Article

Regional Development in Russia: An Ecosystem Approach to Territorial Sustainability Assessment

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Abstract: The current crisis has indicated the need to review the policy of economic growth and globalization towards the search for new sustainable models of the internal territory development able to resist external shocks and threats. To achieve this goal, it is required both to implement sustainability strategies, and to assess the obtained results towards sustainable development. Despite an abundance of literature on sustainability assessment, there is a lack of understanding of the application of sustainability assessment in regional/local contexts. The purpose of the article is to improve theoretical and methodological aspects of the formation of territorial (regional) ecosystems by developing a new approach to assessing its sustainability. We believe that territorial ecosystem sustainability assessment is possible through the entropy of a complex system composed of the entropies of its constituent ecosystems or the entropies of different types of territorial capital (human, production, natural). An application of the entropy approach allows to understand specific features of a particular ecosystem characteristics. We demonstrate our methodology with two empirical case studies of territorial ecosystems of Penza and Vladimir regions. As a result of the analysis, it was found that ecosystem's sustainability is achieved, primarily, due to the natural capital of the territory. The methodology proposed in our study aims at ensuring comprehensiveness and robustness of the evaluation supporting the decision-making process.

Keywords: territorial ecosystem; innovation ecosystem; regional development; sustainability assessment; sustainable development; entropy method; territorial capacity

1. Introduction

The challenges associated with the pandemic, the economic crisis, and the aggravating social stratification in the society are rapidly increasing imbalances in the socio-economic development of the constituent entities of the Russian Federation, which are deterrent for its regional and spatial development. Ultimately, it threatens national and economic security of the country. At present, it has become obvious that each country should rely on its own potential, making use of resources available on inland area (natural, labor, intellectual, etc.), and strive, first of all, to maintain sustainable development. This necessitates a serious modernization of regional policy, namely the search for new

sustainable models of territorial development. This problem is especially relevant for such a spatially extended country as Russia, whose regions differ significantly from each other in their geographical, natural-resource, demographic, cultural-historical, ethnic, and other factors.

One of the most relevant discussed organizational and economic models of socio-economic development are ecosystem models [1–9]. In fact, we can talk about a new approach to spatial territorial development, when the unit of analysis is not an industry, an enterprise, or a region, but a territorial ecosystem (e.g., on the basis of a regional city), which makes it possible to maximize the existing potential (natural, human, scientific, and technical, etc.) of the given territory. Ecosystem flows connect cities, industrial production centers, with remote areas (local communities), which are an integral part of the modern national economy. Thus, one can say that sustainable territorial ecosystems contribute to the development of local communities and, ultimately, ensure balanced spatial development throughout the country.

The authors consider that an ecosystem is the association of independent actors based on the principles of self-organization and self-development to achieve their internal goals, which correspond to requirements and needs of the society. The actors are united in ecosystems according to their functional target interests, forming numerous sectoral, entrepreneurial, innovative, business, and other ecosystems. Functional ecosystems form a unified ecosystem of the territory, intersecting and mutually complementing each other (Figure 1).
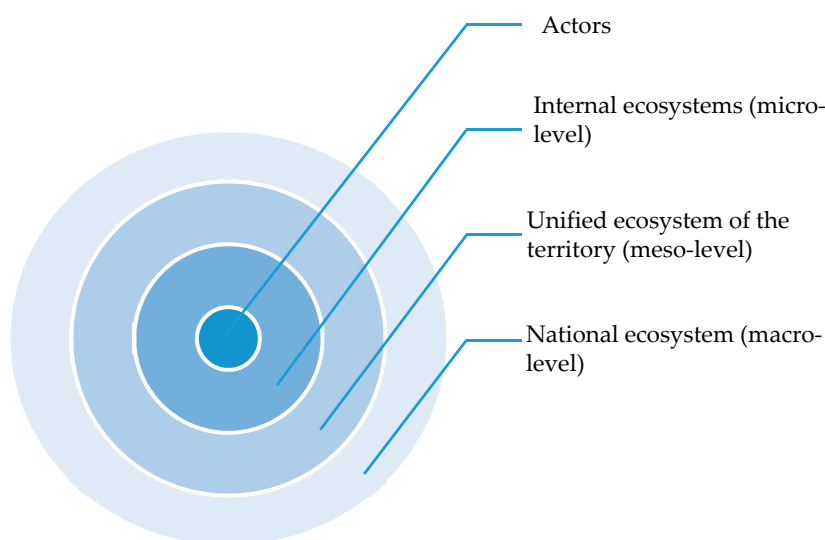

Figure 1. An ecosystem hierarchy Source: Own elaboration.

Thus, the objective of this study is to develop an approach to assess the sustainability of territorial ecosystems as a tool for ensuring the sustainability of the development of local territories. Amid the prolific studies on innovation ecosystems conducted by different schools of thought, there is a relatively sparse research focusing on specific governance approaches useful for managing territorial ecosystems sustainably. We propose a comprehensive technique allowing consistent assessment of the territorial ecosystem sustainability.

This paper makes a significant contribution to the development of scientific thought devoted to the problem of environmental and socio-economic development of regions in terms of studying adequate methods and tools for assessing the sustainability of territorial ecosystems. From a theoretical point of view, the study encourages further research to introduce a strategic framework able to identify different strategies for territorial sustainable outcomes. From a practical point of view, the paper proposes the governance approaches useful for managing territorial ecosystems sustainably. Identification of key factors for maintaining the sustainability of regional development can help authorities and governing bodies to understand ways to monitor current capabilities of territorial ecosystems for maintaining

ecosystem equilibrium in conditions of unstable economic dynamics under the influence of external and internal adverse factors.

The article is organized as follows. Section 2 provides a theoretical overview of territorial ecosystem, related concepts, and approaches. In this section, we analyze sustainability perspective of territorial ecosystems with specific reference to the emerging perspectives on what the role and objective of sustainability and sustainable development assessment should be. Section 3 is devoted to the theoretical foundations of our research introducing our conceptual assumptions and chosen approaches. Section 4 presents a new methodology for assessment of the territorial ecosystem sustainability using the Heisenberg central order theory and the entropy approach. Section 5 further specifies how to operationalize the assessment using the described methodology. We demonstrate our methodology by the example of two empirical case studies of territorial ecosystems of Penza and Vladimir regions. Section 6 highlights the key findings of the study and presents the theoretical contribution and practical significance of the study. In this section, we also discuss propositions arising from the conducted analysis to bring out the features of territorial ecosystems and their implications in terms of sustainable development. Finally, in Section 7, some limitations of the research and points for further discussion are proposed, specifically regarding our concerns on the possibility of performing a more accurate sustainability assessment for different groups of regions.

2. Literature Review

2.1. Conceptualization of Territorial Ecosystems

Over the past 15 years, the concept of an innovative ecosystem has become very popular along with the rapidly growing scientific research in this area.

We agree with authors who criticize the inconsistent use and vague wording of the term "ecosystem" in scientific research [10]. There is often a substitution of concepts: An ecosystem is represented by cluster formations (network innovative ecosystems of a special class) or a triple helix model based on a university-business-state partnership [11]. According to Bruns et al. [12], the "ecosystem" metaphor reflects a tendency in scientific studies to describe the well-known phenomenon of agglomeration effects of regions (urban, regional, national ecosystems) and industries (agriculture, chemical industry, manufacturing, mass media, financial ecosystems) associations of firms (business ecosystems, entrepreneurial ecosystems), or activities (services, innovations, digital ecosystems). As a result, today we have "business ecosystems" [13], "innovative ecosystems" [14], "digital ecosystems" [15], and "university ecosystems" [16] or "financial ecosystems" [17].

"An innovation ecosystem consists of a group of local actors and dynamic processes, which together produce solutions to different challenges" [18].

To conceptualize the concept of a "territorial ecosystem", we consider three main theoretical approaches to innovative ecosystems that are present in the scientific literature: A platform approach or digital ecosystems, regional or local ecosystems, and industrial ecosystems [19].

The platform approach emphasizes the role of digital platforms in innovative development [20–22]. In accordance with this approach, an ecosystem is an open space of collaborating and interacting actors that has been developed around the core (key company). This ecosystem is formed around a multilateral platform that allows actors and stakeholders to generate innovations and creates a friendly environment for the implementation and promotion of innovative products and services. Thus, digital platforms contribute to complex and dynamic interaction, complementarity, and automated transactions between different actors (customers, developers, users, and suppliers) [19].

The regional/local ecosystem approach emphasizes the territorial or regional dimension in the dynamics of the innovation process. The authors [23] emphasize the central role of geographical proximity and interaction between individual actors and institutions in the dynamization of innovative processes. This approach implies special attention to formal and informal relationships and the

dynamics of institutional development. An innovative ecosystem includes three main components that are in close interaction (Figure 2).
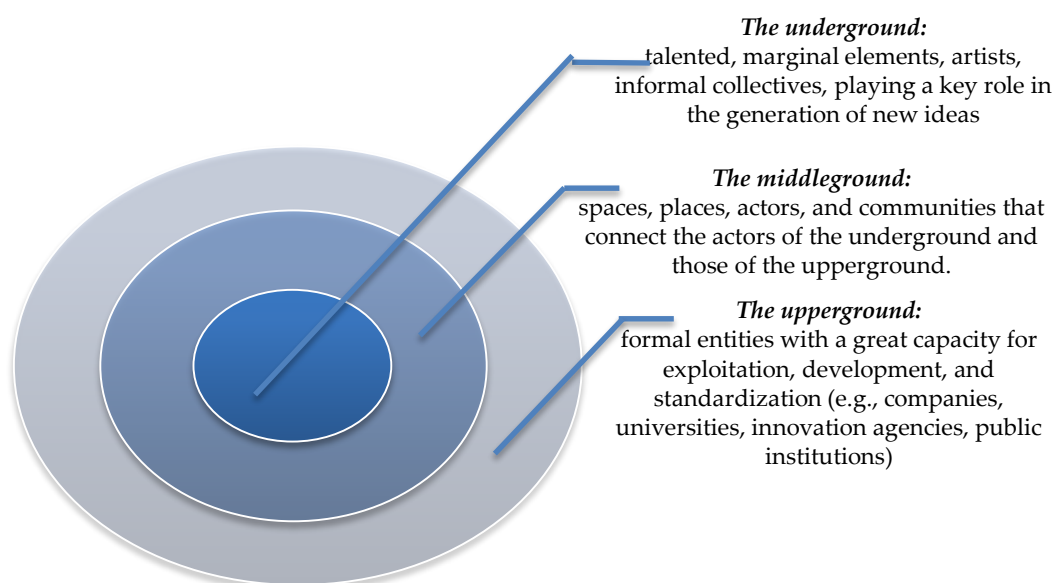
The underground:
talented, marginal elements, artists, informal collectives, playing a key role in the generation of new ideas

The middleground:
spaces, places, actors, and communities that connect the actors of the underground and those of the upperground.

The upperground:
formal entities with a great capacity for exploitation, development, and standardization (e.g., companies, universities, innovation agencies, public institutions)

Figure 2. Regional/local ecosystem components (adapted from [19]).

The third approach of industrial ecosystems was previously studied by us in detail in [8].

Innovations, as a rule, are implemented in a certain territory, which demonstrates the importance of specific local conditions and physical proximity of actors in the process of innovation activity. In addition, a sense of community and belonging is important for local actors which attribute their success to the success of a local or regional community. The territory itself, often being a regional or administrative center, unites actors around the historical knowledge base there, gradually attracting other actors, creative ideas, and investments from outside [24].

2.2. Sustainable Territorial Development and Sustainability Assessment

The term "sustainability" is defined differently, but in practice, it has a three-dimensional nature—economic, social, and environmental. The most acknowledged in the sustainability research definition is that proposed by the United Nations World Commission on Environment and Development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [25].

The development of regions is usually defined as integrated development (social, economic, environmental, technological, and cultural) in a particular territory. The development of a region should be aimed at maintaining a certain standard of living and improving quality through the effective use of economic, social, and natural components of the territory. Regional development in the modern context is at a critical stage when numerous crises and external shocks (financial, energy, food, epidemiological) require a review of the existing economic paradigm of our time towards increasing emphasis on the areas of employment, social progress, quality of life, and improving the environment. Thus, sustainability of a region is the process suggested to improve the quality of life of people within the limitations of the global environment [26,27].

Sustainable territorial development concept "generates awareness of the production and use of resources required for residential, industrial, transportation, commercial or recreational processes" [28–30].

Although there is no doubt about the importance of transferring the concept of sustainable development to the regional level, in practice, the use of this approach is fraught with a number

of difficulties [31]. Difficulties are often associated with monitoring the dynamics of sustainable development of the territory and approaches to its interpretation.

Sustainable development assessment can help decision-makers decide what actions should be taken in order to make society more sustainable [32]. It is conducted to support decision-making in a wide environmental, economic, and social context and goes beyond a purely technical/scientific assessment.

A thorough analysis of the literature on the research topic revealed the following groups of methods for territorial sustainable development assessment:

1. Index-based approach—the group of methods focused primarily on indicators evaluation;
2. Rating systems—these methods are devoted to the comparative investigations of different territorial ecosystems;
3. Principle-based approach—is oriented on checking compliance with the principles of sustainable development in certain territorial ecosystem;
4. Urban metabolism approach—brings an increased focus on recognition of the connection between the spatial component of urban flow and the characteristics of the urban strategies for more sustainable development;
5. Spatial analysis—this method provides different formal techniques, which studies territories using their topological, geometric, or geographic properties in order to assess territorial sustainable development;
6. Eco-efficiency assessment—methods focused on the environmental impacts of an ecosystem alongside its welfare impacts;
7. Impact assessment—approach for modeling of interacting sub-systems representing urban form, land use and transportation, urban metabolism, as well as ecological processes (Figure 3).
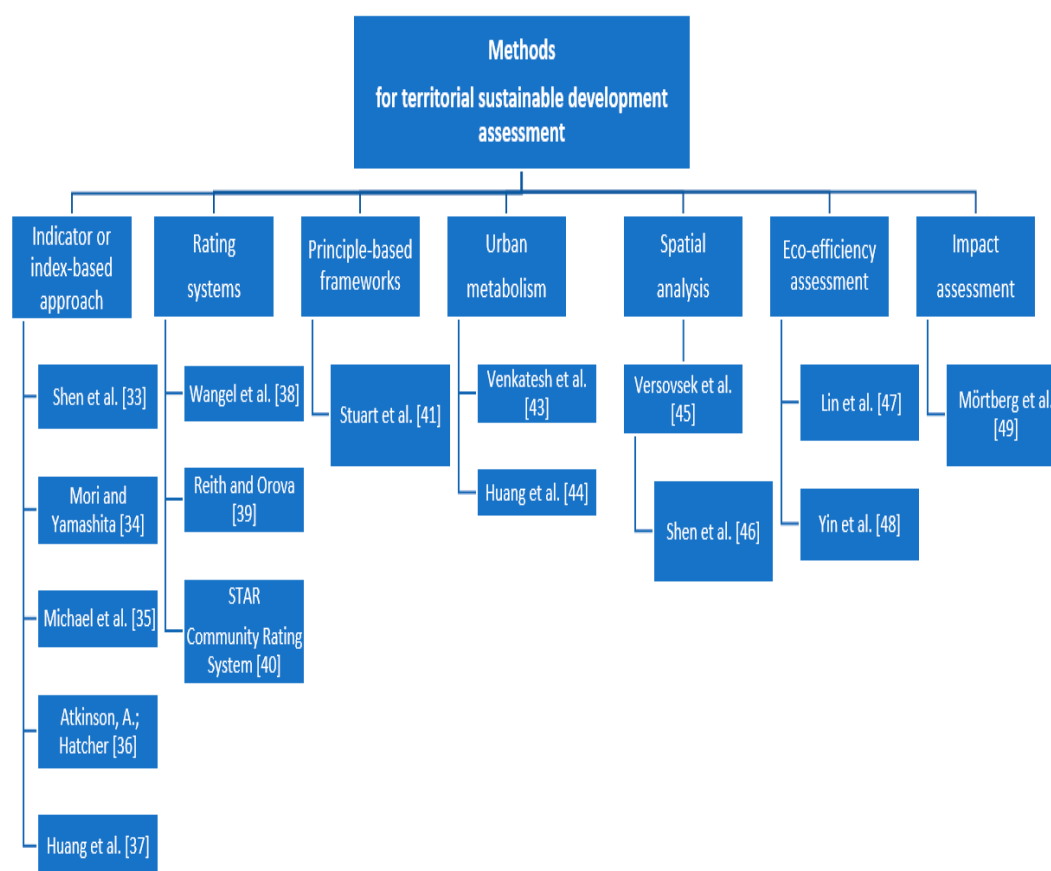
Figure 3. Territorial sustainable development assessment methods from the literature. Source: Own elaboration.

In [33], the authors examined nine different practices and proposed a comparative basis, namely, International Urban Sustainability Indicators List (IUSIL). Mori and Yamashita [34] in their research present a framework of city sustainability index (CSI) including environmental, economic, and social indicators, and categorized them into constraint and maximization groups of indicators. Michael and coauthors [35] developed a set of indicators for urban sustainability and carried and measured these indicators for three countries: Malaysia, Taiwan, and China. Atkinson and Hatcher [36] proposed the "The Compass Index of Sustainability". They demonstrated their suggestions on the example of Orlando, Florida.

In [37] the authors propose a new City Sustainability Index (CSI) focused on the assessment and comparison cities' sustainability development "in order to understand the global impact of cities on the environment and human life as compared with their economic contribute".

Wangel and coauthors investigated "the content, structure, weighting and indicators of two established certification systems for sustainable urban development" [38].

Reith and Orova [39] proposed the urban assessment tool and made comparative investigations of five different assessment sustainability systems.

One of the most comprehensive assessment systems is STAR Community Rating, which "provides communities with a menu-based system to customize their approach based on local conditions and priorities" [40].

Stuart et al. [41] carried out a comparative case study of four mid-sized municipalities in Ontario, Canada, uncovering the language and strategies employed by the municipalities as they relate to the principles of sustainability developed by Gibson [42].

In [43], the authors carried out metabolism-based modelling, which can quantify various flows within an urban water system. Huang et al. [44] calculated energy-based evaluation indexes of urban metabolism and land use change in Beijing by conducting a correlation and regression analysis.

Versovsek and coauthors [45] conducted spatial analysis of six local neighborhoods in the Republic of Slovenia with the aim of seeking reliable metrics to assess the characteristics of urban environments. Shen et al. provided a spatial-temporal analysis and developed a hierarchical index system to monitor and comprehensively evaluate urban sustainability [46].

Lin et al. [47] proposed an assessment tool for measuring the regional sustainability status "which calculates the ratios of welfare and ecological impact". Using this method, they investigated the urban eco-efficiency in Xiamen, China. Yin et al. [48] used eco-efficiency as an index to measure urban sustainable development and described the eco-efficiency of 30 Chinese provincial capital cities.

In [49], developed two potential future scenarios for the Stockholm Region using the LEAM model.

Thus, the literature provided an array of methods and frameworks. As was shown, a vast majority of researches organized sustainable development assessments around the selection and measuring of indicators and indexes [33–37].

To facilitate a holistic approach for assessing the sustainability of territorial ecosystem, we propose to employ the entropy approach. The entropy approach allows us to connect the conditions for sustainability with the parameters of the ecosystem and highlight the areas of sustainability. For example, Liang et al. [50] studied the regional sustainable development capacity using the information entropy concept and dissipative structure theory.

In accordance with the law of entropy, the resources and materials constantly circulate and pass from one state to another. These flows are interconnected and interdependent. That is why entropy is an optimal tool for assessing the sustainability of ecosystems, which cannot be determined by individual unrelated parameters. In any case, changing one parameter will lead to a change in another. Furthermore, it is important to understand and predict the severity of dependence of a change in one parameter on another.

Thus, in this article, we propose to assess the sustainability of regional development through the sustainability of territorial ecosystems using the entropy method.

3. Conceptual Framework

An ecosystem of a territory is a part of the national ecosystem and includes a whole set of micro-level ecosystems. The study of concepts of sustainable development of the territory is possible through an assessment of sustainability of its ecosystem, which, in turn, depends on the sustainability of its constituent ecosystems (actors can be participants in several ecosystems simultaneously) (Figure 4).
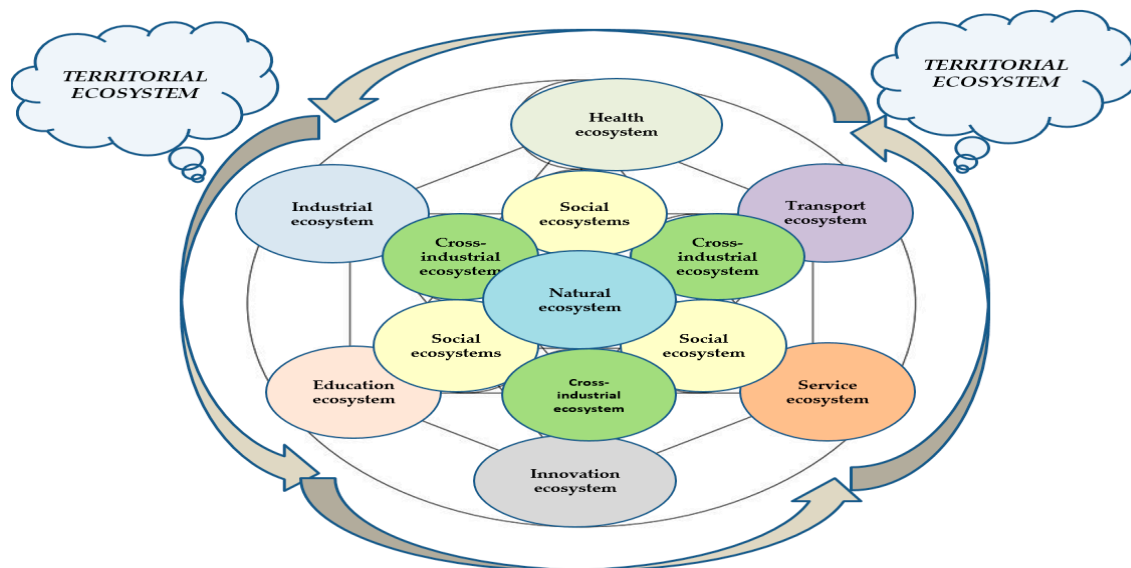

Figure 4. Territorial ecosystem structure. Source: Own elaboration.

A territorial ecosystem is a complex socio-economic system, the sustainability of which is associated with the concept of social entropy. According to K. Bailey (*Social Entropy Theory*) and M. Forsé (*L'Ordre Improbable. Entropie et Processus Sociaux*) [51], the development of social systems is characterized by instability and non-equilibrium as a constant fluctuation between organization and disorganization.

Ecosystems are systems that are characterized by instability and disorganization. The ecosystems are created on the principles of self-organization when there is no external management system. The idea (pacemaker) of ecosystem formation is, for example, a new project, which is the response of economic actors to technological challenges acting as chaos [8]. It is chaos for complex disorganization systems, being ecosystems, that ensures their openness, and acts as an incentive for development. Negative entropy characterizes the development of a system and its openness. The greater the entropy is, the stiffer the structure of system is, and the more unstable the system is from the standpoint of external influences (fluctuations).

Entropy stability is present if the order and organization within the system balance the disorder and disorganization of interactions between actors. It is here when a system can be called sustainable. Each ecosystem strives for entropy equilibrium. The more complex the ecosystem structure is, the larger it is, and the less predictable its behavior is. The sustainability of the ecosystem is ensured by the diversity and complexity of the relationships of the participants included in its composition.

Systems of high sustainability are able to perceive significant effects without substantially changing their structure, that is, without going beyond the equilibrium state. Moreover, the concept of sustainability is not equivalent to the concept of stability, since attention is paid to the invariability of the structure here. Systems of an invariable structure can be called "fragile" by analogy with technical systems. An assessment of socio-economic systems in terms of sustainability is determined, as a rule, by the variability of the environment: Under stable conditions, systems are prone to higher internal organization; under variable conditions, the preference is given to disorganization.

In *Antifragility: Things That Gain from Disorder*, Nassim Nicholas Taleb considers "fragility" of large vertical systems from the perspective of risks in making managerial decisions [52]. A decision

error, taken solely from above of such system, can have disastrous consequences both for the system as a whole, and for its environment. In contrast to such systems, the symbiosis of small systems is much more stable. The adoption of error managerial decision in one subsystem does not have significant consequences for others, which means that the whole system is "anti-fragile" with respect to internal and external challenges (Table 1).

Table 1. Characteristic features of fragility and anti-fragility of socio-economic systems.

Signs of System Fragility with Vertical Management	Signs of Anti-Fragility of Equitable System Symbiosis
Dependence of the entire system existence on the governing body	Independence from any authority
Lack of system self-regulation	Self-organization and self-regulation are characteristic
Low rate of innovation changes	Dynamic, innovative, project-oriented
Process focus	People focus
System inertia	Flexibility to changes
Not customer-oriented	Customer oriented

Therefore, the entropy approach to the analysis of ecosystems at micro- and meso-levels can serve as a tool for assessing the sustainable development of a territory.

The interaction of both ecosystems and their actors is possible through the exchange of energy, being new knowledge, information, unique competencies, and resources, and is ensured through a synergistically friendly environment formed on the basis of ecosystem principles. Therefore, territorial sustainability can be also defined as the ability to provide the activity of all its participants and maintain the functions of energy flows between the subsystems, balanced by socio-economic, technological, and ecological capacities.

A territorial ecosystem is a triad of socio-economic, technological, and environmental symbioses that are formed through harmonious interaction. The limits of potentials and capabilities of actors, the exhaustion of which leads to undesirable changes in the course of economic activity, will be called the capacities of a territory (Figure 5).

Figure 5. The structure of territorial sustainability by capacitive subsystems. Source: Own elaboration.

Summing up, we note the following. There may be two approaches to territorial sustainability assessment. Firstly, the territorial capacity as a triad of socio-economic, technological, and environmental capacities is formed by the capitals of the territory (human, production, natural, etc.). Therefore, we can assess territorial sustainability through territorial capacity assessment. Secondly, there may be an ecosystem entropy approach. In this case, territorial ecosystems (TE) are ecosystems at the meso-level (regional/local), consisting of micro-ecosystems (industrial, innovation, social, etc.) that are combined, intersecting, and complementing each other. Investigation of territorial sustainable development is possible through an assessment of the sustainability of its ecosystem, which, in turn, depends on the sustainability of its constituent ecosystems. Moreover, the sustainability of TE is associated with the concept of social entropy. Therefore, the entropy approach to the analysis of ecosystems at micro- and meso-levels can serve as a tool for assessing the sustainable development of a territory.

Meanwhile, at the micro-level, sustainability of ecosystems affects the emerging capacities of capital (industrial, environmental, social, etc.), which, in turn, ensure territorial sustainability. An ecosystem is considered sustainable only if all capacities are balanced (socio-economic, technological, and environmental). Thus, territorial sustainability can be assessed using the entropy approach both through micro-level ecosystems and through the territorial capital.

4. Research Methodology

The methodology for studying the sustainable development of a territorial ecosystem can be based on the theory of the central order of W. Heisenberg, developed by A. Pozdnyakov [53]. Its nature is that the optimality of the social development vector is determined, first of all, by human activity that meets the requirements of moral relations aimed at developing and improving the wellbeing of people, as well as the conservation of natural resources. Moreover, the development of society should not lead to an increase in the entropy of ecosystems.

The central order [53] is a non-additive set of laws of natural science and social laws of moral relations, implying the expedient and harmonious development of society and the Earth's ecosystem. This means that the activity of any of the systems of society and its constituent subsystems should not lead to an increase in the entropy of the ecosystems and in any of its subsystems. The essence of the idea of the central order is reflected by the well-known Pareto optimality principle—"human activity does not cause losses and benefits other people". This means that none of the components of the social-ecological-economic system, evolving, does not increase the entropy of any other part and its own. We can state that the Sustainable Development Goals formulated by the UN in 2015 exactly correspond to the concept of the central order, since the main idea of sustainable development is to meet the needs of society today in such a way as not to cause losses for future generations.

Self-organization of the actors of the territorial ecosystem is only possible when there is a negentropy flow of energy, material, and information from the environment, which does not require the energy losses produced by the actor himself. That is, for the progressive development of an actor as a socio-economic system, ordered (structured) energy sources in the form of knowledge and information are needed [54]. Each actor, using its own methods of extracting energy from the environment, turns some of its forms into others through exchange with other actors, while does not spend its work on restoring energy with bringing it to the level of reuse. This leads both to cost savings for each actor in the ecosystem, and to the accumulation of energy produced by the actor itself and received from other participants in the ecosystem.

Negentropy is a kind of negative entropy. The first who used this concept in 1943 was E. Schrödinger, who concluded that biological systems for their existence need to extract negative entropy from the environment in order to compensate for the internal production of entropy, and thereby inhibit the state of death [55].

L. Brillouin in 1956, considering the degradation of the quality of energy in a closed system as a consequence of an increase in entropy in it, for brevity began to call negative entropy "negentropy" [56].

Comparing information and entropy, L. Brillouin formulated and introduced into information theory the negentropic principle of information: "information is a negative contribution to entropy" [56].

In the synergetic theory of information, the term "negentropy" is inextricably linked with the concept of reflection; that is, information about "something" reflected through "something".

Figure 6 shows the dependence of territorial sustainable development (meso-level) on the balance of its constituent capacities. The capacitive potential of the territory is formed by different types of capital, the potential of which depends on the stability of functional ecosystems (micro-level). Each functional ecosystem depends on the behavior of its actors and the relationships between them. In substance, Figure 6 illustrates the relationship between the sustainability of the territorial ecosystems and the sustainable development of the territory.

Exceeding the capacities leads to a shift in ecosystem equilibrium, which, in turn, leads to territorial instability.

We consider the terms "sustainability" and "sustainable equilibrium" as equivalent concepts.

In accordance with the theory of entropy, sustainability is the ability of a system to maintain the equilibrium of its internal structure for a period of time, i.e., in case of deviation from the stability of its development, the system does not disintegrate, but retains its integrity in opposition to external and internal destructive influences.
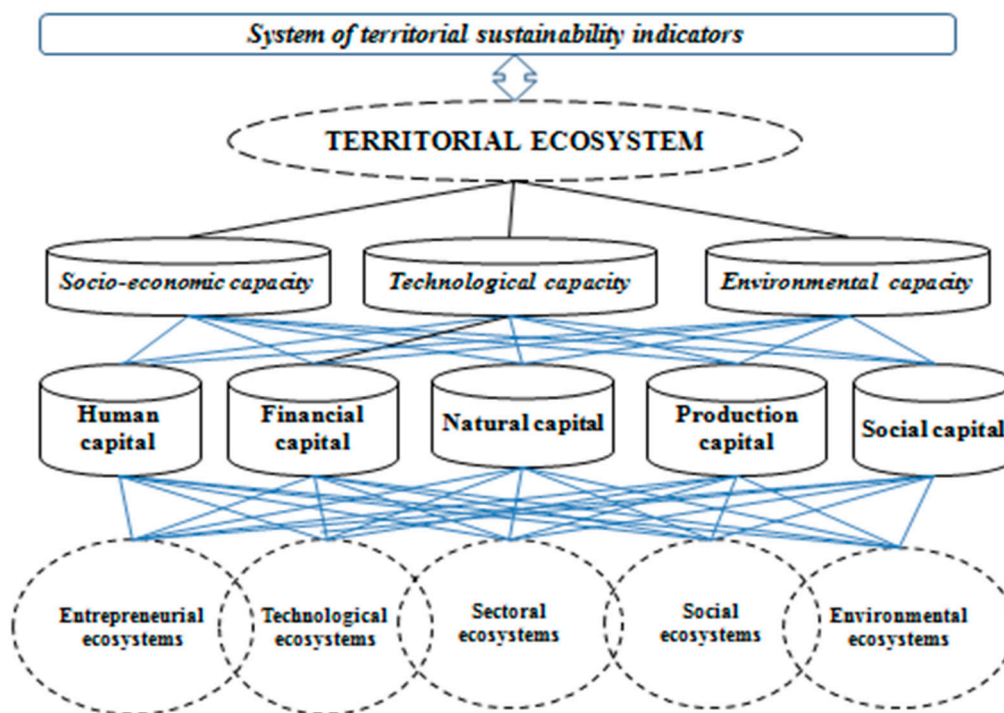
Figure 6. A system of territorial sustainability. Source: Own elaboration.

Sustainability is the ability of a system to ensure a transition from one equilibrium state to another by adapting to the equilibrium and stability of the external environment.

Sustainability is, on the one hand, the equilibrium of the system over a long period of time, while on the other hand, it is a transition from one state of equilibrium to another, or a deviation from the stability of a state or development, followed by a return to its original state without loss of integrity. Moreover, sustainability can manifest itself not only in the form of balance, but also be a characteristic of development, which can be stable or unstable. It is important to note that development is critical to sustainability. The balance and stability are relative and play a subordinate role.

By sustainable development of a region, we mean improving the quality of life of its inhabitants through social and technological development without compromising the ecological potential of the region. Any system can be viewed as a unity of balance (stability) and change (development). Each system strives to maintain its stability. This is possible only when the sum of the system's potentials exceeds the sum of external and internal threats. That is, in order to ensure the sustainable development of the system, it is necessary capacity development. In this work, we try to show that the use of the ecosystem model in different sectors of the region contributes to an increase in its capital, and, consequently, capacity (Figures 5 and 6).

Therefore, an ecosystem is considered sustainable only if all capacities are balanced.

We suggest that the territorial ecosystem sustainability is determined by such factors as:

a)   The potential of actors (the uniqueness of technology, resources, competencies) included in the internal ecosystems of the territory;

b)   The degree of connections between internal ecosystems;

c)   The degree of coherence between different types of capital of the territory.

There is a contradiction here, which is inevitable in the development of any socio-economic system. On the one hand, the more internal ecosystems make up the territorial ecosystem, the more sustainable it is to external challenges, and the more balanced are the different types of territorial capital. On the other hand, the relations determined by the interaction between both internal ecosystems and the actors entail the inevitable risks of conflicts of interest.

Herman E. Daly [54,57], one of the founders of environmental economics, combined the concept of growth limits, welfare economics, environmental principles, and the philosophy of sustainable development into a model that he called sustainable economy. The economic approach to ecosystem sustainability is based on Hicks–Lindahl concept of the maximum total income stream [58], which can be produced provided that the total capital (natural, human, industrial, etc.) by which this income is generated, preserved, or increased. N. Kaitez in *Philosophy of Entropy. Negentropy Perspective* [59] proposed evaluating sustainability through depreciation of capital based on the entropy approach. In his interpretation, entropy (destruction, depreciation) is a loss in the circulation of matter and, at the same time, damage caused by human activity. According to the entropy approach, depreciation of capital is capital that has not been used or has been used irrationally. Accordingly, if the size of the inefficiently spent total capital increases, the level of entropy increases, and the sustainability of the ecosystem decreases. In this regard, we propose to assess territorial ecosystem sustainability through the entropy of the level of utilization of the total capital created by the functional ecosystems of the region (Figure 7).
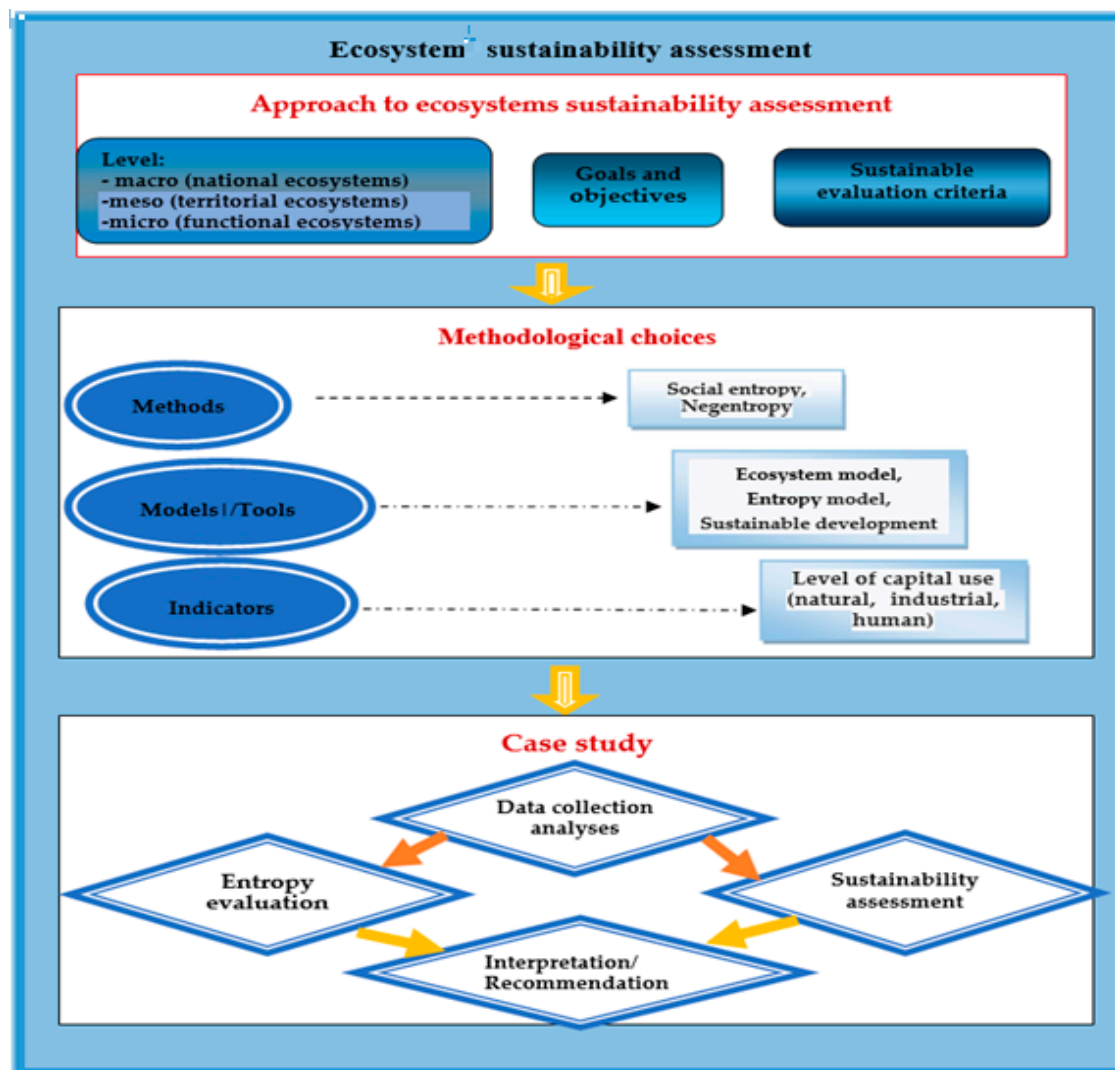

Figure 7. Methodological framework for assessing territorial ecosystem sustainability. Source: Own elaboration.

Assumptions:

1. A territorial ecosystem is considered as a closed ecosystem.

2.　The total capital of the territory is formed on the basis of three types of capital—natural, industrial, and human.

3.　The level of use of each type of capital is estimated by using integral indicators.

There are several types of entropies and methods for their calculating in modern science. Joint entropy or entropy of association is designed to calculate the entropy of interconnected systems. The ecosystem of the territory consists of interconnected micro-level ecosystems. Accordingly, it is advisable to determine the entropy of a territorial ecosystem through the entropy of association.

In this article, the measure of the entropy of a territorial ecosystem is determined on the basis of the adapted Shannon equation:

$$H(x) = -\sum_{i=1}^{m} K_i log_2 K_i \tag{1}$$

where H is the entropy of the level of utilization of the total capital of a territorial ecosystem; K_i is the level of i-type capital use; m is the number of capital types; i are types of capital (natural, industrial, human, etc.) forming the total capital of the territory.

We define a system of indicators for assessing territorial sustainability on the basis of the ecosystem model. To assess the sustainable development of a territory, it is proposed to use the index-based method (Table 2):

Table 2. A system of indicators characterizing the sustainable development of a territory.

Form of Capital	Integral Indicator	Main Indicators
Human capital	Quality of life	Share of population with income below the cost of living Unemployment rate Migration growth (decrease) in population Level of personal security Lifespan Small business development level
Production capital	Scientific and technical development index	Specific weight of innovative goods and services in the total Share of production of high-tech and knowledge-intensive industries in GRP Innovative activity of organizations Share of employees in high-tech economic activities in the total number of employees of organization Number of staff engaged in scientific research and development
Natural capital	Environmental index of a region	Level of water, air, and soil pollution Amount of financing of environmental protection Amount of industrial and solid waste Level of implementation of modern resource-saving "smart" technologies Number of educational environmental programs and projects

The level of human capital use is proposed to be estimated on the basis of an integral indicator of quality of life of the population. This comprehensive indicator includes an assessment of living conditions, the situation in the social sphere, and interregional differences. The RIA Rating (Russian news agency) methodology for calculating the integral indicator of quality of life provides for aggregation of indicators by groups: Income and employment, safety of living, health and educational level, etc. [60,61]. The human capital usage of a territory is determined by the ratio of the actual quality of life index to its maximum possible value (the rating score of a territory of the Russian Federation entity with the maximum value of the quality of life index). Rating score ranges from 1 to 100.

The level of production capital use is based on a comparison of an actual index of scientific and technical development of a region with its maximum possible reference value (the territory of the entity of the Russian Federation with the maximum value of this index). The following indicators characterizing the state of science and technology in regions were used as the initial data for calculating the integral index of regional scientific and technical development: Presence and characteristics of the material base, human resources, innovative activity, and efficiency and scale of scientific and

technological activity. The integrated index of scientific and technological development of a region is calculated by aggregating indicators combined into several groups according to the methodology proposed by RIA (Russian news agency) Rating. The total index can vary in the range from 1 to 100 [62].

Natural capital characterizes, first of all, the ecological state of the living environment. The authors propose to evaluate the level of natural capital usage on the basis of the environmental index of territory [63]. The environmental index is an integral indicator obtained by aggregating three groups of indicators describing the industrial and natural environment, as well as the quality of living environment. The calculation of natural capital use is carried out on the basis of a comparison of the actual level of total environmental index of the territorial ecosystem and the best value of this index in the rating of territories.

The scale for assessing the entropy of territorial sustainability through the entropy of the level of utilization of the total capital created by the functional ecosystems of the region is presented in Table 3.

Table 3. The scale for assessing the entropy of territorial sustainability.

Ecosystem State	Value of Entropy
1. Stationary equilibrium	0–1
2. Stationary nonequilibrium	1.0–1.5
3. Nonstationary equilibrium	1.5–2.0
4. Nonstationary nonequilibrium	>2.0

The entropy of association determines the totality of possible states of a territorial ecosystem: Stationary equilibrium; stationary nonequilibrium; nonstationary equilibrium; nonstationary nonequilibrium. For open micro-level ecosystems that are constantly interacting with each other, a sign of sustainability is a stationary equilibrium state or a stationary non-equilibrium state, when the ecosystem entropy is constant but not equal to its maximum value under the considered conditions.

If we draw an analogy with the criteria for sustainable development, then the stationary equilibrium state of the ecosystem corresponds to strong stability, the stationary nonequilibrium state corresponds to weak stability, and it corresponds to unstable development in nonstationary states. However, a number of researchers (A. Guts, B. Malinetskii) [64] do not consider nonequilibrium and stability of ecosystems to be destructive and negative phenomena. As a result of the transition from equilibrium to a nonequilibrium state, there arises a new, previously unknown order type. The introduction of a new idea "there is no development without instability" into the study shows the multivariance in the development of territorial ecosystems.

The influence of changing external factors increases the overall uncertainty (entropy) of the ecosystem. Accordingly, the ecosystem is more sustainable, if it has the more adaptive capabilities. Creating new connections in the ecosystem between the actors with the greatest potential is the optimal strategy from the point of view of the entropy approach, since it requires minimal energy consumption. Furthermore, under conditions of global instability, the territorial ecosystem can achieve local sustainability due to fluctuation in the micro-level ecosystems that make up the territory.

5. Case Studies

5.1. Description of Territorial Ecosystems of Vladimir and Penza Regions

Based on the above approaches, we will evaluate the sustainability of territorial ecosystems by the example of Penza and Vladimir regions formed around their regional centers: The city of Penza and the city of Vladimir (Figure 8). We have chosen Penza and Vladimir regions, as these are typical industrial regions of Russia. According to the Federal State Statistic Service, more than 70% of regions in the

Russian Federation can be classified as industrial. Accordingly, the recommendations for improving sustainability that we propose for these territories will be relevant for other industrial regions of Russia.
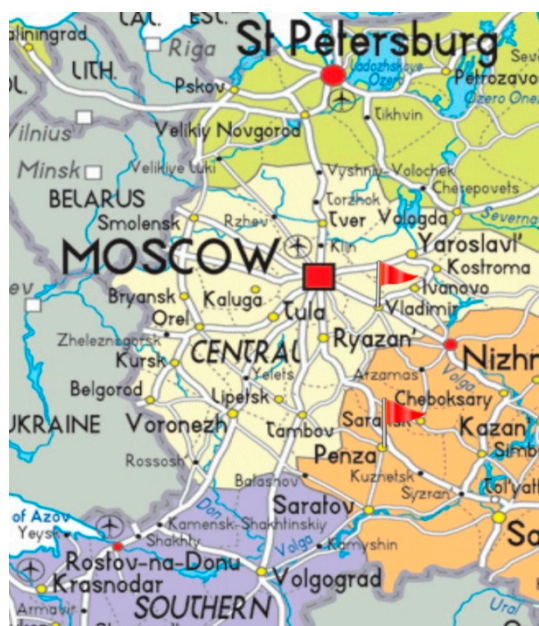

Figure 8. The map with geographical position of Vladimir and Penza regions.

The Penza region as a subject of the Russian Federation (RF) belongs to the Volga Federal District (VFD). According to its performance indicators, it is a typical region of Russia and traditionally takes the 50th position of 85 entities of the Russian Federation in terms of socio-economic development [65].

The city of Penza (the administrative center of the Penza region) is a typical average city of the Russian Federation and takes, on average, the 50th position among the 100 major cities of Russia by the comfort level over the past five years (Table 4). It held the 53rd position in rating of socio-economic development of the region in 2018. As follows from the Table 4, the unemployment rate in Penza has decreased for two years, but in 2019 there was a slight increase. The number of open small and medium enterprises has been growing steadily since 2016. In general, Penza is characterized by a high proportion of small and medium-sized enterprises (SMEs).

Table 4. Dynamics of indicators for the city of Penza. Source: [65,66].

	2015	2016	2017	2018	2019
Rating of Penza by the quality of life level, position	46	46	74	57	51
Population with income below the cost of living as a percentage of the total inhabitants in the Penza region, percentage	14	14.5	14	13.5	13.5
Number of newly opened small enterprises (including micro-enterprises), units	14,728	16,962	19,883	23,660	24,642
Registered unemployment rate, percentage	0.68	0.79	0.67	0.61	0.67

In 2017, business density in the Penza region amounted to 35.2 subjects of small and medium-sized enterprises per thousand residents of the region, which is higher than the average for the Volga Federal District. The largest segment in the structure of small and medium-sized enterprises of the Penza region is the sphere of trade, where 42.4% of all subjects are concentrated. Industry accounts for 9.2% of all SMEs subjects, construction—6.3%, agriculture—5%, and scientific and technical activities—5.6% (Figure 9).
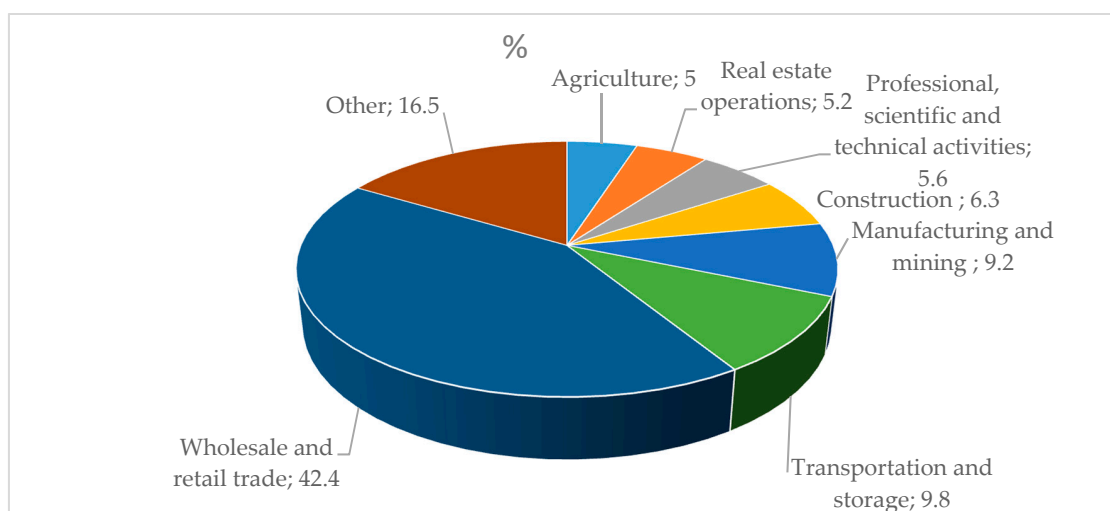
Figure 9. Distribution of SMEs subjects of the Penza region by main types of economic activity in 2017 [66].

The Vladimir region as a subject of the Russian Federation (RF) belongs to the Central Federal District (CFD). According to its performance indicators, it is a typical region of Russia and traditionally takes the 40th position of 85 entities of the Russian Federation [67].

The city of Vladimir (the administrative center of the Vladimir region) is a typical average city of the Russian Federation and takes an average the 50th position among the 100 major cities of Russia by the comfort level over the past five years (Table 5). The unemployment rate in the city of Vladimir is decreasing dynamically; the amount of the population with income below the cost of living is decreasing. Despite the fact that the number of opened small enterprises has begun to decline in the last two years, in general, the number of subjects of small and medium-sized enterprises (SMEs) is stable over the years, as evidenced by the indicators shown in Table 5.

Table 5. Dynamics of indicators for the city of Vladimir [described according to [68].

	2015	2016	2017	2018	2019
Rating of Vladimir by the quality of life level, position	35	63	65	47	42
Population with income below the cost of living as a percentage of the total inhabitants in the Vladimir region, percentage	14.1	14.3	13	12.8	12.6
Number of newly opened small enterprises (including micro-enterprises), units	50	142	107	57	49
Registered unemployment rate, percentage	1.1	1	0.9	0.8	0.8

The indicators shown in Table 6 give reason to assert that, despite the migration outflow of the able-bodied population to other territories of the country, the share of SMEs enterprises in the gross product of Vladimir is increasing, which indicates the growing profitability of SMEs organizations.

Table 6. Activity indicators of small and medium-sized enterprises in Vladimir city (described according to [68]).

Indicators	Years				
	2015	2016	2017	2018	2019
Number of subjects of small and medium-sized enterprises,	21.4	21.7	21.1	21.2	21.2
including individual entrepreneurs, thousand people	12.3	12.0	11.4	11.5	11.5
Share of SMEs enterprises in the gross product of Vladimir,%	13.2	13.4	12.2	13.5	15.1
Migration growth rates per 10,000 population	−11	−2	−21	−24	−22

However, along with the successful development of the urban economy, there are problems due to the increasing load on the environmental component of the urban environment. In this regard, the adaptation of the ecosystem formation methodology [69] is of greatest interest, as applied to the integration processes of economic entities of small and medium-sized enterprises in the field of manufacturing at the city level. The relevance of this aspect is due to the fact that despite the small share of manufacturing (about 8%, Figure 10) in the structure of SMEs of Vladimir, the influence of integration processes in this field of activity can significantly improve the environmental situation in the municipality.
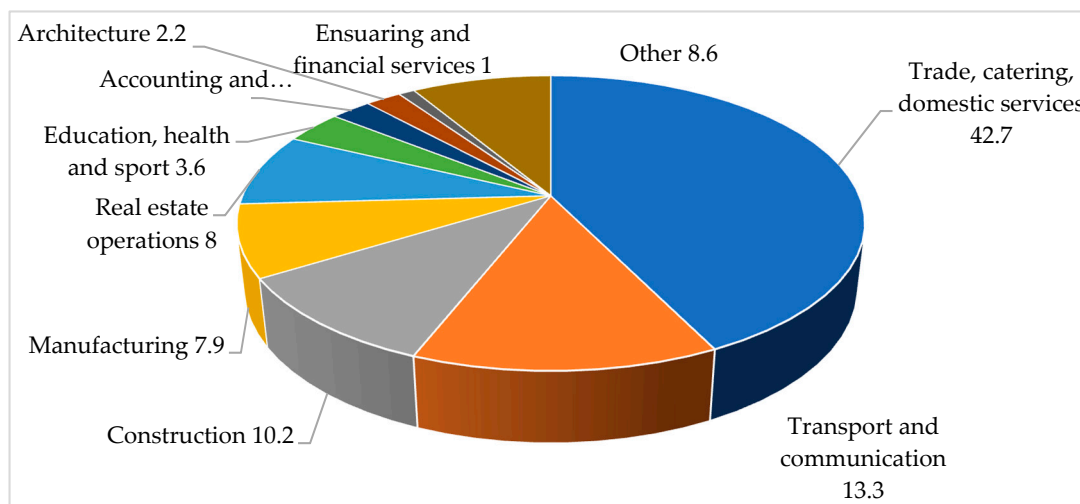

Figure 10. The structure of subjects of small enterprises (described according to: [68]).

The recycling of liquid, solid, and gaseous production wastes for the most part can significantly improve the environment and increase the added value of city organizations.

In this case, it requires the involvement of those employees in the recycling process who have the best competencies for this (co-sourcing), and also in terms of providing specific employees of one organization with the opportunity to work in another organization (out-staffing), or employment of fired workers from one organization to another (outplacement). The principle of complementary competencies of employees of ecosystem organizations makes it possible to organize the interaction of enterprises in which the law of synergy is realized, and efficiency increases along the entire chain of added value.

Though unclaimed information resources of organizations do not destroy the ecology of the city, their possible use indirectly saves material, energy, financial resources when it comes to inventions, knowhow, utility models, etc., which have not become innovations.

Having united into an ecosystem, organizations can save both all types of energy used in the process of their activity (mechanical, thermal, electric), and financial resources not only by tax reduction for environmental pollution, but also through mutual assistance and lending based on co-financing principles of Japanese keiretsu.

The aforementioned characteristics of ecosystems fit the description of classical clusters. However, in the cluster, the goal of creating a technological chain for the production of a specific product is primarily realized, and in the ecosystem, the goal is to improve the ecology of the city through the waste processing from the main business by small and medium-sized enterprises. In other words, the classic cluster "grows" in the ecosystem with SMEs enterprises providing deep processing of natural resources.

5.2. Sustainability Assessment of Territorial Ecosystems of Penza and Vladimir Regions

Assessment of sustainability of territorial ecosystems of Penza and Vladimir regions was carried out on the basis of official information from Federal State Statistic Service (Rosstat) and statistics from federal agencies.

Table 7 shows the data of three integral indicators taken from the official reports of information and rating agencies. Scientific and technical development index was developed by RIA—Russian news agency together with RAEX—rating agency "Expert RA" based on Rosstat data. Environmental index is developed by Green Patrol agency. RIA assessed quality of life in Russian regions. The Resource consumption level indicator (in other words, the level of investment in the development of three types of capital) is taken from the Rosstat report.

Table 7. Statistical data for assessing territorial ecosystem sustainability for 2017–2019, in points.

Territorial Ecosystem	Quality of Life Level			Scientific and Technical Development Index			Environmental Index			Resource Consumption Level		
	2017	2018	2019	2017	2018	2019	2017	2018	2019	2017	2018	2019
Vladimir region	47.34	47.57	47.98	48.49	46.66	45.21	48	49	50	1.5	1.4	1.4
Penza region	49.10	48.51	47.00	46.14	45.84	44.63	53	54	57	2.9	2.7	2.4
The RF entity with a maximum value of indicator	76.92	77.37	79.28	81.68	79.91	78.73	68	69	71	–	–	–

When determining the total capital usage of the territory, the indexes of RAEX, Green Patrol, and RIA rating agencies were used (Table 7).

To assess the human, production, and natural capital usage of a territorial ecosystem, we apply the index method integrating indicators such as quality of life, scientific, and technological development index, and environmental index. The calculation of the level of using the ecosystem capital was carried out by comparing the actual value and the best value of this indicator in the ranking of territories of the Russian Federation (Table 8).

Table 8. Calculation results for the level of capital utilization of territorial ecosystem for 2017–2019, in proportions.

Territorial Ecosystem	Human Capital			Production Capital			Natural Capital		
	2017	2018	2019	2017	2018	2019	2017	2018	2019
Vladimir region	0.62	0.61	0.6	0.59	0.58	0.57	0.71	0.71	0.70
Penza region	0.64	0.63	0.59	0.56	0.57	0.57	0.78	0.78	0.80

The level of using production capital in Penza and Vladimir regions ranges from 56% to 59%. At the same time, the level of using environmental capacity is above average and ranges from 70% to 80%. This situation is typical for territories that include industrial ecosystems. It is necessary to improve the quality of the living environment in Vladimir and Penza regions by implementing an effective environmental policy and creating conditions for increasing entrepreneurial activity. The presence of a deficit or reserve of capacity in the ecosystem reflects the ratio between the level of resource consumption and the natural resource potential of the territory.

To assess the state of territorial sustainability, we determine the entropy of the level of use of the total capital of the territorial ecosystem by Formula (2).

In 2017, the entropy of the ecosystem of the Vladimir region was as follows:

$$H(Vladimir) = -(\,0.62 log_2 0.62 + 0.59 log_2 0.59 + 0.71 log_2 0.71) = 1.22 \tag{2}$$

Similarly, the entropy for the ecosystem of Penza and Vladimir regions for 2017–2019 was calculated (Table 9).

Table 9. Calculation results for the entropy of the level of use of the total capital of territorial ecosystems for 2017–2019.

Territorial Ecosystem	Entropy		
	2017	2018	2019
Vladimir region	1.22	1.24	1.27
Penza region	1.16	1.17	1.18

The higher the level of capital use is, the lower the entropy and, accordingly, the higher the stability of the territory is. The entropy of the territorial ecosystems of Vladimir and Penza regions ranges from 1 to 1.5 according to the entropy assessment scale (Table 3), which corresponds to a stationary nonequilibrium state or weak stability. The stationary state of the ecosystem is characteristic of a "mature" ecosystem. At the initial stages of formation, the processes of knowledge, resources, and capital exchange are very intense, and as a result, the entropy of the ecosystem is high. Thus, the ecosystem is in an unstable state.

As a result of the analysis, it was found that ecosystem's sustainability is achieved primarily through natural capital. The investigated territorial ecosystems should increase the use of human capital [70,71] to ensure balanced and sustainable development in the long term.

6. Discussion

In this article, we have presented a new methodology for assessing territorial ecosystem sustainability using the Heisenberg central order theory and entropy approach developed by N. Kaitez [59] and adapted for the purpose of our study. Using the proposed method, we carried out two empirical case studies of territorial ecosystems of Penza and Vladimir regions in Russia.

At the first stage, we calculated integral indicators that characterize the level of use of three types of capital (human, natural, production). Factor analysis of the data obtained made it possible to identify which types of capital are ineffectively used in the territorial ecosystems of Vladimir and Penza regions.

At the second stage, the entropy of ecosystems was determined and, using the scale proposed by the authors, an assessment of the sustainable development of territories was carried out.

At the third stage, based on a comprehensive analysis of the socio-economic indicators of the territories and the obtained calculation results, measures are proposed to increase the sustainable development of the ecosystems of these regions.

As a result of the analysis, it was found that ecosystem's sustainability is achieved primarily due to the natural capital. The investigated territorial ecosystems should increase the use of human capital to ensure balanced and sustainable development in the long term. In terms of the sustainable development of Penza and Vladimir regions, corresponding laws and policy system need to be developed that consider the coordinated development of the economy, society, and the ecological environment a priority.

The conducted research is in line with previous studies. Liang et al. [50] have shown that the entropy approach can be successfully applied to observe and continuously monitor the actual changes in regional sustainable development levels.

Meanwhile, the proposed approach is based on some assumptions and limitations caused by them.

It is assumed that there is a correlation between the environmental, technological, and social components of total capital. The existence of a relation between the analyzed types of capital has been established in the works of other authors and in the methods for calculating sustainable development indicators developed by international and Russian organizations [33–49].

When assessing the sustainability of ecosystems based on the entropy approach, the choice of tools and model depends on the level of the ecosystem. The adapted Shannon entropy model is only suitable for assessing macro and meso-level ecosystems, under the assumption that the territorial

ecosystem is closed-looped system. It is advisable to evaluate open ecosystems through the entropy of unification.

The system of indicators for assessing the sustainable development of a territory is limited by three integral indicators characterizing three types of capital (human, natural, and industrial). The types of capital can be supplemented depending on the characteristics and specifics of the assessed ecosystem of the territory. For example, for territories that are regional financial centers, it is advisable to take into account the level of use of financial capital. For tourist and cultural centers—social capital. In this regard, in the methodology for assessing the sustainable development of territories, the types of capital and the list of indicators that characterize them may vary depending on the goal and objectives of the study.

Moreover, the index system used in this study does not contain all the territorial ecosystem's capacity influencing factors. Additionally, this research focused on a static analysis of the data indexes, without studying the internal logic relationships between the indexes and their dynamic evaluation.

7. Conclusions and Future Research Directions

This article contributes to the development of scientific thought devoted to the problem of environmental and socio-economic development of regions in terms of studying promising methods and tools for assessing sustainability of territorial ecosystems, which could make up for the lack of sustainable development research. From a theoretical point of view, the study encourages further research to introduce a strategic framework able to identify different strategies for territorial sustainable outcomes.

Thus, the proposed approach to territorial ecosystem sustainability assessment creates an opportunity to employ sustainability assessment of regions not just as a tool for ex post de facto research, but also to guide sustainability visions and strategies for sustainable regional development.

From a practical point of view, the paper proposes approaches helping regional authorities to progress sustainability. Identification of key factors for maintaining the sustainability of regional development can help authorities and governing bodies to understand ways to monitor current capabilities of territorial ecosystems for maintaining ecosystem equilibrium.

We raise the following questions to be addressed as future lines of research. Russian regions are characterized by high differentiation in terms of their level of development, associated with their industry specialization. In this regard, when assessing territorial ecosystem sustainability, it is recommended to divide the regions into groups to compare the same type territories according to development prerequisites (industrial, agricultural, tourism, and financial centers). It is also advisable to carry out comparative analysis and development of a strategy to increase sustainability for groups of regions.

The study of territorial sustainability on the basis of the ecosystem approach is the beginning of a discussion on what real environmental and socio-economic development means for Russian regions, and how to measure it. In the future, the authors plan to include additional economic, social, and environmental indicators in order to transform the index of territorial ecosystem sustainability into the index of "green economy" for the constituent entities of the Russian Federation.

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