by minimizing the sum of squared residuals, suitable for straightforward, interpretable relationships like the impact of education on income [14]. Nonlinear least squares (NLS), on the other hand, is applied to capture complex, nonlinear relationships (e.g., Cobb-Douglas production functions) and requires iterative methods to estimate parameters accurately when relationships between variables are not linear [15]. Since economic relationships are often non-linear, Nonlinear Least Squares (NLS) are also commonly employed to capture more complex dynamics that may not be fully captured by a linear model. The inclusion of NLS complements the OLS analysis by providing a more flexible framework, ensuring that potential non-linearities in the convergence process are accounted for, thereby enhancing the robustness of the findings.

The dependent variable in the convergence equation can be either the regional growth rate between two distinct years, as observed in the work of Young et al., or the average annual growth rate, as evidenced in studies conducted by Goecke and Hüther [16], Puente [17], and Weddige-Haaf and Kool [18]. To ascertain statistical significance, hypothesis tests involving t tests for the regression coefficients and, in the case of OLS estimation, the F test are carried out to assess the significance of the R^2 statistic.

The focal parameter of interest in this model is represented as β; hence, the term "beta convergence" is used to describe the modelled process. When $\beta < 0$ and exhibits statistical significance, it signifies the existence of absolute beta convergence. When additional variables, commonly referred to as conditional variables, are incorporated into the convergence equation, it transforms into a test for conditional beta convergence [6].

An alternative interpretation of the β coefficient can be discerned by considering the speed of convergence, denoted as lambda, λ, and H, which signifies the "Halflife". Halflife represents the time, expressed in the observed time periods under consideration, required to reduce regional disparities by one-half, a concept elaborated upon in works such as those by Allington and McCombie [8] and Schmidt [12].

Sigma convergence can be evaluated through two distinct approaches, contingent on the number of time periods under consideration. Initially, the degree of regional inequality among all regions at a given time point, denoted as σ_t, or the coefficient of variation, cv_t, for GRP per capita in its original or natural-logged form, is quantified. When only two specific years are considered, the quotient of these parameters is computed. For instance, if $\sigma_t 1 > \sigma t_2$, it signifies a reduction in regional inequality from time t_1 to t_2. A significance test can be applied using a straightforward analysis of variance (ANOVA), with the test statistic being the ratio of the underlying variances (σ^2), as elucidated in works by Furceri [19], Schmidt [12], and Young et al. [13].

In the context of a time series, the dispersion parameter is regressed against time and concurrently visualized. A negative slope coefficient of time in this regression signifies the presence of sigma convergence, a concept illustrated in studies by Goecke and Hüther [16], Huang and Leung [20], and Schmidt [12].

III. METHODS

We used the gross regional product by constituent entities of the Russian Federation (gross value added in current basic prices) from 2005 to 2020. The importance of studying GRP in modern Russia is highlighted, for instance, by Solomonov et al. [21].

To achieve the objectives of this study, the research methodology was organized into four key stages, each addressing a specific aspect of the analysis (Table 1).

Table 1. Research methodology stages.

Stage	Description	Methods Used
Data collection	Collected GRP per capita data for 2005–2020 from the Federal State Statistics Service	Literature review
β-convergence analysis	Examined whether poorer regions grew faster than richer ones	Ordinary Least Squares (OLS) and Nonlinear Least Squares (NLS) regression
Sigma convergence analysis	Assessed reduction in economic disparities over time	Variance analysis, standard deviation, ANOVA tests.
Statistical Analysis	Conducted computations and visualization	R Statistical Language

Source: Compiled by authors

At the first stage, we collected statistical data we obtained the data from the official website of the Federal State Statistics Service of the Russian Federation [22]. Due to the lack of data for 2005 and 2010, we excluded the Nenets Autonomous District and the Arkhangelsk Region without an autonomous district (North-Western Federal District), the Republic of Crimea and Sevastopol (Southern Federal District), the Khanty-Mansi Autonomous Region – Ugra, Yamal-Nenets Autonomous District, and the Tyumen Region without Autonomous Districts (Ural Federal District). While the exclusion of regions like the Yamal-Nenets Autonomous District and Crimea, due to data limitations, reduces the generalizability of the findings to all of Russia, the results remain highly relevant. The included regions represent a broad spectrum of Russia's economic diversity, providing valuable insights into national convergence trends despite these exclusions.

At the second stage, we determined the convergence of regional development in Russia based on the indicator of per capita gross regional product using β -convergence and sigma-convergence measures, both with ordinary least squares and nonlinear least squares methods. β-convergence measures whether poorer regions grow faster than richer ones over time, helping to reduce economic disparities. The idea is simple: regions starting with lower income levels (like GRP per capita) should catch up to wealthier regions if economic growth is balanced. This concept provides a way to understand how evenly economic development spreads across regions.

β-convergence (estimated method: ordinary least squares):

$$\frac{1}{T}\sum_{t=1}^{T} ln\left(\frac{Y_{i,t+1}}{Y_{i,t}}\right) = \alpha + \beta \ln(Y_{i,t1}) + \epsilon \qquad (1)$$

$Y_{i,t}$ the income or output level (such as GDP) of region or country i at time t. $Y_{i,t+1}$: The income level of the same region or country i at time $t+1$, the subsequent period. $ln(Y\_(i,t+1)/Y\_(i,t))$: The log growth rate of income from period t to $t+1$. $\frac{1}{T}\sum_{t=1}^{T} ln$: The average growth rate over TTT time periods. α: The intercept term in the regression, representing a constant factor influencing growth. β the coefficient of beta-convergence. If $\beta<0 \backslash beta < 0\beta<0$, it implies beta-convergence, meaning regions with lower initial income levels tend to grow faster. Ln ($Y_{i,t1}$): The natural logarithm of the initial income level of region iii, which helps assess if lower initial levels are associated with higher growth. ϵ the error term, representing random variation not explained by the model.

β-convergence (estimated method: nonlinear least squares):

$$\frac{1}{T}\sum_{t=1}^{T} ln\left(\frac{Y_{i,t+1}}{Y_{i,t}}\right) = \alpha - \left[\frac{1-e^{\beta T}}{T}\right]\ln\left(Y_{i,t1}\right) + \epsilon \quad (2)$$

variables are the same except:

$e^{\beta T}$: The exponential term capturing nonlinearity, which makes the model nonlinear in β.

σ-convergence:

$$\sigma_t = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Y_{i,t} - \overline{Y}_t\right)^2} \quad (3)$$

λ (convergence speed) (represents the annual rate at which regional income disparities are reduced):

$$\frac{-\ln(1+\beta)}{T} \quad (4)$$

Half-life (time required to reduce regional disparities by 50%, derived from λ):

$$H = \frac{\ln(2)}{\lambda} \quad (5)$$

$Y_{i,t}$ – Gross regional product per capita of region i in period t, $\overline{Y}_t$ - arithmetic mean of GRP ($Y_{i,t}$) for all study regions during period t, T – number of years, Xi – a set of other variables (conditions), σ_t – standard deviation of GRP for all the regions, ϵ – model error limit, n – number of regions analysed. This function provides the analysis of absolute and conditional regional economic beta convergence for cross-sectional data using the ordinary least squares (OLS) technique.

At the third stage, using the analysis of variance (ANOVA) method, we determined sigma convergence, and the results are given in Table 3. Sigma convergence analysis examines whether the dispersion or standard deviation (sigma) of a variable decrease over time, indicating convergence. ANOVA can be used to assess sigma convergence in Gross Regional Product (GRP) by comparing the variance in GRP across regions over different time periods. A statistically significant decrease in variance over time would indicate sigma convergence, suggesting that regional GRPs are becoming more similar [23].

At the fourth stage, analyses were conducted using the R statistical language, version 4.2.2 [20] on Windows 10 x64, build 18363, using the following packages: 'report', version 0.5.7 [21], ggplot2, version 3.4.2 [22], 'readxl', version 1.4.2 [23] and 'REAT', version 3.0.3 [5]. R is a powerful tool for economic studies due to its functional programming capabilities and extensive support for statistical analysis. It allows for model specifications to be treated as first-class objects, facilitating complex economic modeling [24].

IV. RESULTS

Beta and Sigma Convergence. Russia, 2005-2020, we determined beta convergence using the ordinary least squares method, and the results are presented in Table 2.

Table 2. Absolute beta convergence. Russia, 2005-2020

Model Coefficients (Estimation Method: Ordinary Least Squares, OLS)				
	Estimate	**Std. Error**	**t value**	**Pr (> | t |)**
Alpha	2.476179e-01	0.033875813	7.309578	2.018217e-10
Beta	-1.145566e-02	0.002993053	-3.827415	2.597945e-04
Lambda	7.681185e-04	NA	NA	NA

Halflife	9.023961e+02	NA	NA	NA

Model Summary

	Estimate	F value	df 1	df 2	Pr (> F)
R-Squared	0.1581138	14.6491	1	78	0.0002597945

Source: Research findings

We obtained similar results using the trend regression function. We obtained estimates, standard errors, t values, and p values for different parameters of the statistical model:
1. Alpha: The estimated value for alpha is 0.2476, with a standard error of 0.0339. A t value of 7.3096 indicates that the estimated value is significant at a high level of confidence. The p value of 2.0182e-10 is very small, suggesting strong evidence against the null hypothesis that the alpha is zero.
2. Beta: The estimated value for Beta is -0.0115, with a standard error of 0.003. The t value of -3.8274 indicates that the estimated value is significant at a high level of confidence. The p value of 2.5979e-04 is very small, suggesting strong evidence against the null hypothesis that Beta is zero.
3. Lambda: The estimated value for lambda is 0.000768, with no standard error provided. Since there is no standard error or t value, we cannot determine the statistical significance of the Lambda estimate.
4. Halflife: The estimated value for Halflife was 902.3961, with no standard error provided. Similar to Lambda, since there is no standard error or t value, we cannot determine the statistical significance of the estimate for Halflife. This implies that the output gap will be reduced by 50% in approximately 902 years.

Regarding the overall model performance, the R-squared value of 0.1581 suggests that approximately 15.81% of the variation in the dependent variable can be explained by the independent variables included in the model. The F value of 14.6491, with 1 degree of freedom in the numerator and 78 degrees of freedom in the denominator, indicates that the overall model is statistically significant. The p value of 0.00025979 provides evidence against the null hypothesis that all the regression coefficients are zero.

These results suggest that the Alpha and Beta parameters have a significant impact on the model, while the significance of Lambda and Halflife cannot be determined due to missing information or unavailability of standard errors. The results obtained in the course of this study provide information about regional beta and sigma convergence, as well as absolute beta convergence (Table 3).

Table 3. Sigma convergence for two periods. Russia, 2005, 2020.

	Estimate	**F value**	**df 1**	**df 2**	**Pr (> F)**
CV 2005	0.5842953	NA	NA	NA	NA
CV 2020	0.5364954	NA	NA	NA	NA
Quotient	1.0890966	1.186131	79	79	0.4498045

Source: Research findings

Absolute Beta Convergence

- Alpha: The estimated value for alpha is 0.2476, with a standard error of 0.0339. A t value of 7.3096 indicates that the estimated value is statistically significant at a high level of confidence. The p value of 2.0182e-10 suggests strong evidence against the null hypothesis that the alpha is zero.
- Beta: The estimated value for Beta is -0.0115, with a standard error of 0.003. The t value of -3.8274 indicates that the estimated value is statistically significant at a high level of confidence. The p value of 2.5979e-04 suggests strong evidence against the null hypothesis that Beta is zero.
- Lambda and Halflife: No standard errors or t values are provided for Lambda or Halflife, so we cannot determine their statistical significance.
- R-Squared: The R-squared value of 0.1581 indicates that approximately 15.81% of the variation in the dependent variable can be explained by the independent variables included in the model. The F value of 14.6491, with 1 degree of freedom in the numerator and 78 degrees of freedom in the denominator, suggests that the overall model is statistically significant. The p value of 0.00025979 provides evidence against the null hypothesis that all the regression coefficients are zero.

Sigma Convergence (SD)

- SD 2005: The estimated standard deviation for the year 2005 is 0.5843, but no additional information is provided, so we cannot determine its statistical significance or interpret it confidently.
- SD 2020: The estimated standard deviation for the year 2020 is 0.5365, but no additional information is given, so we cannot determine its statistical significance or interpret it confidently.
- Quotient: The quotient between the two standard deviations is 1.0891. The F value of 1.1861, with 79 degrees of freedom in both the numerator and the denominator, suggests that the difference in standard deviations is not statistically significant. The p value of 0.4498 supports this conclusion.

In summary, the results indicate significant absolute beta convergence, as both the alpha and beta coefficients are statistically significant. However, the statistical significance or interpretability of Lambda and Halflife cannot be determined due to missing information. The model also suggested that approximately 15.81% of the variation in the dependent variable can be explained by the independent variables. Regarding sigma convergence, no statistically significant difference is found between the standard deviations of the two periods (2005 and 2020), as the F value is not statistically significant.

The results also indicate that there is evidence of absolute beta convergence in the regions being studied, where regions with initially lower values for the variable tend to experience higher growth rates, while regions with initially higher values tend to converge over time (Table 4). The statistical significance of the "Alpha" and "Beta" coefficients indicates that these relationships are unlikely to be due to random chance, although the model overall does not explain a large proportion of the variance in the dependent variable.

Table 4. Natural logarithms of the initial and growth rates of gross regional product per capita, Russian regions, 2005–2020.

Region	ln_initial	ln_growth
Belgorod region	11.471178	0.12721714
Bryansk region	10.818245	0.12929494
Vladimir region	10.972688	0.13015371
Voronezh region	10.942606	0.13970464
Ivanovo region	10.597612	0.12817466
Kaluga region	11.144643	0.13918558
Kostroma region	11.055710	0.10884262
Kursk region	11.198150	0.12652881
Lipetsk region	11.706650	0.10026675
Moscow region	11.559220	0.12508444
Oryol region	11.471178	0.12032568
Ryazan region	10.818245	0.11767405
Smolensk region	10.972688	0.12017124
Tambov region	10.942606	0.12789237
Tver region	10.597612	0.11668862
Tula region	11.144643	0.12776058
Yaroslavl region	11.055710	0.10708435
The City of Moscow	11.198150	0.09412778
Republic of Karelia	11.706650	0.10207930
Republic of Komi	11.559220	0.09654137
Arkhangelsk region	11.767299	0.11254477
Vologda region	11.960042	0.08315727
Kaliningrad region	11.375074	0.12037520
Leningrad region	11.711975	0.11266876
Murmansk region	11.961785	0.12823772
Novgorod region	11.464640	0.10657870
Pskov region	10.929043	0.11763764
The City of Saint-Petersburg	11.862142	0.12827351

Republic of Adygea	10.558790	0.13886014
Republic of Kalmykia	10.404805	0.15642004
Krasnodar territory	11.19539	0.12301040
Astrakhan region	11.15359	0.13475152
Volgograd region	11.24818	0.10910472
Rostov region	11.01163	0.12649377
Republic of Dagestan	10.42939	0.13050021
Republic of Ingushetia	9.766241	0.13991647
Kabardian-Balkar Republic	10.65143	0.10710898
Karachaev-Circassian Republic	10.51790	0.11498942
Republic of North Ossetia–Alania	10.69483	0.12021452
Chechen Republic	9.905406	0.14294571
Stavropol territory	10.885839	0.11690404
Republic of Bashkortastan	11.447673	0.10083667
Republic of Mariy El	10.749130	0.12208479
Republic of Mordovia	10.839240	0.12704636
Republic of Tatarstan	11.761557	0.11078877
Udmurt Republic	11.411073	0.10728248
Chuvash Republic	10.896775	0.11141303
Perm territory	11.692360	0.10070220
Kirov region	10.928213	0.11550690
Nizhny Novgorod region	11.377732	0.11596367
Orenburg region	11.523967	0.11156343
Penza region	10.862144	0.13235398
Samara region	11.732665	0.09332225
Saratov region	11.092193	0.11316239
Ulyanovsk region	10.998841	0.11968865
Kurgan region	10.853677	0.11594899
Sverdlovsk region	11.596321	0.11257467
Tyumen region	13.419810	0.07036871
Chelyabinsk region	11.504488	0.10338310
Republic of Altai	10.682636	0.12481068
Republic of Tyva	10.556586	0.12532028
Republic of Khakassia	11.262727	0.12403213
Altai territory	10.893259	0.11255722
Krasnoyarsk territory	11.934192	0.12211485
Irkutsk region	11.541555	0.12096294
Kemerovo region	11.559470	0.08803352
Novosibirsk region	11.390481	0.11356298
Omsk region	11.598833	0.08646554
Tomsk region	11.953534	0.08030288
Republic of Buryatia	11.255620	0.09205344
Republic of Sakha (Yakutia)	12.164709	0.12041501
Zabaykalsky territory	11.030703	0.12499879
Kamchatka territory	11.769433	0.13247860
Primorsky territory	11.435009	0.12272324
Khabarovsk territory	11.663563	0.11558409
Amur region	11.391854	0.12426160
Magadan region	11.969077	0.17046221
Sakhalin region	12.347130	0.14604673
Jewish autonomous region	11.255698	0.10962488

Chukotka autonomous area	12.376383	0.15442497

Table 5 presents the results of the convergence analysis obtained using the nonlinear least squares method, which are similar to the results obtained using the trend regression method. We obtained estimates, standard errors, t values, and p values for the coefficients of a model fitted using the nonlinear least squares (NLS) estimation method. These coefficients are specifically related to the concept of absolute beta convergence.

Table 5. Absolute beta convergence. Russia, 2005-2020.

Model Coefficients (Estimation Method: Nonlinear Least Squares, NLS)				
	Estimate	**Std. Error**	**t value**	**Pr (> | t |)**
Alpha	2.476179e-01	0.033875814	7.309578	2.018218e-10
Beta	1.256951e-02	0.003614078	3.477930	8.295001e-04
Lambda	8.432784e-04	NA	NA	NA
Halflife	8.219672e+02	NA	NA	NA

Source: Research findings

1. Alpha: The estimated value for alpha is 0.2476, with a standard error of 0.0339. A t value of 7.3096 indicates that the estimated value is statistically significant at a high level of confidence. The p value of 2.0182e-10 is very small, suggesting strong evidence against the null hypothesis that the alpha is zero.
2. Beta: The estimated value for beta is 0.0126, with a standard error of 0.0036. A t value of 3.4779 indicates that the estimated value is statistically significant at a moderate level of confidence. The p value of 0.0008 is small, suggesting evidence against the null hypothesis that Beta is zero.
3. Lambda: The estimated value for lambda is 0.0008, but no standard error is provided. Therefore, we cannot determine the statistical significance of this estimate or the associated t value.
4. Halflife: The estimated value for Halflife was 821.9672, but no standard error was provided. This implies that the output gap will be reduced by 50% in approximately 821 years. Thus, we cannot determine the statistical significance of this estimate or the associated t value.

Regarding the statistical significance of the coefficients

Both the alpha and beta coefficients are statistically significant. The estimated value for Alpha suggests a baseline level, while the estimated value for Beta indicates the rate of convergence. The significance of Lambda and Halflife cannot be determined due to missing information or unavailability of standard errors. These results suggest that the model provides evidence of absolute beta convergence, where the variable of interest tends to converge over time to a common value across different regions or units.

Overall, these results suggest that there is evidence of absolute beta convergence in the data, where regions with initially lower values for the variable of interest tend to experience faster growth rates, while regions with higher initial values catch up over time. The statistical significance of the coefficients "Alpha" and "Beta" indicates that these relationships are unlikely to be due to random chance.

Sigma convergence for two periods (ANOVA)

The estimates for the standard deviation in the two periods are as follows, SD 2005: 0.5842953 and SD 2020: 0.5364954. No additional information such as standard error or t value is provided. The quotient between the two standard deviations is 1.0890966.

The analysis of variance (ANOVA) resulted in an *F* value of no value provided, with degrees of freedom (*df1* and *df2*) of no value provided. The interpretation of this result is unclear without more information.

In summary, the absolute beta convergence analysis suggested that regions with initially lower values tended to experience higher growth rates over time. The statistical significance of the "Alpha" and "Beta" coefficients indicates that these relationships are unlikely to be due to random chance. On the other hand, the sigma convergence analysis indicates that there is no strong statistical evidence to conclude that the

standard deviation of the variable significantly changed between 2005 and 2020. The coefficient of variation did not significantly differ from that of ANOVA (Table 6).

Table 6. Sigma convergence for two periods. Russia, 2005, 2020.

	Estimate	F value	df 1	df 2	Pr (> F)
CV 2005	0.05169358	NA	NA	NA	NA
CV 2020	0.04103196	NA	NA	NA	NA
Quotient	1.25983720	1.186131	79	79	0.4498045

Source: Research findings

These results provide information about the coefficient of variation (CV) results for two different years, as well as a quotient between them:

1. CV 2005: The estimated coefficient of variation in the year 2005 is 0.0517. However, no additional information, such as the standard error, degrees of freedom, or p value, is provided. Therefore, we cannot determine the statistical significance or interpret the estimate confidently.

2. CV 2020: The estimated coefficient of variation in 2020 was 0.0410. Similar to the previous case, no additional information is provided, so we cannot make conclusive interpretations about the statistical significance or estimate accuracy.

3. Quotient: The quotient between the two coefficients of variation estimates is 1.2598. This quotient is calculated by dividing the estimate for CV 2020 by the estimate for CV 2005. The F value is 1.1861, with 79 degrees of freedom in both the numerator and the denominator. The p value is 0.4498, which is not statistically significant.

In summary, the provided results do not contain sufficient information to interpret the statistical significance or accuracy of the coefficient of variation estimates for the years 2005 and 2020. The quotient between the estimates suggests a slight increase from 2005 to 2020, but this difference is not statistically significant based on the given F value and p value.

We graphically represent the results of our convergence analysis in Figure 1. The plot in Figure 1 shows a declining curve, which is an indication of beta convergence. The beta convergence model is statistically significant ($F \approx 14.65$, $p < 0.001$), as are the coefficients α ($t \approx 7.31$, $p \approx 0.0000000002$) and β ($t \approx -3.83$, $p < 0.001$). We also found evidence for absolute beta convergence because of a negative slope ($\beta \approx -0.0115$). We did not find evidence for sigma convergence because of the positive slope of the curve ($\beta \approx 0.013$) ($F \approx 1.186$, $p < 0.001$).

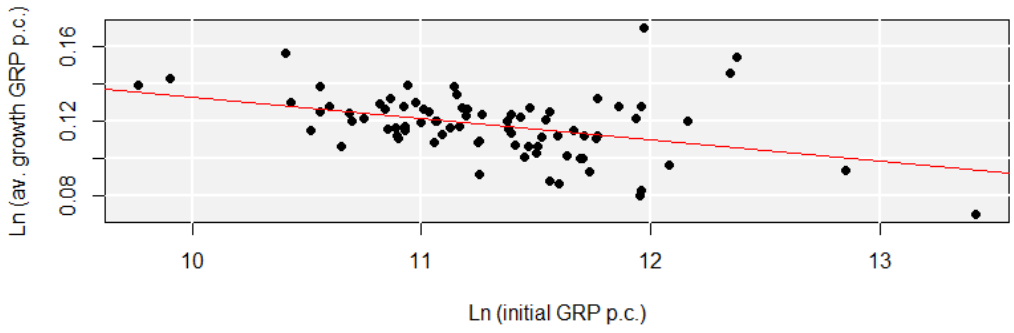

FIGURE 1. Beta convergence of the Russian regions in 2005–2020.

Source: Research findings

However, beta convergence can be regarded as a very slow process: the Halflife value shows that, resulting from the beta convergence model, the regional disparities in GRP per capita among Russian regions will be halved in approximately 902 (OLS method) or 821 (NLS method) years. The calculated speed of convergence (λ) shows a harmonization between regions of 0.07% per year (OLS) and 0.08% per year (NLS).

V. DISCUSSION

The results indicate that there is no strong statistical evidence of sigma wave convergence between 2005 and 2020 for the specific variable being studied. The coefficient of variation in 2020 is slightly smaller than that in 2005, but this difference is not statistically significant based on the provided p value. This suggests that the relative variability of the variable did not change significantly over the analysed time period.

Our results are quite comparable to those that Wieland [6, p. R12] obtained for Germany (1,356 years). This poses an interesting problem, as Germany was divided into the East and West until 1990, while Russia has been and remains a single state. What explains the lack of sigma convergence in the case of Russia? This is a rather complex issue, in particular, researchers position Russia's slow convergence in the international context, presenting this situation as a combination of unique factors (such as resource concentration, industrial diversification and economic policy). Research on this topic is actively being carried out; in particular, it is considered necessary to highlight the results of a study of growth models in the constituent entities of the Russian Federation conducted by Taymaz [29], including a study of whether all regions are converging on a common path of growth or forming several convergence clubs [30,31]. At the same time, we consider it necessary to note the economic and social consequences of regional divergence for Russia based on the current policy. Stable differences (which we identified as a result of the study) can lead to further migration to richer regions, creating a burden on urban infrastructure and increasing the socio-economic gap.

Although a number of researchers criticize the sigma-convergence methodology (for example, for the "number of restrictions" (Rey, Dev [32, p. 219]; see also Kong et al. [33], who introduced the concept of "weak σ-convergence"), this approach is still widely used in scientific circles and provides adequate results.

The results of our research show that, unlike in Kaldor's view [34, p. 338], we can identify the fate of an area based on the fate of its inhabitants. In this case, we mean the constant migration of the most able-bodied part of the population of the regions to wealthy metropolitan agglomerations. We share the view of the Braudel school, which Pomeranz [35, p. 15] cites, that "the profits accumulated by a few very wealthy people; the institutions that facilitated this kind of accumulation often involved special privileges that interfered with neoclassical markets". This view coincides with Wallerstein's view that "continued accumulation of profits in the free-labor "core" of that economy has required the continued existence of poor, generally unfree "peripheries" [35, p. 15]. Scheidel [36, p. 411] called this phenomenon "predatory behavior by those powerful enough to appropriate wealth well in excess of what their activities might earn them in competitive markets – what economists call rents". We agree with Myrdal's assertion cited by Reinert [37] that rich nations as a group seem to converge into a cluster of wealthy countries, while the poor seem to converge towards poverty, with the gap between them rising.

VI. CONCLUSION

In the conducted analysis, it is posited that the significance is solely in the beta convergence of regions within Russia. Hence, it is undetermined whether there was a decline in regional inequality in Russia during the analysed period. The findings suggest that the low rate of convergence among Russian regions, coupled with the absence of convergence indicators, implies divergent economic processes in these regions. As noted in the "Materials and Methods" section, this research has data limitations, covering only the period from 2005 to 2020. Over time, sigma convergence might become apparent.

Future research is recommended to focus on identifying factors that hinder sigma convergence in Russian regions and to perform analysis at a more granular level, such as the municipal level, although relevant data availability may be a constraint. Following Temple [33], future research should aim to determine whether regions converge to steady paths, the speed of this convergence, and appropriate measures for the convergence rate.

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Author Contribution

All authors made an equal contribution to the development and planning of the study.

Data Availability Statement

The data and code can be provided upon request.

Conflict of Interest

The authors declare no conflicts of interest.

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