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Economic development impact upon the environment

A serious scientific problem is estimation of the environmental effect of economic development and identification of patterns in interrelations between environmental and economic characteristics of ongoing processes. The models based on such patterns should enable investigation of potential development scenarios in strategic planning and their comparative analysis. Various scenarios of economic development of the Russian Federation (RF) or its regions may have very different environmental consequences, which must be taken into account as limitations in decision-making.

To handle the problem one first of all needs to work out the requisite tools: mathematical models that enable investigation of interrelations between economic and environmental parameters, and identification of regularities, as well as techniques that allow for quick estimations. One has to build fairly simple and convenient functions that would describe relations between economic and environmental indices, which parameters would be stable and meaningful to both economists and ecologists, complement existing models and generate new possibilities. With the proposed approach we can determine the relationships between parameters of functions and indices of different levels (the economy in general and its individual sectors), estimate the effect of structural shifts in the economy and of changes in the structure of investments by types, examine different variants of resource distribution among sectors, and construct the ones optimal by various criteria.

The difficulty is that the effect of economic development on environmental indices varies depending on the type of activity and structure of investments. Economic development mainly leads to quantitative growth, most projects tend to have negative environmental effect, and foundation of new industries increases the load on the environment in one way or another. Other projects – innovative and modifying the structure of the economy, may have the positive effect of reducing the environmental load through modernization of the industrial process, introduction of new technologies, etc. The greatest effect comes from investments in machines and equipment.

Nature conservation, projects to improve treatment systems reduce the harmful impact on the nature with various degrees of effectiveness, which can be estimated by data analysis and identification of equations. On the other hand, some current costs and investments do not lead to any changes in the environment. For those features to be reflected in special functions one needs to analyse simple functions based on real data and built by analogy with production functions, and to suggest new ones, which enable investigation of environmental-economic processes.

The idea to introduce special functions came up when dealing with the problem of building scenarios of environmental change in Northern regions depending on the economic policy. After data had been analysed and models had been built for Republic of Karelia, Murmansk and Arkhangelsk Regions, the conclusion was drawn that special functions similar to production ones can be developed to describe environmental-economic processes (White, 2005).

Data. The study is based on the information available from statistical yearbooks on RF and its regions. The environmental indices descriptive of the state of the environment and the effect of the economy on it are investigated – point-source pollutant emissions, polluted effluent discharges to surface waters, water uptake from natural sources, toxic waste production, etc. To solve some problems, simple indices are processed into integrated ones, which reflect the overall effect of the economy on various characteristics.

Integrated indices comprise individual environmental indices and demonstrate the macrolevel of the region’s development and state of the environment, and its environmental safety. The most widespread form of an integrated index is the following:

$$Z = \sum_j Z_j \frac{P_j}{Np_j} ,$$

where: j is the number of the simple environmental index; P_j – weighting factor of the j^{th} index (usually set equal in calculations); Z_j – actual value of the j^{th} environmental index; Np_j – normalizing factor (the value of the index in the first year, usually standing for the 100%).

The following indices are considered to assess the economic development – gross domestic product (GDP) and its structure by industries, gross regional product (GRP) and its structure, basic assets and their structure, investments and their structure, etc. Calculations for major indices (GDP, GRP, amount of investments, and some others) are carried out for both integrated and simple indices. Indices by industries are used in equations with simple indices. E.g., emissions from vehicles depend on transport development parameters.

The dynamics of environmental parameters is influenced also by nature conservation activities, which are described by the following indices – investments in fixed capital aimed to promote nature conservation and sustainable utilization of natural resources, current costs of nature conservation, etc.

The data are to be made comparable, which is a difficult but not an impossible task, and the indices most accurately reflecting the changes that have taken place as well as suitable for building special functions are selected during economic analysis. Therefore, one most often considers cumulative investments – the sum of investments cumulated over 3-5 years, or in some cases (identification of incremental functions) investments over one year are used.

Conversion of statistical accounting from industries to types of activity has generated certain problems in building dynamic series in a comparable form, but these can be overcome by introducing coefficients and converting data by industries from the 1990s to data by types of activity.

The impact of various production facilities on the environment differs greatly, and industries (types of activity) may be aggregated into several sectors for the purposes of the analysis. Grouping into sectors enables examination of the structural policy and analysis of the consequences of potential strategic decisions so that the environmental impact of the various economic development scenarios can be assessed. The key factor is the non-uniform distribution of investments among sectors. Aggregation can be based on either simple or integrated indices depending on the task, and the sectors compiled using different indices would differ somewhat.

Three sectors were distinguished in the present study. Based on point-source atmospheric emissions the sector featuring the heaviest environmental impact comprises the following industries – electric energy, fuel, ferrous and non-ferrous metal industries, and transport. The second sector includes the following industries – chemical and petrochemical, construction materials, forest industries, agriculture, food industry, machine engineering, housing and public utilities. Their specific emissions are lower than the average in the economy. The rest of the industries, first of all services, fall into the third sector.

Mathematical model. The main advantage of the proposed pollution functions (PF), which integrate economic and environmental indices, is that they help investigate the dynamics of the environmental efficiency of investments, analyse the effect of changes in the structure of investments and the economy, and take account of the possibility of one factor compensating for another. PF can be a two- or a three-factor function, based on simple or on integrated environmental indices:

$$Z(t) = F(U_1(t), U_2(t), t)$$

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where: $Z(t)$ is the environmental index in question, $U_1(t)$ – factor describing economic development, which, as a rule, tells negatively on the environment (investments in the economy, investments in new construction projects, GDP, GRP, etc.), $U_2(t)$ – factor describing conservation activities and enhancing the environment (investments in nature protection, current costs of nature protection, etc.), $U_3(t)$ – factor reflecting structural changes in the economy, which, as a rule, have positive effect on the environment (investments in modernization of production facilities, etc.). One may assume function F to be single-valued, continuous and twice differentiable. The factors are positive; increase in the costs of a factor usually results in a reduction in its efficiency.

To reflect the specific characteristics of environmental-economic processes we introduce the notions of the marginal rate of compensation (the amount of one factor required to maintain the environmental impact at a constant level when another factor is changed) and elasticity of compensation (the degree of difficulty in compensating for one factor with another). This characteristic may either be constant or depend on certain indices. If, for instance, elasticity of compensation is zero a change in one factor would result in a proportionate change in the environmental impact that cannot be compensated by another factor.

We introduce the notion of homogeneity of degree γ of function *F*, if it satisfies the following conditions:

$$F(\lambda U_1(t), \lambda U_2(t), t) = \lambda^{\gamma} F(U_1(t), U_2(t), t)$$

Calculations have shown homogeneity to be much below one, and functions homogenous of degree zero, which sometimes describe real processes quite well, are of particular interest:

$$F(\lambda U_1(t), \lambda U_2(t), t) = F(U_1(t), U_2(t), t)$$

We introduce the notion of factor elasticities, which are logarithmic derivatives of PF by factors. Parameters ε_1 and ε_2 can be defined as elasticities of pollution for a factor, which predetermine its efficiency. They describe the degree of impact of the factors: if GRP (or another economic index) grows by 1% the investigated environmental index grows by ε_1%, and if investments in nature protection (or another conservation index) are increased by 1% it would change by ε_2%, decrease to be more exact, since elasticity ε_2 is negative.

We introduce the notion of neutral environmental progress, which is related to changes in the pollution level dependent on time or on other factors. Neutral environmental progress is most significantly influenced by structural shifts. To estimate the degree of their effect we built the following equations for the two-factor PF

$$\varepsilon_1 = \sum_i \varepsilon_{1,i} \times \frac{Z_i(t)}{Z(t)}$$

$$\varepsilon_2 = \sum_i \varepsilon_{2,i} \times \frac{Z_i(t)}{Z(t)}$$

$$p = \sum_i p_i \times \frac{Z_i(t)}{Z(t)} + \varepsilon_0$$

$$\varepsilon_0 = \sum_i (\varepsilon_{1,i} \times (I_{1,i} - I_1) + \varepsilon_{2,i} \times (I_{2,i} - I_2)) \times \frac{Z_i(t)}{Z(t)}$$

where *Z(t)* is the environmental index under consideration, I_1 – logarithmic derivative of an economic index, I_2 – logarithmic derivative of a conservation index, *t* – year, *i* – sector.

At the first stage of the study carried out for the three regions we used the simplest functions:

$$Z(t) = A(t) \times U_1^{\mu}(t) \times U_2^{-\eta}(t) \qquad (1)$$

This PF enables very convenient calculations – when its logarithm is found, it becomes linear and has plain environmental meaning. Often, $A(t) = exp(p \times t)$, where: *p* is the rate of neutral environmental progress, which characterizes the effect of the factors unaccounted for in the formula, including structural shifts, modernization of production facilities, $\mu \geq 0$, $\eta \geq 0$. Parameters $\varepsilon_1 = \mu$ and $\varepsilon_2 = -\eta$ are factor elasticities. The simplest and most convenient here is the linear function

$$Z(t) = B(t) \times U_1(t) + C(t) \times U_2(t) + D(t) \qquad (2)$$

The main drawback of this function is that compensation is infinite – a change in one index can be easily compensated by changing another one, which is far from the reality. A second problem consists in frequent use of the cumulative investment volume as one of the main factors. To eliminate this problem we additionally used a modification of the linear function:

$$\Delta Z(t) = B(t) \times \Delta U_1(t) + C(t) \times \Delta U_2(t) + D(t) \qquad (3)$$

In this case we consider the increments of indices, wherefore the volume of investments over a year or several years can be used as the factor with weights that account for the construction lag. There remains the problem of infinite compensation, and the vagueness of retirement can be neglected since changes in pollution volumes are most significantly affected by new investments, and retirement can be roughly estimated using previous years' investments.
In addition to functions (8.1)-(8.2) we considered more complex ones, with a limiting factor, which proved to be close to the reality in some time periods:

$$Z(t) = A(t) \times \min\{a \times U_1(t), b \times U_2(t)\} \qquad (4)$$

A change in one of the indices in function (8.4) cannot be compensated by another one. E.g., investments in environment protection are inefficient and production grows (or declines) without any changes in the technology. A second option is where production grows in those spheres that have hardly any effect on the environment (such as IT or education), and investments in nature protection significantly reduce discharges from most polluting industries (metal processing, pulp-and-paper industry).

Calculations for Republic of Karelia and other regions have demonstrated application of functions similar to the widely known production functions alone is not very relevant. Environmental-economic processes have their own distinctive features, and specialized functions need to be built. Judging by the computations performed one can assume factor elasticities would gradually change, probably decrease. More up-to-date technologies are introduced, and their impact is lower than that of existing ones, replacement of treatment systems for more advanced ones generates lower effect than their original installation, restrictions on environmental impact grow stricter, but changes decrease. Several types of functions with changing factor elasticities have been suggested, and computations were performed for the following ones:

$$Z(t) = A(t) \times U_1^{\mu}(t) \times U_2^{-\eta}(t) \times \exp(a \times U_1(t) / U_2(t)) \qquad (5)$$

$$Z(t) = A(t) \times U_1^{\mu}(t) \times U_2^{-\eta}(t) \times \exp\left(\frac{a}{U_1(t)} + \frac{b}{U_2(t)}\right) \qquad (6)$$

$$Z(t) = A(t) \times U_1^{\mu}(t) \times U_2^{-\eta}(t) \times \exp(a \times U_1(t) + b \times U_2(t)) \qquad (7)$$

$$Z(t) = A(t) \times U_1^{\mu}(t) \times U_2^{-\eta}(t) \times \exp(a \times U_1(t) \times U_2(t)), \qquad (8)$$

Factor elasticities of PF data depend on the indices and their ratios, and may vary quite significantly. Function (5) is homogeneous; when indices in function (6) grow factor elasticities approach parameters μ and η; factor elasticities in function (7) are linear in the indices. Other variants of the functions are also feasible.

Data analysis. To roughly estimate the relationship between the indices of the main parameters of PF – factor elasticities and the rate of neutral environmental progress, we analysed data and built various graphs of environmental and economic indices and their ratios. As the result, periods with potentially different behaviour of the main characteristics of the process in question were identified, assumptions concerning the type of PF were made, potential limitations on PF parameters were determined.

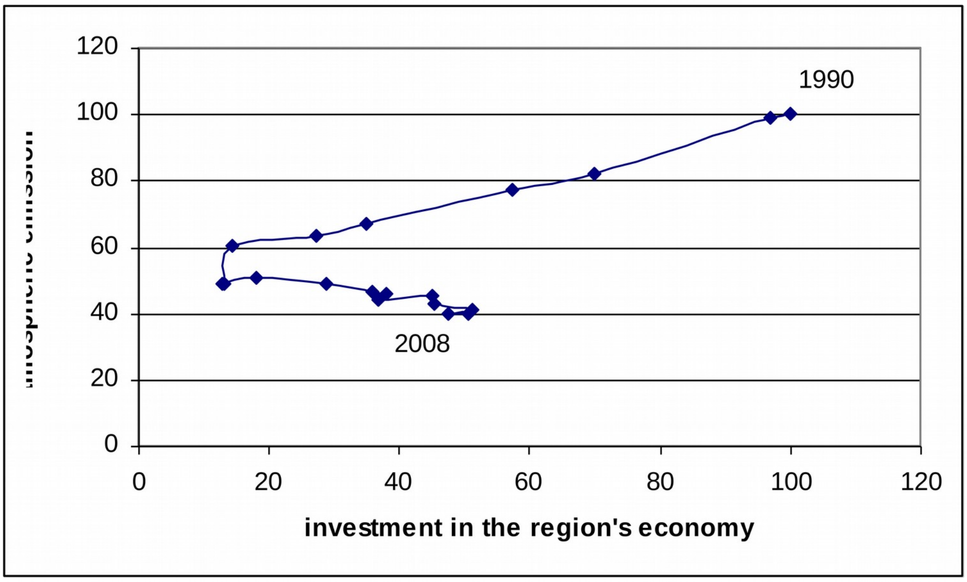

Fig. 1. Connection point-source pollutant emissions (1990 = 100%) and investments in fixed capital of Karelian economy (1990 = 100%).

Figure 1 shows data on Republic of Karelia. One can discern two trends, each roughly described by linear relationship. Before 1998, with a nearly 10-fold reduction in investments in the region's economy atmospheric emissions dropped by 40%, whereas afterwards, when investments in the economy increased four times, much of it channeled to modernization of production facilities and introduction of more up-to-date technologies, emissions decreased by another fifth – to 48% of the 1990 level.

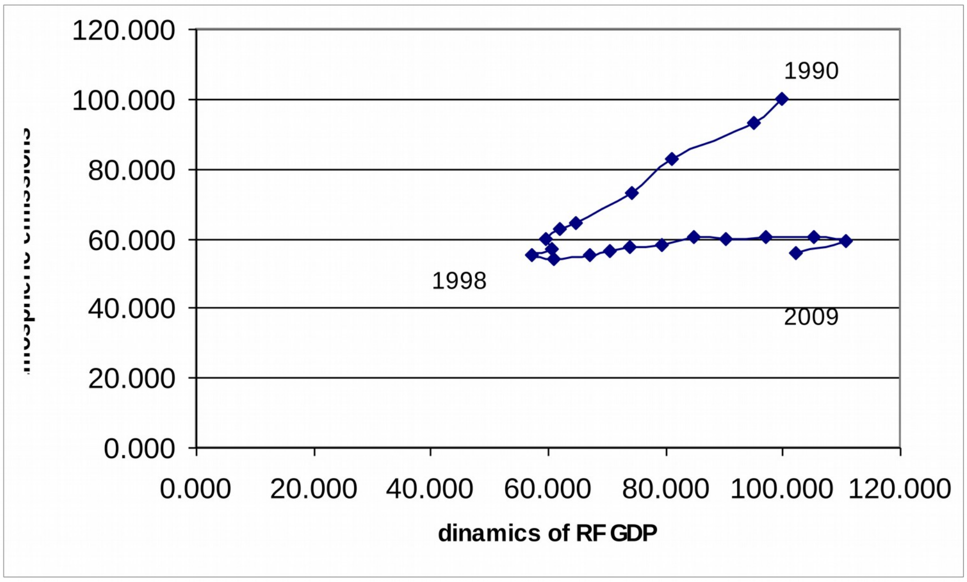

Fig. 2. Connection point-source pollutant emissions (1990 = 100%) and dynamics of RF GDP (1990 = 100%).

A similar relationship is demonstrated by data on the Russian Federation. Figure 2 shows the dynamics of RF GDP. One can see also that since the late 1990s the growth of GDP has not caused significant increase in atmospheric emissions. The graph suggests there are two periods differing in characteristics.

If however time dependence (neutral environmental progress does not equal zero) and the second factor are taken into account, differences between the periods may vanish. Plotting of the graph of the same pollution level by factor correction (the coefficient is determined from the ratio of the emissions level to 1990 values) shows the difference between the two periods is insignificant.

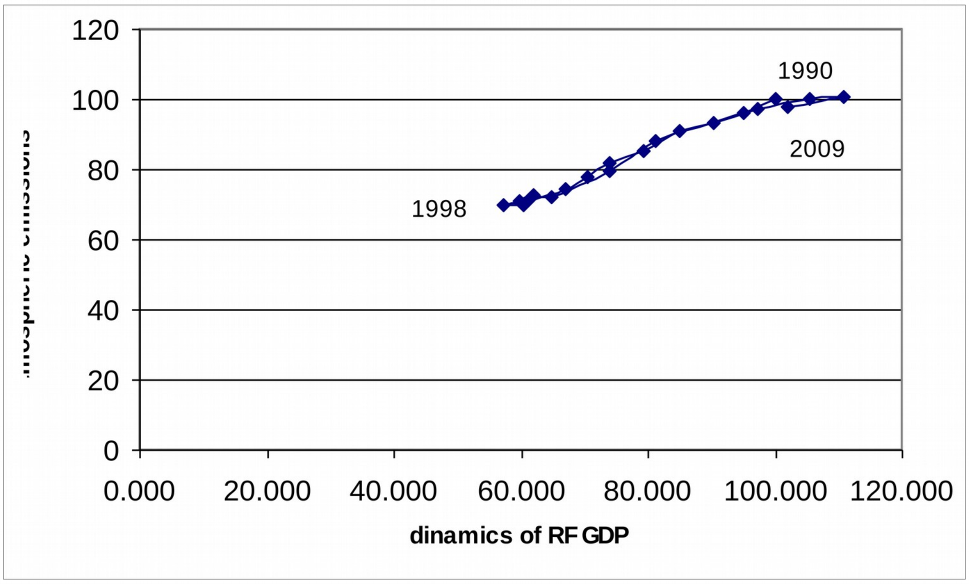

Fig. 3. Connection point-source pollutant emissions (1990 = 100%) and dynamics of RF GDP (1990 = 100%) if emission increase on 3% in year (exist neutral environmental progress *p* =-0.03).

Figure 3 illustrates how the dependence of pollutant emissions on RF GDP dynamics changed at emission corrections – 3% reduction a year owing to the factors not accounted for in this model (most probably connected with modernization of production facilities). The two lines coincide, so PF can as well be build for the period of 1990-2015 as a whole.

Building the functions. Analysis of data on the three regions proved one can build functions with parameters quite stable over certain time periods. Trial calculations for the three regions resulted in identification of several kinds of PF and the technique for finding their parameters. The main problem is the short data series; all types of functions can be estimated for the period of 1990-2015; problems sometimes arise when doing calculations for specific periods.

Below we report the results of the calculations for Republic of Karelia and Russia through which we determined the effect of changes in the indices on the dynamics of atmospheric emissions. Calculations were carried out for the whole period of reforms, for the two periods, and sometimes excluding early 1990s. We used data on point-source pollutant emissions, GRP or GDP, investments in fixed capital and investments in fixed capital targeted at environment protection.

Calculations were performed for the functions presented above. Linear PF (8.2) with constant coefficients yielded meaningful results only in some variants of calculations on the Russian Federation. For the period of 1990-2007, when GDP was used as the first index, we got B=0.50 and C=-0.06; similar results were obtained for investments in basic assets (B=0.60, C=-0.11) with the background of good statistical characteristics.

In calculations on the PF modification (3) with constant coefficients the only meaningful result was obtained for GDP in the period of 1991-2007 with the background of good statistical characteristics (B=0.21 and C=-0.11). If the dependence of the absolute term on time is included, the statistical characteristics would remain nearly unchanged but the coefficients would change somewhat (B=0.19, C=-0.12).

Calculations for functions (2) and (3) have shown that the closest to Russian realities is the dependence of coefficients $C(t)$ and $B(t)$ on time, whereas $D(t)$ can be considered constant. This is important because, as calculations for the three northern regions show, the effect of change in economic indices on the environment kept decreasing during the reforms, whereas nature conservation activities were gaining in significance. Calculations on RF using (3) yielded a similar result – factor elasticity decreased for GDP and increased for nature conservation investments:

$$\Delta Z(t) = (1.89 - 0.017 \times t) \times \Delta U_1(t) + (0.011 \times t - 1.19) \times \Delta U_2(t) + 0.29$$

More realistic is the non-linear function (1), where the elasticity of compensation equals 1, its environmental-economic message is clear, but some problems exist in the use of investments as indices. Calculations using RF data resulted in higher values of elasticity for GDP. For explored period and investments over 1 year, μ=0.51 when neutral environmental progress was not taken into account and μ=0.68 when it was (its value was negative, ca. -0.03). The result for cumulative investments over 3 years with account of neutral environmental progress was about the same – μ=0.69. In the calculations for the second period elasticity μ is within the 0.21-0.3 interval depending on the limits of the period and the number of years for which investments are summed up. One can conclude the effect of GDP modification on the dynamics of atmospheric emissions has dropped significantly.

Coefficient η turned out to be close to zero; it ranged between 0.001 and 0.04 when we changed the period covered by calculations and the number of years of investments summed up, and in the presence/absence of neutral environmental progress. Neutral environmental progress is negative, being about -0.03; when it is taken into account parameter η tends to zero.

From the calculations for the first and second periods we got high values of the correlation and Fischer’s coefficients, and likewise for the whole period when investments over 1-3 years were summed up and neutral environmental progress was taken into account. Calculations on longer investment summing periods are unreliable, since data from the two periods mix together and the indices were changing in the opposite directions in these periods.

More complex functions (8.5) – (8.8) yielded more interesting results. Equation (8.5) enables estimation of homogeneity and dynamics of factor elasticities. According to the calculations, homogeneity is within 0.1-0.5. Elasticity for GDP somewhat decreases, staying within 0.4-0.6, and elasticity for conservation investments slightly grows, being about -0.1. Introduction of neutral environmental progress (it equaled about -0.026) slightly shifted the estimates: elasticity for GDP increased significantly, and, naturally, so did homogeneity. Significant difference between factor elasticities indicated building of the function with zero homogeneity is problematic in this case, as corroborated by the calculations.

Calculations for function (8.6) have shown a homogeneous function can be built, but the degree of the indices’ effect on the pollution dynamics would most probably decrease. In calculations based on the explored period, elasticity for GDP was 0.5-0.6, and for conservation investments it varied from -0.1 to -0.2. In this case however, statistical characteristics are rather low, the correlation coefficient is only R=0.57. Introduction of neutral environmental progress immediately improves the statistical characteristics (R=0.99, F=408), and when it is taken into account elasticity increases to 0.7 for GDP and nearly to zero for conservation investments. Neutral environmental progress is negative and equals about -0.03, like for function (8.6). Differentiation between the two periods indicates the effect of GDP decreased notably (elasticity dropped from about 0.9 in the first period to 0.2 in the second one), whereas that of conservation investments increased (elasticity changed from nearly zero to -0.2).

Calculations by formula (8.7) yielded similar results. In calculations on years 1990-2007 elasticity for GDP was 0.53-0.55, for conservation investments – around -0.2. In the first period elasticities were nearly the same as in function (8.6), whereas in the second one the effect of conservation investments was about twice greater. Statistical characteristics in all the variants of calculations were approximately the same as for function (8.6).

Calculations for Karelia using the linear PF (8.2) for explored years with GRP as the first index yielded B=0.92 and C=-0.0012 with good statistical characteristics. For the incremental PF, coefficients differ notably (B=0.47 and C=-0.0009) and statistical characteristics are worse.

Calculations by PF (8.1) resulted in high elasticity values for GRP for years 1990-2008: μ=0.74 and η =-0.119. For PF (8.8) applied to explored years we got μ=0.79 and η =-0.085, and parameter a=-0.0000001 (the low value is due to the fact that investments in air protection increased 352-fold over explored pieriod).