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Article

Cultural and geographic drivers of tourism cluster development in the Turkestan region of Kazakhstan

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Abstract: Globally, tourism clusters play an important role in improving the economic competitiveness and investment attractiveness of a country, sustainable development of local culture and recreational resources, tourism enterprises and tourism in regions. After all, tourism clusters mainly provide for the development of tourism infrastructure systems and allow for the optimisation of environmental, social and economic impacts. In this regard, the issues of environmental, technological and socio-economic interrelation in the sustainable development of tourism in the regions of Kazakhstan can be solved through tourism clusters. In particular, the Turkestan region has great opportunities for the development of cultural and cognitive, medical and health tourism through the creation of a tourism cluster and achieving economic growth through the creation of modern tourist complexes. Therefore, the purpose of this study was to examine the cultural and geographical prerequisites and opportunities for the formation of a tourism cluster necessary for the sustainable development of the Turkestan region. The study used the interview method to identify the main problems and the opportunities for the creation of a tourism cluster were assessed using SWOT analysis. As a result of the research, the need to improve infrastructure (40%), improve the quality of service (27%) and strengthen marketing efforts (17%) to increase the tourism potential of the Turkestan region was identified. At the same time, the Mausoleum of Khoja Ahmed Yasawi (61%) was recognised as one of the most attractive tourist attractions in the Turkestan region. In addition, the historical and cultural objects of the Turkestan region, participating in the tourist cluster, were identified and the structural model of the tourist cluster formation was developed. Thus, this study shows that the formation of a tourism cluster in the Turkestan region contributes to the improvement of infrastructure and economic development of the region and increases the international tourist flow between Turkic countries.

* * * * *

1 Introduction

Tourism is now recognised as one of the most important sectors of the global economy and contributes to socio-economic development, job creation and regional competitiveness (Moldagaliyeva et al., 2024). The development of tourism clusters is considered in the world practice as an effective mechanism of organisation and management of tourism (Niyazbayeva & Yessengeldina, 2016). Tourism clusters are mainly focused on optimising environmental, social and economic impacts, ensuring the development of tourism infrastructure systems (Alimova et al., 2020). Therefore, the development of tourism clusters allows the effective and sustainable development of tourism activities, as well as the formation of

promising projects in the field of tourism (Gáll & Strežo, 2019). The importance of tourism clusters is characterised as a means of increasing the efficiency of regional tourism groups and solving social problems, determines the necessity of applying the cluster approach for the purposes of sustainable development (Ivanovic et al., 2010; Larionova et al., 2017). Thus, creating tourist clusters in regions with historical and natural attractions, assessing their structure and potential, the investment potential of the cluster zone is determined.

In the world practice there are clusters in various tourist destinations, in particular, the features of tourist clusters in European countries and their impact on the regional economy, the necessary prerequisites for the creation of a cluster are considered in detail (Gorbunov et al., 2018). Cluster models of the USA, India, Russia and China are recognised as a factor in increasing the competitiveness of the national economy (Doçaj et al., 2018; Cao & Sarker, 2022). Therefore, formation of clusters in the tourism industry in these states plays a high role in enhancing the investment attractiveness of the state. The formation and development of tourism clusters occupies an important place in increasing the economic competitiveness and investment attractiveness of countries (Shah & AhmadWani, 2014). In this context, the tourism industry between the countries along the Silk Road in Central Asia (in the border areas of the Silk Road) is developing (Mitroshenko, 2020). That is why Uzbekistan and Kazakhstan direct the development of mutual historical and cultural tourism to the factors of demand of tourist groups (Issakov et al., 2023). Development of local culture and recreational resources, tourism enterprises and tourism in the border regions becomes very important on the way of development of tourism industry in the region of Central Asian countries (Kantarci et al., 2014; Hall & Page, 2016).

The interconnection of environmental, technological and socio-economic changes in the sustainable development of tourism in Kazakhstan is closely linked to the emergence of tourism clusters (Zharkenova et al., 2023). This is due to the fact that tourism clusters contribute to the economic competitiveness of the recreational area and the development of intersectoral co-operation (Kenzhebekov et al., 2021). In the conditions of Kazakhstan, measures for the development of tourist clusters are aimed at the development of the national economy, so it is necessary to increase the competitiveness of tourist centres, clusters of tourist facilities, given the lack of quality infrastructure and unprofitability of the industry (Tokbergenova et al., 2023). Natural, cultural and mixed sites on the territory of Kazakhstan are important elements of the tourism cluster and increase the ecological, economic and political significance of the country (Koshim et al., 2023). To develop Kazakhstan's tourism industry, it is necessary to take effective measures to increase the economic, environmental and political importance of tourist facilities through clustering, improving the quality of infrastructure and attracting international investment. It is also necessary to provide normative and legal support of cluster policy within the framework of the concept of formation and development of clusters in Kazakhstan (Concept of cultural policy of the Republic of Kazakhstan, 2023).

In this regard, studies on the development of the tourism industry in Kazakhstan and its socio-economic efficiency highlight the importance of clustering, the need to restructure concentrated tourist facilities, and the need to take into account regional climatic features (Aktymbayeva et al., 2023). Based on these studies, it is very important to develop tourism clusters in Kazakhstan, to study their geographical, socio-economic impact and to introduce international experience. Despite support in this direction from the government, there are no concrete actions on cluster development of tourism in Turkestan, Almaty, Akmola and East Kazakhstan regions (Askeyev & Baizholova, 2021). Especially in Turkestan region, where there are all prerequisites for the formation of a tourism cluster, tourism is still not formed in a cluster context. Therefore, the purpose of this study was to examine the cultural and geographical prerequisites and opportunities for the formation of a tourism cluster necessary for the sustainable development of the Turkestan region. Since the potential of the tourism cluster of Turkestan region has not been fully explored, the model of tourism cluster development has not been specified, and the impact on the sustainable development of the tourism industry in Kazakhstan has not been assessed. This is stated in the works of many domestic scientists: for example, Abishov and Abishova (2023) in their study 'Mechanisms of Agritourism Development in Turkestan region' argue that tourism development in

Turkestan region becomes important to modernise not only the natural resources of rural areas, but also the culture, traditions, history, national cuisine of the Kazakh people, which will allow the development of clusters. Furthermore, Nakhimbekova et al. (2024) in their work analysed the branding elements affecting the image of Turkestan region and the impact of the use of information technology in the tourism business on the quality of services. It follows that the region has all the prerequisites for tourism development, sufficiency of tourist facilities and the need to develop a model of cluster development.

This research is aimed at studying the cultural and geographical prerequisites and opportunities for the formation of a tourism cluster, necessary for the sustainable development of Turkestan region, in the course of the study widely used methods of interviewing, SWOT-analysis, modelling. A review of the latest Kazakhstan and foreign literature was conducted and Michael Porter's model 'Diamond' was taken as a basis for the development of tourism cluster model. This study will help to form tourism clusters in the Turkestan region, improve the region's infrastructure and increase economic efficiency. Tourism clusters contribute to attracting investment by creating new jobs and increasing competitiveness. Therefore, the development of historical and cultural tourism of Turkestan region creates conditions for the inflow of tourist groups and growth of demand. In addition, the Turkestan region will become a basis for development as an international tourist destination, attracting investments through a positive tourist image of the region, development as a new tourist destination and construction of new resorts meeting international standards. Also, such topical issues as non-compliance of service facilities with international standards, lack of roads to tourist sites and lack of infrastructure at historical and natural tourist sites will be proposed as a direction for future research.

2 Materials and methods

Currently, there are great opportunities in Turkestan region to achieve economic growth through the development of cultural and cognitive and health tourism and the creation of modern tourist complexes (Akbar et al., 2019). Turkestan region borders with the tourist areas of Uzbekistan and Kyrgyzstan (Figure 1). Turkestan region is characterised not only by historical sights, unique architecture and natural landscapes, but also one of the regions of the republic where health tourism is developed (Baltabayeva et al., 2019). Tourists from different parts of Kazakhstan and neighbouring countries come here to relax and improve their health. Health tourism in the Turkestan region meets all the requirements of tourists for full-fledged recreation and recovery (Doskhozina & Yessekeyeva, 2019). Regular visits to sanatoriums in the region fully satisfy the need for recreation, recovery and treatment using various components of the natural complex (landscape, comfortable climate, healthy regime, environment replacement, etc.) and significantly improve the quality of life. In addition, objects of cultural and cognitive tourism in Turkestan region will allow you to learn the history and culture of Kazakh society and see sacred tourist sites.

In this regard, this study aimed to fully explore the tourism cluster potential of Turkestan region, develop a structural model of the tourism cluster and assess its impact on the sustainable development of tourism in Kazakhstan. The study reviewed the works of world scholars (55 literature sources) and determined the relevance of the topic. The literature review was conducted as an ongoing process throughout the research period, while primary data collection through interviews was carried out during 01.09.2024–20.10.2024. The world experience of tourism clusters has been studied, structural models of clusters in developed countries have been analysed. At the same time, in order to identify the main issues in the industry were asked interview questions prepared together with young scientists of Abai University (01.09.2024-20.10.2024) received answers from the respondents. By means of interviews with various stakeholders (tourists, tourism professionals, local residents) (30 respondents) the current state and possibilities of cluster development were fully assessed. While the sample size is modest for a study of this regional scope, it is appropriate for the qualitative, in-depth interview approach employed, and findings should be interpreted as exploratory rather than statistically representative. Thus, it was fully possible to deepen the study of the main problems of creating a tourism cluster of Turkestan region and identify ways to solve and improve it. The following questions (Q) were asked during the interview:

- Q1. Tell us more about yourself, what neighbourhood will you be from?
- Q2. How do you assess the tourism potential of Turkestan region today?
- Q3. What factors, in your opinion, contribute to the development of tourism in the region?
- Q4. What tourist objects are the most attractive for Turkestan region?
- Q5. Are you satisfied with the quality of the tourist services offered and the itineraries in the tourist destinations?

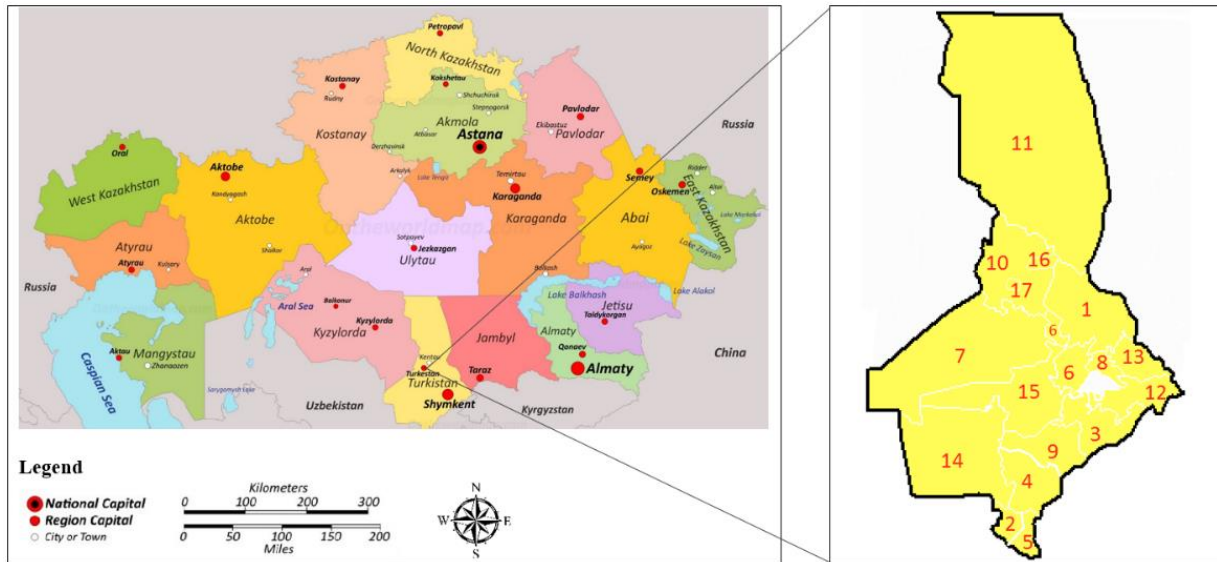


Figure 1. Map of the Turkestan region district: 1) Baidibek 2) Zhetysay 3) Kazygurt 4) Keles 5) Maktaaral 6) Ordabasy 7) Otyrar 8) Sairam 9) Saryagash 10) Sauran 11) Sozak 12) Tolebi 13) Tulkubas 14) Shardara 15) Arys city 16) Kentau city 17) Turkestan city.

In the study, consent to the interview was determined by telephone call, and the interview itself was conducted face-to-face and online ZOOM. The duration of each interview was 10-15 minutes, at which stage the data obtained was recorded and processed on tape for qualitative analysis. In addition, during the research we conducted a SWOT analysis to analyse the opportunities for creating a tourism cluster in the Turkestan region. The analysis considered the strengths, weaknesses, opportunities and threats of tourism in the Turkestan region.

In creating a tourism cluster model of Turkestan region, we comprehensively studied the tourism industry of the region using the Michael Porter Diamond model (Fang et al., 2018). The four key elements of this model helped us to effectively structure tourism competitiveness. With the help of this model, the directions necessary for the development and development of Turkestan region's tourism potential were identified. The main objective was to contribute to the economic growth of the region and its international recognition by creating a tourism cluster of Turkestan region. The flowchart of this research in full is presented in Figure 2.

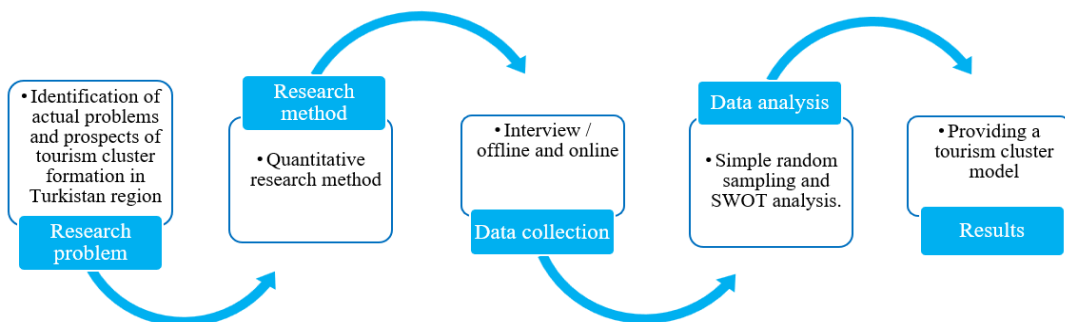


Figure 2. Research Flowchart (Source: Compiled by the authors)

3 Results and discussion

As a result of the study, out of 30 respondents who participated in the interviews, 5 were from Baidibek, 4 Saryagash, 4 Sairam, 3 Otyrar, 3 Zhetysai, 2 Tulkubas, 2 Tulebi, 2 Kazygurt, 1 Maktaaral, 1 Shardara, 1 Sozak districts, 2 respondents were from Turkestan. The majority of respondents appreciated these historical monuments, reporting that attendance at the Khoja Ahmed Yassawi Mausoleum and the neighbouring Arystan Bab Mausoleum and the Ukasha Ata Memorial Complex in Turkestan has been increasing over the years. After all, these places are tourist sites of great importance for tourists interested in the history of Kazakhstan and Central Asia. The opinions of respondents regarding the current tourist potential of Turkestan region were also analysed, and the assessments of three main groups (high, average, low) were determined. The results, along with recognising the rich historical heritage of the region, showed the need to develop infrastructure and quality of services (Figure 3a). In addition, the main directions of the region's development to increase the tourism potential of Turkestan region have been identified. The respondents' answers showed that improving infrastructure, improving the quality of services and strengthening marketing efforts play an important role. According to respondents, the main factors contributing to tourism development are infrastructure development (40%) and quality of services (27%) (Figure 3b).

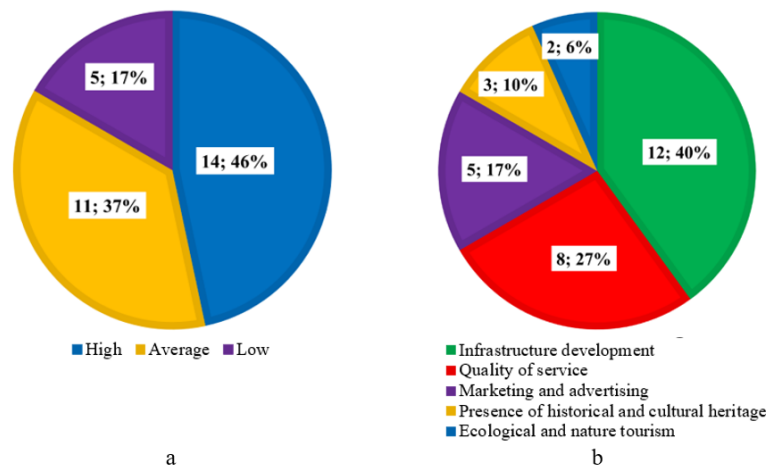


Figure 3. Answers of respondents: a) Assessment of tourism potential of Turkestan region. b) Main factors contributing to tourism development, %

Turkestan region as a rich region of cultural and historical heritage of the country is particularly popular among tourists. Tourist sites of the region attract with their history, architecture and natural features. Respondents chose the mausoleum of Khoja Akhmed Yasau (61%) as the most attractive tourist site in Turkestan region (Figure 4).

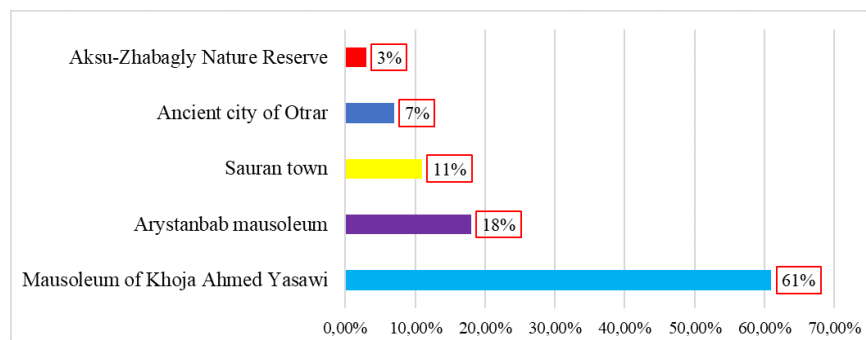


Figure 4. Most attractive tourist destinations, %

After all, there are several historical sites within the Khoja Ahmed Yasawi Mausoleum and Hazret Sultan Reserve-Museum, such as: the underground Kiluet Mosque, Juma Mosque Museum, Rabiga Sultan

Begin Mausoleum, and many others. Arystan Baba Mausoleum is in second place (18%). Every tourist going to the mausoleum of Khoja Ahmed Yasawi will first spend the night in the mausoleum of his teacher Arystan Baba. The third place is occupied by the town of Sauran, the name of the town is found in written sources since the 10th century (Smagulov, 2008; Iskakova et al., 2021). Archaeological excavations and restoration projects are ongoing at the site. Fourth, the city of Otrar is one of the most ancient cities of Central Asia, formerly known as Farab, a center of trade and crafts, a city of diplomatic, military and strategic importance (Abzhalov & Kozha, 2022). In fifth place, Aksu-Zhabagly reserve was recognized as the most visited by tourists (Akbar & Yang, 2022). In addition, a large number of tourists visiting the Karatau Nature Reserve, Sairam-Ugam National Park and Akmeshit Cave are noted. They are widely known to tourists as one of the attractive attractions of Turkestan region.

Regarding service quality, respondents in Turkestan region were asked: “Are you satisfied with the quality of the tourist services offered and the itineraries in the tourist destinations?” In response, 50% of respondents answered that they are not satisfied with the quality of services. Despite the development of tourism in the region of the oblast, a number of issues related to the organization of tourist routes (33% of respondents) still need improvement. In addition, respondents (17%) believe that in this direction it is necessary to organize new programs and excursion routes, to ensure in accordance with them the quality of service. Thus, the results of the interviews to assess the tourism potential of Turkestan region showed high potential of the historical and cultural riches of the region. Respondents highly appreciated the tourism potential of the region, but noted the low level of infrastructure and quality of services as important obstacles. Infrastructure development, quality of services and prioritization of marketing were identified as the main factors influencing tourism development. The need to effectively promote the cultural heritage of Turkestan and the importance of forming a tourist brand of the region was emphasized. The Mausoleum of Khoja Ahmed Yasawi was also recognized as the main attraction of the region, and the need to improve tourism services and routes, as well as information provision was identified. To develop tourism in the Turkestan region it is necessary to improve quality standards and infrastructure development. In this regard, we conducted a SWOT analysis to fully assess the tourism opportunities of Turkestan region (Table 1). The results of the conducted SWOT analysis are used to identify the strengths and weaknesses of the organization or region, as well as opportunities and threats related to the structure of the tourism cluster of Turkestan region.

Table 1. SWOT analysis matrix

	Opportunities:	Threats:
	- development of cultural tourism; - renewal of tourist products; - growth of foreign tourists.	- lack of economic stability; - the emergence of new competition.
Strengths:		
1. Historical and cultural heritage	- organizing cultural tours, festivals and events; - establishing partnerships and developing special programs between domestic universities and research centers.	- public accessibility of historical sites may lead to the loss of cultural values; - increased tourist flows, negatively affecting the lives of local people.
2. Development of tourist infrastructure	- improvement of roads and transportation services; - development of tourist routes; - attraction of investments.	- infrastructure improvements can lead to environmental problems.
3. State support for tourism development	- attraction of investments into the sphere of tourism through state support; - formation of tourist brand of Turkestan region on the international market	- financial dependence; - misdirection of government support.
4. High quality service	- to be competitive in the tourism industry by training skilled workers; - attracting customers through quality service.	- outflow of tourists to competitors as a result of lack of quality service; - deterioration in the level of service.

Table 1. (Continued)

	Opportunities:	Threats:
	- development of cultural tourism; - renewal of tourist products; - growth of foreign tourists.	- lack of economic stability; - the emergence of new competition.
Weaknesses:		
1. Lack of tourism infrastructure	- infrastructure development contributes to job creation, improvement of the quality of tourism services.	- construction works and infrastructure development may affect the environment; - financial difficulties may result in projects not being completed on time.
2. Weakness of advertising and marketing	- presentation of tourist products of Turkestan region in the national and international markets through strengthening of advertising; - popularization at tourism exhibitions and festivals, strengthening of positions in the international market.	- weakness of publicity may lead to incomplete disclosure of the area's potential.
3. Problems for foreign tourists	- provision of preferential tours and packages for visiting tourists, creation of special routes; - increasing the interest of foreign tourists through strengthening tourist cooperation with neighboring countries.	- higher prices for travel expenses, accommodation and other services of visiting tourists may lead to fewer foreign tourists; - language problems of foreign tourists, lack of language among locals and in the service sector may lead to a negative impact of the tourist experience.
Note: compiled by the authors based on interview responses and literature review		

Thus, for the sustainable development of tourism in the Turkestan region, travel agencies need to organize powerful advertising campaigns and popularize the historical and cultural heritage of the region. It is important to develop high-level customer service programs and develop tourist destinations (Garda, 2022). These measures will create a permanent customer base and increase the region's competitiveness in tourism. Tourism development in the region is of great macroeconomic importance, as the region's tourism potential has not yet been fully realized (Kuralbayev et al., 2017). The study showed that although the level of respondents' satisfaction with tourism services varies, there are no significant differences by demographic and business characteristics. This suggests the need to increase the popularity of tourist destinations and develop unique tourism products. The provision of similar services by many enterprises in the region leads to a neutral assessment of their competitiveness. Thus, we have fully covered the historical and cultural features of the Turkestan region as components of the tourism cluster.

Due to the fact that the main purpose of forming a tourist cluster in the Turkestan region is to increase the flow of tourists and increase the duration of stay of tourists, we have combined all tourist facilities in the region into the components of the cluster (Figure 5): The first component is historical and cognitive tourism, including historical and cultural sites located in Turkestan city, Otrar, Sauran and Baidibek districts. The second is ecological tourism, including specially protected natural territories (reserves 'Aksu-Zhabagly' and 'Karatau', as well as national natural park 'Sairam-Ugam' and regional natural park 'Syrdarya-Turkestan') and Zhetykol in the vicinity of the city of Turkestan. The third group of therapeutic tourism clusters, including resort zones Saryagash, Arys, Mankent. Thus, the development of grouping of tourism types in the region opens the way to additional income and socio-economic stability of the local population.

The formation of tourism cluster in Turkestan region can become an important factor of socio-economic growth of the region. Close cooperation between the public and private sectors is necessary to increase the potential of tourism in this region. The state should promote tourism development at the regional level and focus on creating new opportunities for domestic and international tourists (Mamutova, 2020; Nakhipbekova et al., 2023). In addition, it is important to improve the infrastructure of tourist destinations, support the construction of new facilities and modernize historical and cultural heritage. The

competitiveness of the region's tourism will be enhanced by improving the quality of services and affordability of prices (Tiberghien, 2019). Tourism organizations should adapt to the needs of the market and implement modern technologies. As one of the directions of state support it is possible to increase the efficiency of the coordinating council of the tourism cluster. To increase the number of visitors to the region, it is necessary to conduct advertising campaigns and marketing research (Tuyakbayev et al., 2021). This opens up new opportunities for business owners in the region and strengthens their economic stability.

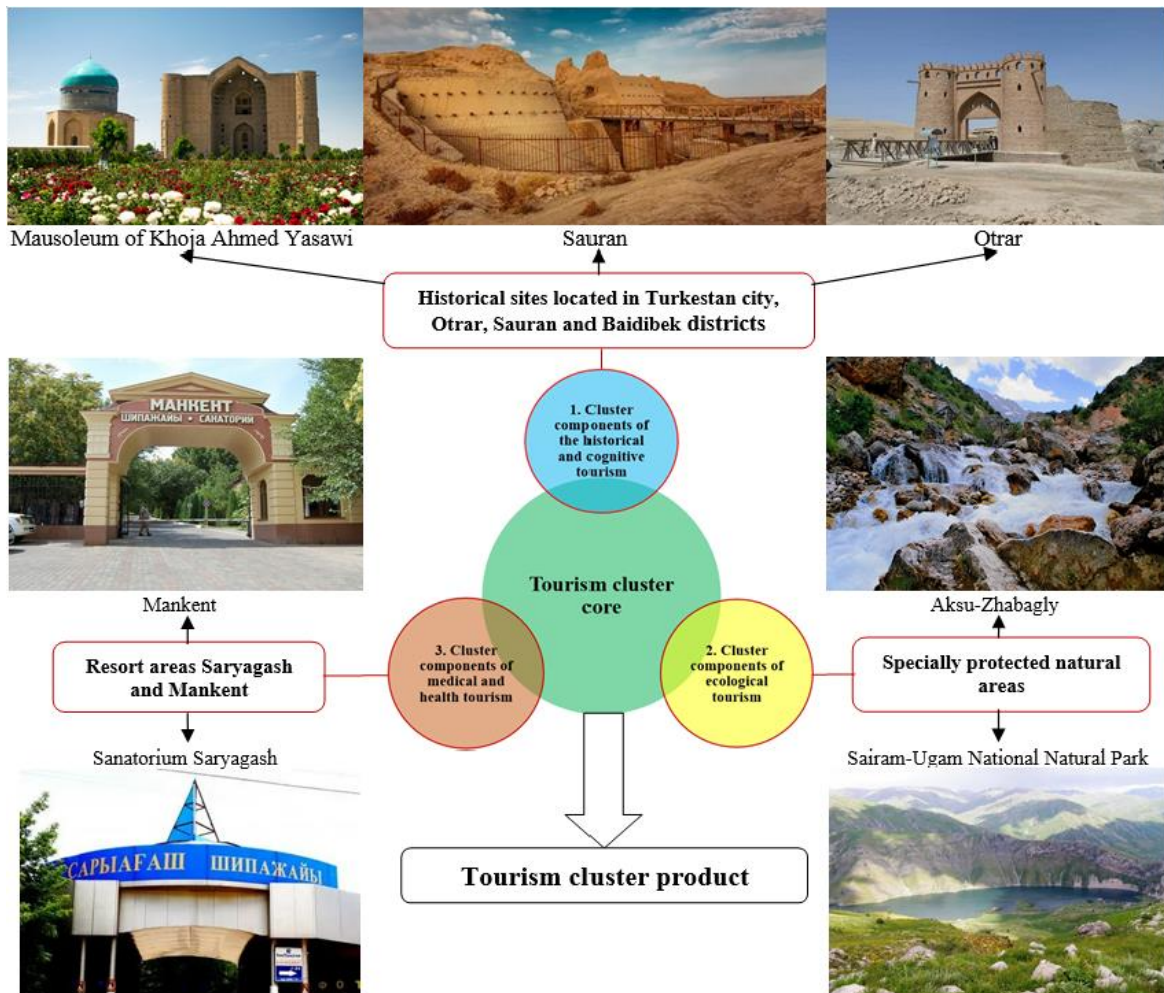


Figure 5. Structural model of tourism cluster formation in Turkestan region

Thus, the development of tourism cluster in Turkestan region should include social and cultural aspects. There is an opportunity to improve the quality of life in the region by attracting local residents to the tourism business. It is possible to improve the level of service by introducing training and professional development programs for local entrepreneurs. It is especially necessary to effectively utilize historical and cultural sites and natural resources. To increase the popularity of tourist destinations, it is necessary to strengthen cooperation between tourism organizations and local authorities (Mamirkulova et al., 2020). In addition, it is possible to increase the attractiveness of the region by diversifying tourism products. After Covid-19, it is important that tourism development measures are permanent. At the same time, research results and statistical data play an important role in tourism planning and decision-making. The unique geographical and cultural features of Turkestan region make it possible to turn the region into a tourist center of international level (Aktymbayeva et al., 2020). Therefore, the cluster approach to development affects not only economic but also social change.

In order to develop the tourist cluster of the Turkestan region, it is necessary to strengthen the advertising of unique tourist routes in the region and mandatory propaganda on national channels. It is important to develop and support wide distribution of guidebooks and thematic maps on tourist routes in Kazakh, Russian and English languages. In addition, it will be profitable for foreign tour operators and media representatives to organize information tours including special itineraries (Gidebo, 2021). One of the priorities should be the popularization of tourism as an integral part of a healthy lifestyle and the development of the necessary infrastructure for this purpose. The active participation of private tourism business owners in these processes contributes to the effective utilization of the advantages of the cluster approach. The growing demand for tourism leads to the emergence of new tourist facilities in the region and expansion of the scale of operations. Attracting investment in the construction of small and medium-sized hotels and resorts is an important part of cluster development (Rakhmetulina & Omurzakov, 2018). Moreover, due to the development of new tourist facilities and services, Turkestan Oblast can become an attractive tourist region. Using the natural and cultural potential of the region, it is possible to create a world-famous tourist center (Seken et al., 2019). These steps will contribute to increasing the economic and social importance of the tourism industry in the Turkestan region.

In this direction, foreign scientists who have studied tourism clusters in different countries and regions of the world have highlighted a number of important aspects. For example, in Australia and New Zealand the development of tourism industry is based on the conservation of natural resources and environmental sustainability (Jackson & Murphy, 2006), this corresponds to the practice of sustainable eco-tourism development in the Turkestan region. According to German experience, public-private partnerships and the introduction of modern technologies are particularly important for the effective organization of tourism clusters (Dressler & Paunović, 2021), this provides great opportunities for the development of public-private partnerships in Turkestan. Meanwhile, Spain and Italy focus on the development of cultural tourism and historical heritage preservation (Tóth et al., 2014), which has great practical significance in the effective utilization of historical and cultural heritage of Turkestan.

Analyzing the strengths and weaknesses, opportunities and risks associated with the sustainable development of tourism in Turkestan region, it is possible to identify similarities and differences with foreign experience. The main advantage of the region is its rich historical and cultural heritage and infrastructural development potential, which echoes the special attention to historical and cultural tourism in Spain and Italy. However, there are also weaknesses such as inadequate infrastructure and lack of human resources, which is comparable to similar problems we have encountered in developing tourism clusters in Germany and Australia. In terms of opportunities, the potential for the development of ecological and cultural tourism, as well as social-private partnerships and the introduction of modern technologies is particularly important, which shows the region's flexibility in adapting foreign experience. But threats such as economic instability, natural disasters, political factors can hinder the development of international tourism, which is one of the main issues often discussed in foreign studies.

4 Conclusion

So, a large number of historical and natural objects in Turkestan region is a prerequisite for the formation of a tourist cluster, which determines the tourist potential of the region. However, the scattered location of objects is unfavourable for tourists. The quality and price of services provided in the relevant infrastructure of Turkestan region such as roads, transport, accommodation and recreation facilities may cause difficulties in the formation of a tourism cluster. This is because the quality of services may not match the price or may not exist at all. To attract tourists to the Turkestan tourism cluster, it is very important to have effective marketing and promotion strategies and plans. Therefore, in order to create a successful tourism cluster in the Turkestan region, it is necessary to convince local businesses, government agencies and community members to co-operate with one goal. This is necessary to increase tourism activity and form a tourism cluster. Competing tourist destinations can make it difficult to attract visitors to the cluster, so clusters need to identify and utilise their unique selling points to stand out from

competitors. Also, it is necessary to maintain high standards of quality of services, attractions, facilities, create a positive reputation and encourage repeat visitors to the tourism cluster. Enterprises within the tourism cluster should be prepared to work closely with government agencies to clearly understand regulatory requirements and address any problems. This study has several limitations that should be acknowledged. The interview sample of 30 respondents, while appropriate for qualitative inquiry, limits the generalisability of findings to the wider population of Turkestan region stakeholders. Additionally, the data collection period of approximately two months may not capture seasonal variations in tourism activity. Future research should employ larger-scale quantitative surveys to complement the qualitative insights obtained here. Comparative studies examining mutual tourist flows among Central Asian countries – particularly between Kazakhstan, Uzbekistan, and Kyrgyzstan along the Silk Road corridor – would significantly deepen understanding of cross-border cluster development opportunities and regional tourism integration.

In this regard, based on the evaluation of the development of tourism clusters, the proposed model of tourist cluster to systematise the service of tourist facilities in Turkestan region will help to increase the tourist flow in the region and increase the number of tourists coming from abroad. Besides, among Turkic countries Turkestan region will become the basis for the development of International tourist destination, attraction of investments through positive tourist image of the region, development of agrotourism (rural tourism) as a new tourist destination and construction of a new resort town (through expansion of the resort area) in Saryagash district corresponding to international standards. This will also help to address pressing issues such as the lack of compliance of roadside facilities (food outlets and toilets) with international standards, lack of roads to tourist sites and slow development of infrastructure around historical and natural tourist sites.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ulzhalgas Tokbergenova	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

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Article

Scientific and theoretical foundations of the formation of views on the concept of geographic environment

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Abstract: The geographical environment is a fundamental concept in geography that provides the theoretical basis for understanding interactions between natural and human systems. However, inconsistent definitions of its structure, boundaries, and methodological foundations continue to limit its theoretical coherence and interdisciplinary application in addressing contemporary environmental challenges. This study aims to examine the historical evolution of the geographical environment concept, critically evaluate the principal theoretical approaches developed by different geographical schools, identify the key methodological challenges associated with its interpretation, and develop an updated conceptual model reflecting its natural-social characteristics. The research employs historical-geographical and comparative analyses, qualitative content analysis, and structural-functional conceptual modeling to synthesize existing theoretical perspectives and establish a comprehensive conceptual framework. The findings demonstrate that the geographical environment should be understood as a dynamic, integrated natural-social system continuously shaped by reciprocal interactions between environmental processes and anthropogenic activities operating across multiple spatial and temporal scales. The analysis identifies persistent theoretical ambiguities regarding the definition and scope of the concept and highlights the importance of integrating perspectives from geography, ecology, sociology, economics, and environmental sciences to strengthen interdisciplinary research on coupled human–environment systems. Based on these findings, an updated theoretical model is proposed that illustrates the transition from a static perception of nature to a co-evolutionary framework emphasizing the mutual interdependence of society and the biosphere. The proposed framework provides a robust theoretical foundation for interdisciplinary geographical research and offers practical guidance for sustainable regional development, environmental management, spatial planning, ecosystem conservation, and evidence-based decision-making in response to increasing anthropogenic pressure and global environmental change.

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1 Introduction

The global challenges facing humanity today—such as climate change, the depletion of natural resources, and increasing human pressure—require a reevaluation of the “human-nature-society” system at the international level. The 2030 Agenda for Sustainable Development, adopted by the United Nations (UN), and UNESCO’s strategic initiatives on environmental protection have established the preservation of the planet’s ecological integrity as a global priority. In these documents, a scientifically grounded

understanding of the interrelationship between natural systems and social development is presented as a guarantee of a sustainable future. In this global context, modern geographical science stands out as a complex interplay of various disciplines in which knowledge and perceptions of the natural environment converge (United Nations, 2015).

Modern geography is a complex interplay of various sciences and disciplines in which knowledge and perceptions of the natural environment are interwoven (Abdullaev & Islomov, 2016). One of the fundamental concepts of modern geography is the geographical environment; this concept expresses a specific set of general and essential characteristics of an object (Shalnev & Degtyareva, 2011), which is viewed as a dynamic environment divided into countless individual elements that shape the natural conditions of society's existence (Stozhok, 2011). The concept of the "geographical environment" was initially viewed solely as part of the geographical envelope, but later became an established and essential foundation of social life, coming to encompass productive, economic, and social infrastructure components. This concept is approached from a unique perspective in each field of science. Since it is philosophically considered insufficient to view the geographical environment solely as a natural category, some scholars have proposed abandoning the use of this concept to avoid contradictions (Cherkashin, 2021).

Debates over the concept of the geographical environment continue, and this term is still perceived as a concept that has not received full theoretical justification. For example, while some view the geographical environment as a concept reflecting the interaction of social and natural laws, others reject the legitimacy of including humans in the geographical environment, arguing that "humans play the role of 'masters' in their interaction with nature" (Fedyunina, 2012). In the works of many renowned geographers, the geographical environment is regarded as the unifying principle of geographical research. Even in the early stages of the Siberian School of Geography's development, scholars considered the study of the geographical environment and the development of scientific foundations for its comprehensive use to be the primary subject of geography. They believed that the geography of the future was a science "specializing in and focused on the study of the environment of human society, primarily the natural environment" (Cherkashin, 2020).

The issue of the interaction between society and nature has become one of the pressing issues of our time. It is impossible to analyze the relationship between humans and nature without examining concepts such as "geographical environment," "environment," "biosphere," and "noosphere," as well as their interrelationships (Volkov, 2010). Human dependence on the nature surrounding them—or, more precisely, on the geographical environment—has never been disputed, although the degree of this dependence has been assessed differently by various scholars (Andreev, 2009). Thus, some scholars view the geographical environment as part of the geographical envelope that has been subjected to human development, integrated into the production process, and constituting the material basis of society's existence. Due to changes in society and the world, the concept of the geographical environment in the modern world is characterized not only by a multitude of different interpretations but also by its interdisciplinary nature. This concept is gradually moving beyond the scope of classical geography and finding wide application in other fields of science. It is noted that global environmental degradation is also intensifying. However, the pace of measures aimed at environmental protection clearly lags behind this process. In one of their papers, American scholars write: "The question is whether the geographical environment is part of the economy or, conversely, whether the economy is part of the geographical environment?" (Kirvel, 2009; Gorbunov, 2013).

Contemporary research has yet to fully elucidate the complete structure and dynamics of the geographical environment. Previous studies have failed to fully describe the interaction between natural and social factors and have reached differing conclusions when assessing human impact on the geographical environment. It can be said that, at present, there is no comprehensive study of the impact of society's economic activities on the geographical environment and their effects on natural systems, nor of the long-term ecological and geographical consequences of anthropogenic changes.

As the geographical sciences become increasingly integrated and converge around the unified subject of the geographical environment, it is becoming increasingly difficult to reconcile physical geography with the natural sciences, and economic geography with the social sciences and, more broadly, with the traditional classification of sciences, which no longer meets contemporary requirements. Solving complex geographical problems requires drawing on knowledge from other sciences to achieve a comprehensive understanding of territorial systems, but the use of such data and knowledge leads to a loss of the geographical uniqueness of the research (Cherkashin, 2020). It is therefore crucial to foster a shared understanding of the concept of the “geographical environment” among scholars in other fields. The aim of this study is to address the shortcomings of current research through a comprehensive analysis of the structure and dynamics of the geographical environment. The study aims to clearly describe the interaction between social and natural factors, assess the long-term ecological and geographical consequences of anthropogenic changes, and examine changes in the geographical environment using a combination of interdisciplinary approaches. The results obtained during the study provide a deeper understanding of the connections between the natural and social components of the geographical environment.

2 Materials and methods

This article draws on several scholarly sources and methods to define the concept of the geographical environment. The literature review examined the works of leading scholars who have studied the term “geographical environment.” Their work, in turn, was based on many years of research that enabled them to view the geographical environment as a dynamic system comprising numerous components of the natural and social environments. The research material for this article is based on the scientific works of the classics of geographical science — Reclus (1986), Mechnikov (1995), Baransky (1956), Pletnikov (1971), Kalesnik (1970), Saushkin (1973), and other scholars who studied the formation of the concept of the geographical environment. The study of the modern geographical environment is closely linked to contemporary social, economic, and environmental trends, as the expansion of human activities, urbanization, climate change, and technological development have a significant impact on the structure of the geographical environment and its relationship with ecosystems.

Currently, Fedyunina (2012), Shalnev & Degtyareva (2011), Abdullaev & Islomov (2016), Borankulova & Murzinova (2018), Kirvel (2009) and Andreev (2009) are studying issues related to the geographical environment. Their works extensively examine the interaction between humans and nature, the influence of natural and social factors, as well as methods for managing and effectively utilizing the geographical environment. For example, in her work “The Geographical Environment and Social Development”, Fedyunina (2012) examines several interesting theories that address issues related to the environment’s influence on humans. These theories include geographical nihilism, possibilism, geographical probabilism, environmentalism, environmental conservatism, historical materialism, and geographical determinism. These theories vividly demonstrate the influence of the geographical environment on human behavior, material life, and culture, which proves the multifaceted nature of the concept of the geographical environment.

During the course of the study, methods of description, comparison, systematic analysis, selection, and differentiation of necessary data were employed, as well as the synthesis and analysis of various scientific approaches to the research topic. This allowed for a comprehensive examination of the research object and the identification of key trends and interrelationships between the geographical environment and society.

3 Results and discussion

The original meaning of the concept of “geographical environment” is viewed as a natural component (Fedyunina, 2012). For example, the works of certain thinkers of the Ancient East, particularly ancient philosophers and historians (Aristotle, Hippocrates, and others), contain interesting observations on the role of the geographical environment. Since historiography played an important role in ancient societies,

and the first elements of political science, political economy, and social philosophy were beginning to take shape, the attention of ancient authors to the problem of the conditioning of social phenomena by the geographical environment was a natural phenomenon.

In the Middle Ages, Arab and Chinese scholars paid particular attention to the issue of the geographical environment. Among them, Ibn Khaldun (1332–1406) holds a special place. He explained the differences in the way of life, psychological makeup, behavior, and customs of various tribes and peoples by the natural, particularly climatic, conditions in which they lived.

The systematic development of the concept of the “geographical environment” began in the 18th century. Jean-Jacques Rousseau (1712–1778) developed the theory of “natural man” (the savage), who lives in harmony with nature, believing that civilization would have a negative impact on human society. Enlightenment scholars who studied the historical stages of economic development, the evolution of material culture, crafts, progress, and other issues also attached great importance to the role of climate, soil, natural transportation routes, and other factors. The 18th century also saw the emergence of stage-based theories of human economic development: these examined the stages of transition from hunting and gathering to animal husbandry, from there to agriculture, and then to trade and industry. The most famous foundational work examining the interrelationship between geographical and socio-political factors is Charles Montesquieu’s (1689–1755) “The Spirit of the Laws”, which laid the groundwork for the theory of geographical determinism. According to the author, certain climatic and geographical conditions influence the structure of the state, shaping the country’s legislation and the behavior of its population.

This concept was definitively established in science at the end of the 19th century through the works of Reclus (1986) and Mechnikov (1995). Émile Reclus viewed the concept of the “geographical environment” not only as “pure” nature, but also as something closely linked to social elements. His fundamental principle is the assertion that life is in complete harmony with the environment. In this regard, the scholar sought the origins of civilization in the context of human adaptation to the natural environment. His historical-cultural concept is based on the study of the static and dynamic properties of the geographical environment. Here, the static environment represents the influence of the geographical environment in space, while the dynamic environment represents the study of its influence over time (Odintsev, 2006; Grinin, 2011).

In the modern period, Kotlyakov noted that the geographical shell has not been preserved in its original natural state. Currently, the term introduced by Shalnev and Degtyareva (2011) is considered more accurate and comprehensive. According to Shalnev’s definition: “The geographical environment is a system of aggregate and unique properties of individual spherical and territorial formations in geospace, constituting a part of the universe of the material world, the Solar System, and the planet Earth. Its characteristics manifest as an invariant system that stabilizes the human habitat through constant object-oriented and subject-object relationships within specific geospatial structures” (Fedyunina, 2012).

Thus, the development of the concept of the “geographical environment” has undergone a long historical evolution, from the first observations of ancient philosophers regarding the interconnection between nature and society to modern comprehensive scientific concepts. Each historical period expanded the scope of this understanding and contributed to a deeper explanation of the interaction between humans and the natural environment. The main stages of this development are presented in Table 1.

Table 1. Stages in the Development of the Concept of Geographical Environment

Period	Description	Representatives
Ancient Period	Ancient authors noted that the environment, particularly the climate, influences the physical characteristics of peoples, their customs and behavior, the level of development and political structures of society, types of economic activity, and population size.	Aristotle (384–322 BCE), Polybius (200–120 BCE), Posidonius (135–51 BCE), Strabo (64/63 BCE–23/24 CE), Hippocrates (460–370 BCE), and Vitruvius (1st century BCE).

Table 1. (Continued)

Period	Description	Representatives
Middle Ages	In the Middle Ages, very little attention was paid to the role of the geographical environment due to the predominance of theological interpretations of history.	Isidore of Seville (560–636), Ibn Battuta (1304–1377), Ibn Khaldun (1332–1406).
Mid-17th to 19th Centuries	Seventeenth-century thinkers sought general social laws analogous to those of physics and geometry, without developing comprehensive theories on the influence of the geographical environment. In the 19th century, philosophers and historians with a philosophical orientation abandoned the search for immutable foundations of human nature and turned to studying the historical roots of the phenomena of their time, as well as the causes that contributed to the organic and systematic development of society.	Carl Ritter (1779–1859), Lev Mechnikov (1838–1888), Friedrich Ratzel (1844–1904)
Early 20th–21st Centuries	In modern geography, discussions within the framework of the theory of the geographical environment continue to this day, though they are not as heated as they once were. According to Professor V. A. Shalnev, the theories of globalistics and the geoversum can be considered the foundation for the development of the theory of the geographical environment.	Nikolai Baransky (1881–1963), Innokenty Gerasimov (1905–1985), Vladimir Pavlovich Maksakovsky (1924–2011).

The historical development of the concept of the geographical environment has laid the foundation for its current understanding. Its historical evolution from antiquity to the present day has revealed the multifaceted nature of the geographical environment and allowed it to be examined from various perspectives. In the 21st century, this concept has taken on new meaning and has become one of the fundamental categories of modern geographical science.

As historical development shows, the geographical environment should be viewed not only as a collection of natural or social components, but also as a complex system that takes into account their interrelationships and dynamics. In this sense, contemporary researchers seek to interpret the geographical environment as a dynamic system that evolves in space and time.

Borankulova & Murzinova (2018) views the geographical environment as an open dynamic system that evolves in space and time. In her view, the geographical environment emerged as a result of evolution, and its main components were formed not only from space but also from interconnected and interdependent natural complexes or elements. By studying the geographical environment from a functional perspective, she examines its most important functions: the formation of climate, the distribution of light, heat, moisture, and pressure, as well as the formation of climatic zones and microclimates. In her view, precipitation affects soil moisture, river flow, and land use, while meteorological phenomena play a regulatory and destructive role. Water is the primary dynamic component that links all elements of the geographical environment; its circulation is essential for the functioning of natural systems and the sustenance of life. Water is vital for living organisms and human economic activity, while the seas and oceans are rich in resources and energy potential and provide access to transportation routes. Borankulova studies the geographical environment from the perspective of geographical patterns and functions, believing that the geographical environment has a significant influence on the development of human society and connects it with culture and society. In this regard, Borankulova’s work resonates with the works of Fedyunina and Wallis (Borankulova & Murzinova, 2018).

In her work “The Geographical Environment and the Development of Society,” Fedyunina (2012) demonstrates that people are always surrounded by the geographical environment, and therefore an unconditional interaction exists between them. This interaction is divided into two aspects: the influence of nature on people and the influence of people on nature. The work examines a variety of interesting theories regarding the influence of the environment on people. In particular, she analyzes geographical nihilism, which, in turn, denies the influence of the geographical environment on society. The author

disagrees with this theory, since human activity is impossible without nature. The author also examines the theory of probability, according to which the natural environment provides only opportunities, the realization of which depends on people and their level of culture. The focus is also on the ecological approach, which views humans as part of the biosphere and allows for the purposeful transformation of nature in the interests of society, as well as on environmental protection, which aims for the rational use of natural resources and their equitable distribution. The overview concludes with the theory of historical materialism, which emphasizes that the geographical environment plays a decisive role in social development but is not a determining factor, since the mode of production of material goods plays the decisive role (Fedyunina, 2013).

By comparison, foreign authors such as Wallis (1926) take a philosophical approach to the geographical environment. In his work "The Geographical Environment and Culture," he notes that humans are a product of the Earth's surface and can sustain life only by maintaining a connection with nature. In his view, the geographical environment is the cradle of human genius, a cradle that rocks impulses and motives, allowing people to control their own destiny (Wallis, 1926). A scientific approach in a direction opposite to that of Wallis (1926) is presented in the work by Shalnev and Degtyareva (2011), "The Geographical Environment: Controversial Issues and Ways to Resolve Them." Their work notes that the geographical environment is a categorical concept pertaining to the theoretical foundation of general geography and is the least understood among the geographical sciences. In the study of the methodology of the geographical environment, humans are considered alongside biological entities. In this sense, approaches based on geospace and activity should be viewed as the methodological foundation of the concept of the geographical environment, while theoretically, a distinction should be made between categorical concepts such as the factors and conditions of geospace, relationships within geospace, and continuity in the hierarchical sequence of environment formation (Shalnev & Degtyareva, 2011).

In modern geographical science, the geographical environment is viewed not only as a set of natural components but also as a complex multilevel system formed through the interaction of natural and social factors. The intensification of interdisciplinary research has expanded the scope of this concept and contributed to the emergence of various scientific approaches to its interpretation.

Contemporary researchers note that the geographical environment manifests itself in several interrelated scientific dimensions. First, it is viewed as a structural element of the Earth's geographical envelope. Second, the geographical environment is recognized as an independent scientific concept reflecting the characteristics of the interaction between nature and society. Third, it can be viewed as the result of the long-term historical development of natural and anthropogenic processes. This multifaceted concept is explained by the complexity of the Earth's geographical envelope, as it forms a unified and constantly changing system of interconnected natural spheres (Table 2).

Table 2. Theoretical Framework of the Concept of the Geographical Environment

Geographical Environment		
As a concept	Yu.K. Pletnikov	"The geographical environment is a concept encompassing that part of nature which, at a certain stage of historical development, becomes involved in the sphere of social life, creating the material conditions necessary for the existence and development of human society" (Pletnikov, 1971)
	S.V. Kalesnik	"The geographical environment is that part of nature on Earth that is directly involved in the sphere of human society's life, necessary for its existence, and as a concept characterizes the system of interrelationships between society and nature in a specific historical period" (Kalesnik, 1970)
	I.V. Saushkin	"The geographical environment is a scientific concept that surrounds human society, constantly interacts with it, and thus establishes an integral system of Earth's nature (the geographical envelope or a part thereof) distinct from the rest of the world" (Saushkin, 1973)

Table 2. (Continued)

Geographical Environment		
As an element	E. Reclus	“The geographical environment is the sum of all external conditions that give rise to life. It is an element that determines human diet, mode of habitation, and even the direction of human thought, serving as the foundation of the historical process” (Reclus, 1986)
	L.I. Mechnikov	“The geographical environment, primarily the hydrological factor, acts as a necessary element that prompts people to cooperate. It is an external situation without which social progress is impossible” (Mechnikov, 1995)
	N.N. Baransky	“The geographical environment is viewed in geography as an element of the productive forces, a material base whose qualitative uniqueness influences economic specialization and the social division of labor” (Baransky, 1956)
	V.A. Anuchin	“The geographical environment is not pure nature; it is the result of long-term interaction between society and nature—a nature that has been significantly altered by human labor and bears the imprint of human activity” (Anuchin, 1960)
	E.B. Alaev	“The geographical environment is the part of the geographical envelope that interacts directly with society and represents the materialized result of this interaction, which is reflected in cultural landscapes and the technosphere.” (Alaev, 1983)
	A.A. Grigoriev	“The geographical environment is the end result of a complex historical process of development of the natural crust, during which natural connections are supplemented and altered by connections of anthropogenic origin” (Grigoriev, 1966)

Authors have differing perspectives on the concept of the geographical environment, a phenomenon linked to the historical development of geography and the emergence of new methodological and philosophical approaches. However, their definitions share several common principles. First, all researchers view the geographical environment as a system closely linked to human activity and essential to the functioning of society. Second, it is perceived as a dynamic structure evolving in time and space, in which natural and social components constantly interact. Third, the geographical environment is understood as a holistic system comprising both material natural elements and the results of their transformation under human influence.

Differences in the authors’ approaches indicate an emphasis on different aspects of the same phenomenon. Thus, scholars who define the geographical environment as a concept (Kalesnik, 1970; Pletnikov, 1971; Saushkin, 1973) emphasize its theoretical, systemic, and historical-social criteria. They emphasize that the geographical environment is not merely a set of natural conditions, but a system of relationships between people, society, and nature that has developed over a specific historical period and reflects concrete socio-natural relationships.

Authors who view the geographical environment as a system (Baransky, 1956; Reclus, 1986; Mechnikov, 1995) focus on the structural components of the environment and their functions. The elements of the geographical environment ensure human survival and determine human lifestyles, economic activities, and socio-economic interactions. This approach emphasizes specific factors, such as hydrology, climate, soil, and resources, which constitute the material foundation of society and serve as instruments for its development.

Researchers who focus on the outcome of the geographical environment (Anuchin, 1960; Grigoriev, 1966; Alaev, 1983), study the result of the interaction between humans and nature. In this sense, the geographical environment is not merely nature, but the result of long-term socio-natural interaction, materialized in cultural landscapes, the technosphere, and anthropogenic changes in natural systems. Here, the historical variability of the environment and its ability to reflect traces of human activity while maintaining a connection with its natural foundation are emphasized.

The authors’ approaches do not contradict one another but rather complement each other, revealing various levels of analysis of the geographical environment: from theoretical and systemic understanding to the analysis of historically established and materially recorded results of the interaction between society and nature through the study of specific components and their functions. Based on this integration, a

modern concept of the geographical environment is formed, which views it as a complex phenomenon consisting of a concept, an element, and a result.

The modern “concept-element-result” model (Figure 1) allows for a comprehensive assessment of the geographical environment, linking theoretical categories to specific components and outcomes of the interaction between humans and nature.

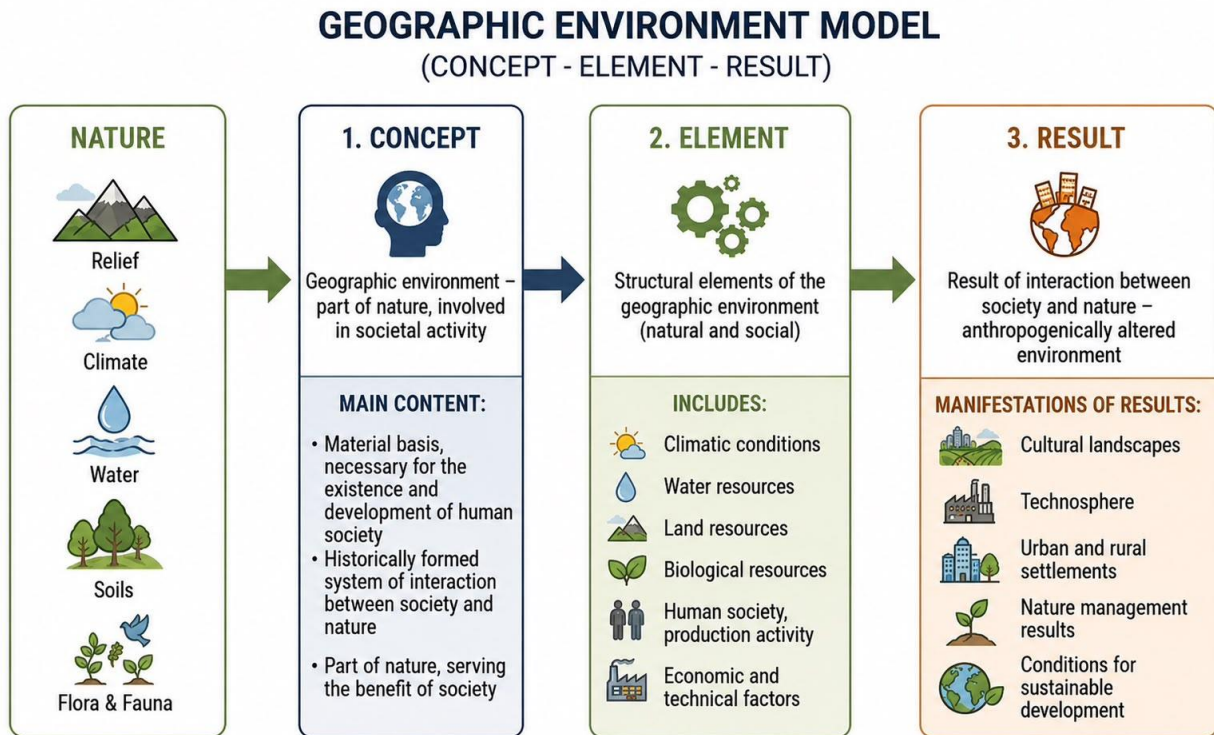


Figure 1. Description of the “Concept-Element-Result” model

This model provides a systematic view of the geographical environment and is methodologically useful for analyzing its structure, functions, and impact on society. However, it is important to note that understanding of the geographical environment was not limited solely to the views of the Russian classics. Foreign geographical science has also developed its own approaches to interpreting the geographical environment, reflecting different emphases and research methods. The following table presents the theoretical framework of the concept of the geographical environment as developed by foreign scholars (Table 3).

Table 3. Theoretical framework of the concept of the geographical environment in foreign scholarship

Geographical Environment		
As a foundation	Karl Sauer	“The geographical environment is the ‘natural foundation (areas, climate, resources) which, under the influence of a human group’s culture, is transformed into a dynamic system—the cultural landscape’” (Sauer, 1925)
	Richard Hartshorne	“The geographical environment is an integrated spatial interweaving (spatial complex) of natural and cultural foundations, which acquire meaning only through their unique mutual interplay within a specific territory (area).” (Hartshorne, 1939)
	Dervent Whittlesey	“The geographical environment is a stable natural foundation, constituting a spatial base and an unchanging material substrate upon which successive human cultures carry out their economic activities, transforming this basis in accordance with their technologies.” (Whittlesey, 1929)

Table 3. (Continued)

Geographical Environment		
As a totality	Harlan Barrows	“The geographical environment is the totality of the physical-geographical conditions of a territory, considered exclusively as the habitat and area of adaptation for the human organism and social groups” (Barrows, 1923)
	Torsten Hagerstrand	“The geographical environment is a spatial-temporal continuum filled with physical objects (biological, technological, and natural) that impose strict physical and temporal constraints on the trajectories of human life” (Hägerstrand, 1970)
	Ellen Churchill Semple	“The geographical environment is a set of differentiated physical factors, including climatic conditions, topographical features, hydrographic barriers, and natural resources of a territory, which, in their systemic unity, act as the main driving force determining the physical, economic, and social development of humanity” (Semple, 1911)
As a natural state	Richard Chorley	“The geographical environment is an objective, open geosystem functioning as a thermodynamic mechanism in which its basic natural state is determined by a constant balance, self-regulation, and an intensive exchange of matter and energy between geophysical components” (Chorley, 1962)
	David Stoddart	“The geographical environment is an objective, open geosystem functioning as a thermodynamic mechanism in which its basic natural state is determined by a constant balance, self-regulation, and an intensive exchange of matter and energy between geophysical components” (Stoddart, 1965)
	Karl Butzer	“The geographical environment is a macrospatial physical matrix (context), whose dynamic natural state is shaped by global paleoclimatic, hydrological, and geomorphological processes, serving as a rigid external foundation for the evolution of life” (Butzer, 1964)

An analysis of the concept of the geographical environment in foreign geographical thought reveals a fundamental pattern: this concept has never had a static or unified meaning. Its definition has depended directly on the scientific paradigm prevailing during a given period. The differentiation of foreign scholars’ understanding of the geographical environment into three key categories—as a foundation, as a complex, and as a natural state—is driven by profound epistemological and ontological reasons.

The understanding of the geographical environment as a “foundation” took shape during the crisis of radical geographical determinism in the first third of the 20th century and was intended to distinguish the spheres of influence of nature and society. Scholars such as Sauer (1925), Hartshorne (1939), and Whittlesey (1929) sought in their works to demonstrate that physical-geographical conditions do not alter the course of history, but merely provide a framework for these changes. In their works, the geographical environment is not viewed as a dynamic system, but rather plays the role of a stable foundation. For example, Sauer’s (1925) concept notes that nature is static, with dynamics introduced by external events—human culture. This concept largely contributed to the development of regional geography and human geography, as it was this concept that indicated that space acquires scientific meaning only when it is transformed by humans. While geographical determinism prevailed in the field of geography prior to Sauer (1925), in his seminal work “The Morphology of the Landscape”, he asserted that human geography should not study how nature “shapes” humans, but rather how humans transform nature through their culture. This approach significantly changed not only human geography but also the very concept of the geographical environment.

However, viewing the geographical environment exclusively as a passive material basis and a “canvas” for society’s cultural activities (within the traditions of Sauer’s school) eventually revealed its epistemological limitations. The further evolution of foreign geographical thought required a shift from a substratum-based understanding of the environment to its operational analysis. As a result, within the framework of anthropocentric and adaptationist approaches, researchers’ focus shifted from the passive “basis” to its internal content. The geographical environment began to be interpreted as a dynamic set of

differentiated physical factors, barriers, and conditions, each of which exerts a direct, measurable influence on the trajectory of human life. The geographical environment came to be viewed as a “set” of individual elements, each of which affects human life. For example, Semple (1911), in her works, took a specific element of the geographical environment and studied its influence on human nature, while Barrows’s (1923) works were primarily focused on the study of farmland and ecology. A qualitative leap occurred in the methodology of Hägerstrand (1970), who, using three-dimensional spatiotemporal modeling, formalized the components of the environment, transforming the physical, technological, and institutional barriers of a territory into a measurable system of mathematical constraints on human activity.

The geographical environment began to be viewed as a natural state only in the mid-20th century, when scholars consciously distanced themselves from sociological interpretations of the geographical environment, returning geography to the realm of the strict natural sciences. During this period, the geographical environment was removed from the category of “space for humans” and transformed into a dynamic system, where it began to be perceived through the prism of various physical qualities, such as energy balance, material cycles, and geomorphological cycles. The shift from simply structuring elements to understanding their systemic significance led to the increasing complexity of theoretical models of the geographical environment in the West. This process developed along three main lines: from a passive perception of the environment as a spatial basis to its interpretation as a set of barriers and, finally, to its interpretation as an autonomous natural state of an open system. This paradigmatic evolution, reflecting a shift in research approaches (from substratum-based to adaptive and system-physicalist), is clearly conceptualized in the second theoretical model (Figure 2).

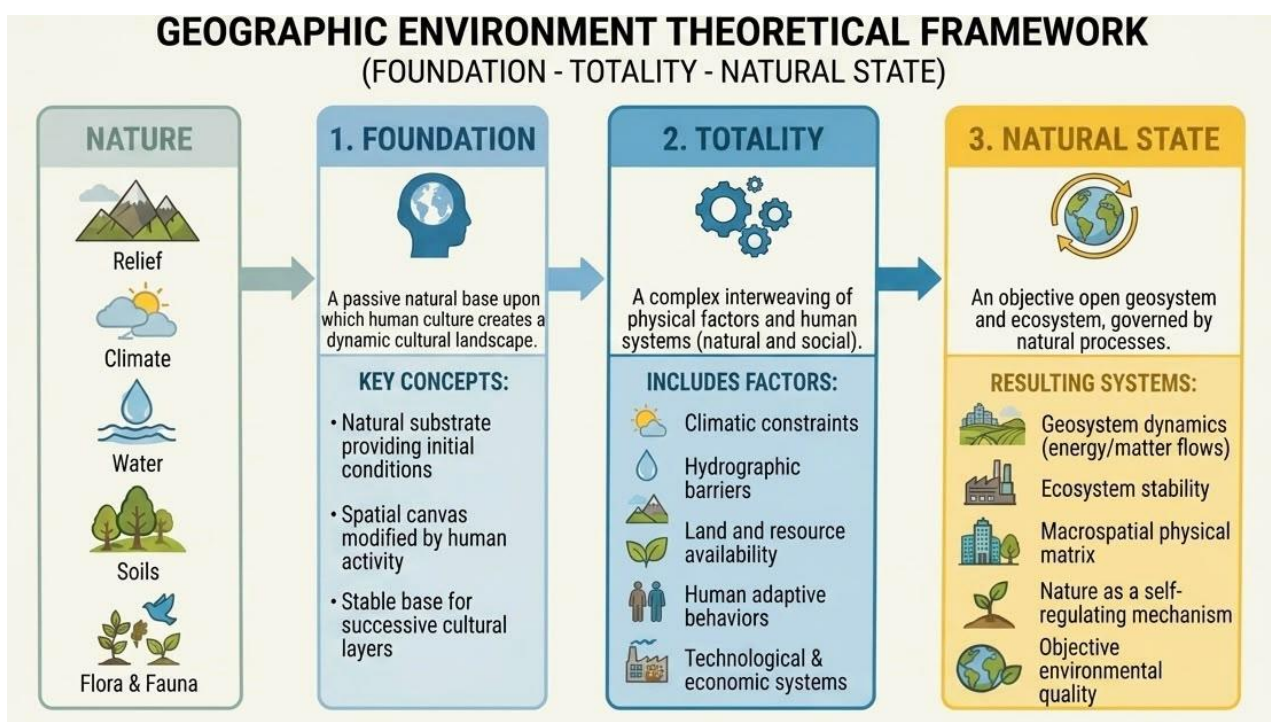


Figure 2. Paradigmatic evolution of the "Geographical Environment" concept in Western geographical thought

As the theoretical framework demonstrates, the concept of the geographical environment has undergone a profound process of de-sociologization and mathematization. While in the “Foundation” block the environment functions as a starting substrate whose value is manifested solely through human cultural activity, a significant shift occurs in the “Total” block. The environment becomes more complex, transforming into a network of physical, hydrographic, and technological constraints that actively govern the logistics and behavior of human groups. Finally, the “Natural State” is generally considered the most systematic block, where the geographical environment is enclosed within an objective and self-sufficient geosystem. Here, its qualities are determined not by humans and their life activities, but by geographical

mechanisms, energy flows, and material flows.

A retrospective analysis of the evolution of the concept of the “geographical environment” in foreign scholarship allows us to conclude that Western geographical thought exhibits a high degree of methodological flexibility and pluralism. Having traveled a path from a substrate-passive “foundation” (a stage for cultural processes) through an anthropocentric “aggregate of factors and barriers” to the autonomous “natural state” of a self-regulating open system, the concept of the geographical environment has transformed from a descriptive spatial category into a complex, interdisciplinary object of systems analysis. Throughout the 20th century, the development of concepts regarding the geographical environment in the USSR and the West proceeded under conditions of profound methodological determinism. While foreign researchers demonstrated great flexibility, easily shifting from interpreting the environment as a passive cultural canvas to its mathematical formalization, Soviet classics (Grigoriev, 1966; Anuchin, 1960) were forced to develop their scientific apparatus within the rigid framework of dialectical materialism. This predetermined the emergence of a fundamental epistemological conflict: while Western geography sought to unite physical space and culture into an indivisible continuum, Soviet science prioritized a strict distinction between the blind laws of nature and the socio-productive laws of societal development.

An analysis of the proposed definitions shows that many authors focus on the individual properties of the geographical environment but do not examine its fundamental characteristics—genesis, internal structure, and complex spatiotemporal relationships (Stozhok, 2011). Nevertheless, a common conceptual thread emerges: the geographic environment is interpreted as a holistic space in which natural and anthropogenic systems function in inseparable unity. In this regard, contemporary researchers are increasingly turning to an interdisciplinary approach.

The special issue “Virtual Geographic and Ecological Environment Analysis” is dedicated to the use of geoinformation and digital technologies for analyzing and modeling the state of the environment and assessing the impact of human activities on it (Yu, 2021).

Similarity: In Yu’s work, the concept of the geographic environment is considered as a system that shapes the ecological and social landscape.

Difference: The article analyzes the issue of using geospatial technologies to assess the interaction between natural and human components.

Lü’s study examines the concept of a “geographical scenario” as a theoretical basis for the development of virtual geographical environments (Lü et al., 2018).

Similarity: In his work, Lü defines the environment as a dynamic part of the geographical envelope.

Difference: The article states that the interaction between nature and society leads to specific territorial scenarios suitable for virtual modeling.

In their article, Yang et al. (2024), Xu et al. (2024) and Wang et al. (2024) examine the influence of the geographical environment on public trust and define the role of tourism in this process.

Similarity: views the geographical environment as a concept directly linked to economic activity and ecosystem quality.

Difference: the article extensively analyzes the need to account for environmental dynamics in spatial planning and management.

The transformation of classical concepts in the digital age deserves special attention. In his work, Khoroshilov and Katsko (2015) examines the essence of geoinformation space and the virtual geographic environment and their scientific significance.

Similarity: Khoroshilov demonstrates the connection between the concept of the geographic environment and geographic space.

Difference: The article examines the active integration of elements of the geographic environment into GIS technologies.

The study of the geographic environment from a sociological perspective is presented in the works of Shteinberg (2025). The work analyzes the influence of the geographical factor on human development and

the formation of society.

Similarity: Shteinberg considers the concept of the geographical environment as an external determinant influencing processes of integration and conflict.

Difference: the geographical environment is studied from a sociological perspective.

An interdisciplinary expansion of the concept of the geographical environment occurred in the works of Golubchikov (2023). He is dedicated to the study of the theory of landscape therapy and the therapeutic impact of the natural environment on living systems.

Similarity: In his work, Golubchikov examines the concept of the geographical environment and studies it within an interdisciplinary framework.

Difference: He links the concept of the geographical environment to medicine through the concept of landscape therapy.

4 Conclusion

Based on an analysis of the approaches taken by various authors, it can be concluded that the geographical environment is a multi-layered and multifaceted phenomenon. While one group of scholars emphasizes the historical, social, and systemic nature of this concept, another examines the specific natural and social components it encompasses and the functions they perform. A third group of researchers places greater emphasis on the end results of the interaction between humans and nature, i.e., the formation of cultural landscapes and anthropogenic changes. These approaches do not contradict one another; on the contrary, they complement our understanding by revealing the theoretical, structural, and outcome-oriented aspects of the geographical environment. Such integration allows us to consider the object as a whole within the framework of the “concept–element–result” triad, which is highly effective for analyzing its structure and impact on society.

Guided by this systemic approach and taking into account natural and anthropogenic factors, we can provide a modern definition of the geographical environment as follows “The geographical environment is a historically and spatially evolving system of natural and anthropogenic components that shape the living conditions of people, society, and culture, where each element contributes to the functioning of the environment while yielding materialized results in the form of altered landscapes and sustainable socio-natural systems.” Thus, the geographical environment is defined as a complex dynamic system in which natural and social processes are closely interrelated.

The conceptual solutions proposed in this paper pave the way for bridging the long-standing methodological divide between the fields of physical and socio-economic geography. By combining the architectural-structural level (“concept – element – result”) and the paradigmatic-evolutionary approach (“foundation – aggregate – natural state”), the article develops a universal analytical tool. This approach demonstrates that these categories do not contradict one another but, on the contrary, indicate stages of the researcher’s gradual immersion into the object: first, the initial state of the territory is recorded; then, the operational factors influencing it are measured; and finally, the self-regulatory functions of the Unified Geosystem are modeled.

The methodological value of this scientific synthesis lies in its ability to fully respond to the challenges of the Anthropocene era—that is, the present day—when human economic activity has become a powerful global geological force. Reinterpreting the classical heritage of domestic and foreign geographical schools from the perspective of the modern systems paradigm helps purge the scientific apparatus of outdated one-sided assertions and dualistic dogmas. The geographical environment is no longer viewed as merely a passive backdrop or shell upon which humans exert an external influence. It takes on the character of a dynamic system in which natural cycles and sociocultural trajectories converge to form a single co-evolutionary continuum.

From a practical standpoint, the developed models and the proposed integrated definition provide a reliable applied foundation for strategic spatial planning, geo-ecological auditing, and long-term regional forecasting. A clear distinction between the initial elements of the environment and the actual material

results of its development allows for an accurate assessment of the ecological carrying capacity of landscapes, a correct calculation of anthropogenic load, and the minimization of risks associated with natural resource use. In addition, the identified systemic connections will give new impetus to the modern process of digitizing geographic knowledge, including the design of virtual geographic environments (VGE) and the creation of digital twins of real territories, as well as the development of intelligent systems that support decision-making.

Thus, this study not only synthesizes years of theoretical debate on the nature of the geographical environment but also identifies new directions for interdisciplinary research. Restoring the status of the geographical environment as a fundamental and dynamic category will significantly strengthen the position of geography as an integral meta-discipline capable of comprehensively and accurately addressing contemporary global environmental, economic, and social challenges.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Aknura Alimkhanova	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		
Dina Borankulova	✓	✓		✓		✓	✓		✓	✓	✓			

- | | | |
|-----------------------|--------------------------------|----------------------------|
| C : Conceptualization | I : Investigation | Vi : Visualization |
| M : Methodology | R : Resources | Su : Supervision |
| So : Software | D : Data Curation | P : Project administration |
| Va : Validation | O : Writing - Original Draft | Fu : Funding acquisition |
| Fo : Formal analysis | E : Writing - Review & Editing | |

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Article

Formation and accuracy assessment of a GNSS/GIS basis for geodynamic monitoring of Almaty city

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GNSS; GIS; geodynamic monitoring; geodetic network; ground deformation; Almaty.

Abstract: Almaty is located in the seismically active zone of the Northern Tien Shan, where the development of engineering, transport, and underground infrastructure requires a reliable geodetic basis for regular control of the spatial position of the ground surface and engineering facilities. The aim of this study is to establish an initial GNSS/GIS basis for subsequent geodynamic monitoring of Almaty and to assess the accuracy of coordinate solutions obtained from one campaign of static GNSS observations. The study uses a GNSS network consisting of the reference station ALMA and the observation points CHIL, ESIK, FABR, and KGAI. The observations were processed in the South Geomatics Office software package using GPS, GLONASS, and BeiDou signals. The results of the three-dimensional network adjustment show that the root mean square errors of the observation points range from 0.004 to 0.010 m, confirming the suitability of the network for high-precision geodetic observations. The GIS component is presented as a spatial framework for mapping the GNSS network and for subsequent comparison of repeated measurements with a digital elevation model, fault zones, engineering-geological conditions, urban density, and infrastructure objects. Since the study is based on one observation epoch, it does not calculate actual displacement vectors or deformation rates. The scientific contribution of the study lies in clarifying the methodological role of a high-precision GNSS/GIS basis as the first stage of a long-term geodynamic monitoring system for the urbanized and seismically active territory of Almaty. Future research should include repeated GNSS observation campaigns, continuous monitoring stations, and the integration of InSAR and geological datasets to quantify deformation rates, improve seismic hazard assessment, support infrastructure resilience, and enhance evidence-based urban planning and disaster risk management in Almaty.

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1 Introduction

The current development of satellite geodesy and geoinformation technologies has significantly expanded the possibilities for studying deformation processes in seismically active and urbanized territories. For large cities located in mountainous and foothill regions, spatial control of the ground surface has both scientific and applied importance. High population density, the concentration of engineering structures, transport facilities, underground infrastructure, and high-rise buildings increase the requirements for the accuracy of geodetic observations and for the interpretation of coordinate data. In international practice, Global Navigation Satellite Systems (GNSS) are regarded as one of the key tools for recording modern ground movements, assessing the stability of geodetic points, and constructing

coordinate time series (Bock & Melgar, 2016; Hofmann-Wellenhof et al., 2008; Teunissen & Montenbruck, 2017).

A unified reference frame and a stable geodetic basis are particularly important in such studies. Modern realizations of the International Terrestrial Reference Frame, including ITRF2020, allow station position time series, linear velocities, and nonlinear motion components to be considered, which is essential for the analysis of crustal deformation and for the comparison of results obtained in different observation epochs (Altamimi et al., 2023). In geodynamic monitoring, this means that the accuracy of a single coordinate solution is only the first stage. The reliable identification of deformation requires repeated measurement campaigns, comparable processing methods, control of systematic errors, and statistical assessment of the significance of detected displacements.

Almaty is one of the most important urbanized centers of Kazakhstan and is located within the influence zone of active tectonic structures of the Northern Tien Shan. The seismotectonic setting of the city is associated with the proximity of the Zailiysky Alatau mountain range, pronounced fault tectonics, contrasting relief, and historically known strong earthquakes. Recent studies indicate that the northern front of the Zailiysky Alatau and adjacent areas show evidence of Late Quaternary and modern tectonic activity, while buried and surface fault structures may influence the seismic risk of the urban area (Grützner et al., 2017; Amey et al., 2021). Therefore, establishing a stable geodetic basis for regular control of deformation processes is an urgent task for Almaty.

The seismic hazard of Almaty has been considered in studies devoted to probabilistic seismic hazard assessment, seismic microzonation, and the analysis of engineering-geological conditions. These studies emphasize that hazard assessment should take into account not only the parameters of possible seismic events, but also local soil properties, relief, building characteristics, and the degree of engineering development of the territory (Silacheva et al., 2018; Silacheva et al., 2020). Consequently, geodynamic monitoring cannot be limited to measuring the coordinates of individual points. Its results should be embedded in a spatial analysis system in which GNSS data are compared with natural and anthropogenic factors.

Geographic Information System (GIS) technologies make it possible to move from a point-based representation of GNSS observations to a spatially organized model of the territory. In a GIS environment, the coordinates of monitoring points can be linked with a digital elevation model, geological and tectonic layers, engineering-geological data, urban building density, transport corridors, and underground structures. This approach provides opportunities for cartographic visualization, spatial comparison, and preliminary identification of areas that require more detailed control (Zaczek-Peplinska et al., 2025). For Almaty, this task is especially relevant because the city includes plain, foothill, and slope areas that differ in terms of ground-surface stability.

In recent years, combined approaches involving GNSS, GIS, and Earth observation methods have increasingly been used to study deformations in urbanized territories. For example, research on Almaty and its surroundings based on Sentinel-1 and SBAS-InSAR data has shown the possibility of identifying spatial patterns of ground movement and comparing them with faults, tectonic boundaries, and urban infrastructure (Bayramov et al., 2024). However, InSAR results require independent ground validation. In this respect, GNSS networks can serve as a reference basis for verifying remote sensing data and for forming long-term series of high-precision coordinates.

At the same time, it is necessary to clearly distinguish between the establishment of a geodetic basis and geodynamic monitoring itself. A single campaign of static GNSS observations makes it possible to determine point coordinates, assess adjustment accuracy, and form the initial observation epoch. However, such a campaign does not allow actual displacement vectors, horizontal and vertical deformation rates, or temporal trends to be calculated independently. For this purpose, at least two, and preferably several, repeated campaigns conducted according to a unified methodology are required. This methodological distinction is important because, without it, conclusions about geodynamic processes may be broader than the available data allow.

The initial manuscript was focused on the integration of GNSS and GIS technologies in the geodynamic monitoring system of Almaty. However, the joint use of GNSS and GIS cannot itself be treated as a new scientific idea because this approach is widely used in modern geodesy and geoinformation analysis. Therefore, the scientific contribution of the revised article has been clarified. It consists of establishing an initial GNSS/GIS basis for Almaty, assessing the accuracy of coordinate solutions at five points of the observation network, and developing the logic of further use of this basis for repeated measurements, displacement calculation, and spatial interpretation of deformation processes.

Thus, the research problem is that the conditions of Almaty require not only a high-precision GNSS network, but also a methodologically correct scheme for its inclusion in a GIS-oriented system of long-term geodynamic monitoring. This scheme should account for the limitations of a single observation epoch and define the subsequent stages required for calculating real displacements and deformation rates.

The aim of the study is to establish and assess the accuracy of a GNSS/GIS basis for subsequent geodynamic monitoring of Almaty city. To achieve this aim, the following tasks were addressed: an observation GNSS network consisting of the ALMA reference station and the CHIL, ESİK, FABR, and KGAI points was formed; static GNSS observations were processed; a three-dimensional adjustment of the network was performed; coordinate accuracy was assessed using RMS and RMSE indicators; the GIS component was described as a spatial basis for further comparison of GNSS data with natural and anthropogenic factors; and methodological limitations related to the absence of repeated measurement epochs were identified.

2 Materials and methods

The study was carried out in the territory of Almaty and the adjacent foothill areas of the Northern Tien Shan. This territory is characterized by a complex tectonic structure, pronounced relief heterogeneity, high seismicity, and intensive development of urban infrastructure. These conditions determine the need to establish a stable geodetic basis for regular monitoring of the spatial position of observation points.

When interpreting the results, it is necessary to consider that potential deformation processes in Almaty may be associated with both natural and technogenic factors. Natural factors include tectonic activity, relief conditions, seismic impacts, and engineering-geological features. Technogenic factors include dense urban development, high-rise construction, the development of transport networks, the operation of underground structures, and local changes in hydrogeological and ground conditions.

The study used a GNSS network consisting of one reference station, ALMA, and four observation points, CHIL, ESİK, FABR, and KGAI. The ALMA station was adopted as the fixed initial station with known coordinates. The remaining points were used to assess the spatial configuration of the network, the quality of the baselines, and the accuracy of the coordinate solutions.

The observation points were selected to cover different parts of the study area and to ensure the geometric stability of the network. The presence of baselines of different lengths increases the reliability of the adjustment and makes it possible to control the effect of random measurement errors. Since the original observation logs were not available to the corresponding author, the exact dates of the field measurements, receiver models, antenna models, and individual session parameters should be verified by the authors before final archive submission.

Static GNSS observations were performed using dual-frequency multi-constellation GNSS receivers capable of tracking GPS, GLONASS, and BeiDou signals. The observations were carried out in static mode, which corresponds to the tasks of high-precision coordinate determination and subsequent use of the points as a reference basis for geodynamic monitoring. The methodological foundations of such work are consistent with general principles of GNSS geodesy and post-processing of satellite observations (Hofmann-Wellenhof et al., 2008; Teunissen & Montenbruck, 2017; Orynbasarova et al., 2023).

The initial observation data were recorded in RINEX format and processed in the South Geomatics Office software package. The processing workflow included project creation, definition of the WGS 84/ITRF2020 coordinate system, import of observation files, control of data quality, baseline processing,

ambiguity resolution, network consistency checks, and three-dimensional adjustment. Similar GNSS network adjustment and quality-control principles are widely used in engineering-geodetic and geodynamic applications (Gargula, 2011; Karpic et al., 2022; Karpic et al., 2023).

Quality control of the initial observations included analysis of satellite geometry, sky plot distribution, signal-to-noise ratio, multipath effects, and the stability of phase measurements. Observations with low signal quality were excluded from further processing. Particular attention was paid to the correctness of integer ambiguity resolution, since the fixed ambiguity solution is one of the main indicators of the reliability of carrier-phase processing.

The quality of the baseline solutions was assessed using RMS and ratio parameters. Solutions with RMS below 30 mm and ratio not less than 3 were considered acceptable. After baseline processing, network consistency was checked, residual errors were analyzed, and a three-dimensional least-squares adjustment was performed. The resulting coordinates were then used as the initial coordinate basis for subsequent GIS visualization and interpretation.

The GIS component of the study is intended for spatial systematization and interpretation of GNSS results. In the current revision, it is considered as a preparatory spatial framework rather than as a complete hazard-zonation model. This distinction is important because the available data consist of one GNSS observation epoch and therefore do not yet allow the construction of full displacement fields.

The recommended structure of the subsequent GIS database includes the following layers: GNSS observation points, network baselines, a digital elevation model, tectonic and fault structures, engineering-geological conditions, transport and underground infrastructure, urban building density, and areas of potential geodynamic risk. In the future, such layers will make it possible to compare GNSS-derived displacements with factors controlling the stability of the urbanized territory.

At this stage, the GIS analysis performs two functions. The first function is cartographic representation of the network configuration and spatial relationships between points. The second function is preparation of the methodological basis for future spatial comparison. After repeated GNSS campaigns are conducted, the GIS environment will allow maps of displacement vectors, deformation rates, and priority zones for geodetic control to be created.

Because the current study presents one observation epoch, actual displacements and deformation rates were not calculated. For subsequent stages of monitoring, the following computational scheme is proposed. Horizontal and vertical displacements between two epochs are determined as coordinate differences: $\Delta E = E_2 - E_1$, $\Delta N = N_2 - N_1$, and $\Delta H = H_2 - H_1$. The horizontal displacement magnitude is calculated as $D = \sqrt{(\Delta E)^2 + (\Delta N)^2}$. Displacement rates are determined as the ratio of displacement to the time interval between observation epochs: $V_E = \Delta E / \Delta t$, $V_N = \Delta N / \Delta t$, and $V_H = \Delta H / \Delta t$.

The statistical significance of the displacement should be assessed by considering the combined uncertainty of two observation epochs: $\sigma_{\Delta} = \sqrt{(\sigma_1^2 + \sigma_2^2)}$. A displacement can be interpreted as statistically significant only when its value exceeds the selected confidence threshold. Such an approach makes it possible to avoid overinterpretation of random coordinate fluctuations as real geodynamic deformation.

3 Results

As a result of the revision, the general methodological scheme of the study was clarified. The GNSS block provides high-precision coordinate determination of the observation points and the formation of an initial coordinate epoch. The GIS block provides spatial organization of the obtained results, cartographic visualization, and preparation for subsequent comparison with natural and anthropogenic factors.

The integration of these two blocks is intended for future analysis of displacement fields, deformation rates, and zones requiring priority control. In the present study, the practical result is not a completed geodynamic zoning map, but a verified initial coordinate and spatial basis for long-term monitoring (Figure 1).

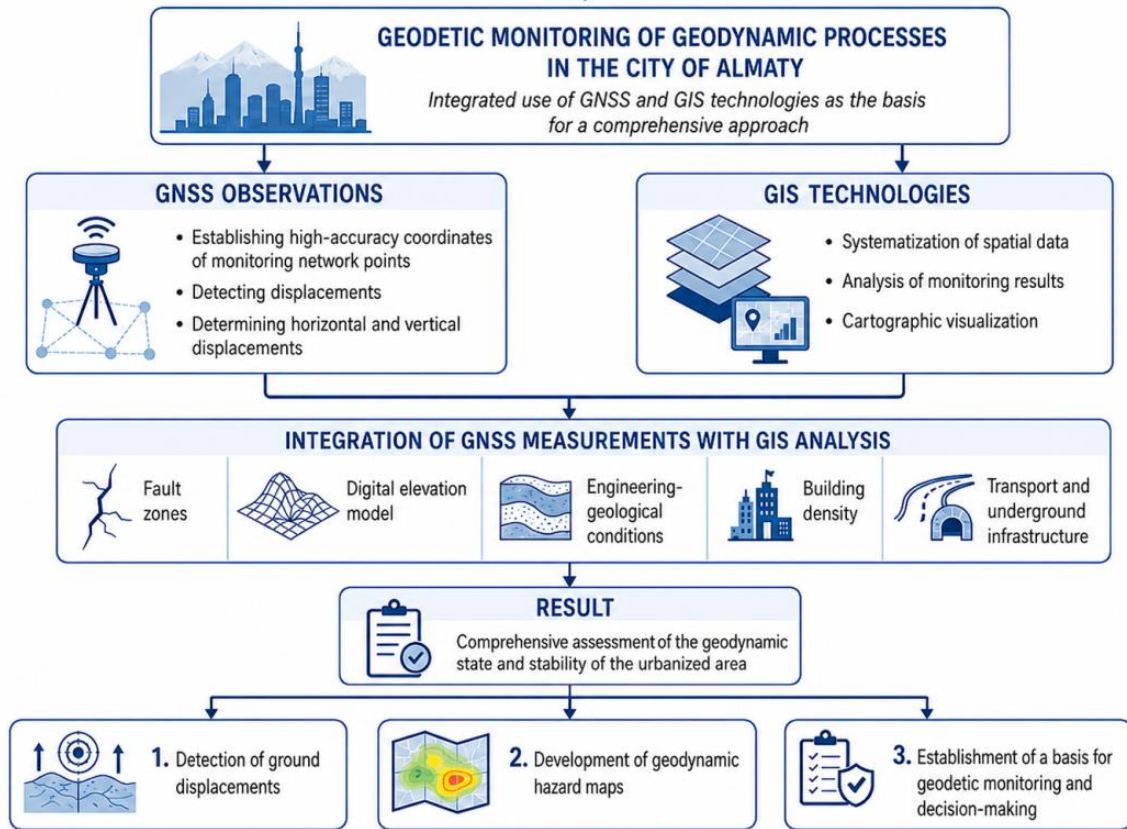


Figure 1. Methodological scheme for integrating GNSS and GIS technologies in the geodetic monitoring of geodynamic processes in Almaty. *Source: compiled by the authors*

The GNSS network consists of the ALMA reference station and the CHIL, ESIK, FABR, and KGAI observation points (Figure 2). The ALMA station was used as the fixed initial point during adjustment. This explains the zero RMS and RMSE values for ALMA. Therefore, the ALMA values should not be interpreted as an independent accuracy estimate, but rather as a consequence of its status as the fixed control point.

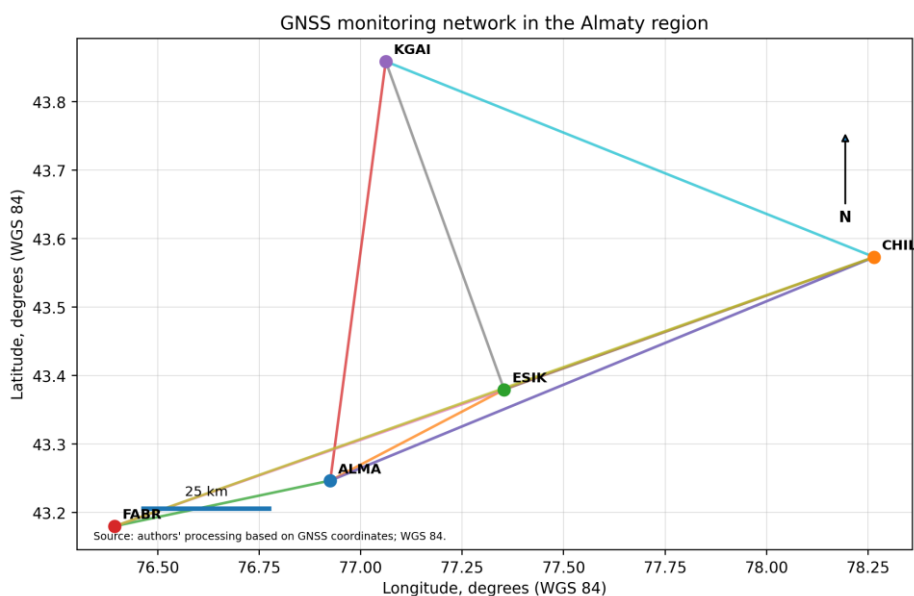


Figure 2. GNSS monitoring network, including the ALMA reference station and the CHIL, ESIK, FABR, and KGAI observation points. *Source: authors' processing based on GNSS coordinates in WGS 84.*

The network configuration provides the initial coordinate basis for subsequent repeated GNSS campaigns. The obtained coordinates can be used as the first observation epoch, relative to which future displacements, displacement vectors, and deformation rates can be calculated.

The results of the three-dimensional adjustment are presented in Table 1. The station coordinates are given in the spatial X, Y, and Z coordinate system. RMS and RMSE indicators obtained during the processing in South Geomatics Office are also provided for each station.

Table 1. Results of the 3D adjustment of the GNSS network in the spatial coordinate system

Station	X, m	Y, m	Z, m	RMS, m	RMSE_X, m	RMSE_Y, m
ALMA	1052765.268	4533187.935	4348007.129	0.000	0.000	0.000
CHIL	941381.750	4532011.170	4374236.020	0.006	0.002	0.004
ESIK	1016628.710	4531019.831	4358735.673	0.010	0.003	0.007
FABR	1095957.369	4528248.252	4342694.948	0.004	0.002	0.003
KGAI	1031402.321	4489757.831	4397096.542	0.005	0.002	0.003

Note. ALMA was used as the fixed reference station. The zero RMS and RMSE values for ALMA are the result of the adjustment constraint. Coordinates and accuracy indicators are based on the authors' processing in South Geomatics Office.

The lowest RMS value among the observation points was obtained for FABR and equals 0.004 m. The highest RMS value was obtained for ESIK and equals 0.010 m. The RMS values for CHIL and KGAI are 0.006 m and 0.005 m, respectively. These results indicate centimeter-level accuracy of the coordinate solutions and confirm the suitability of the network as an initial geodetic basis for repeated observations.

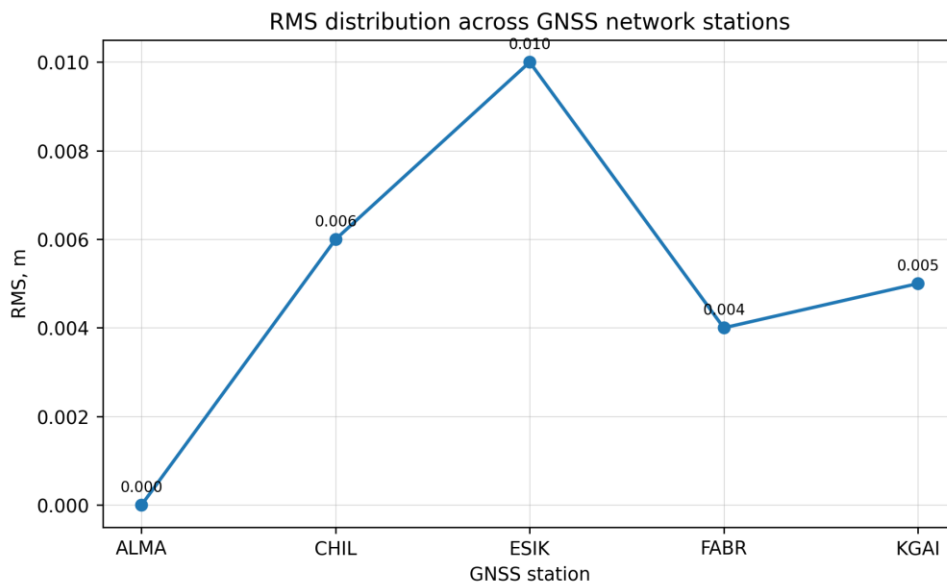


Figure 3. RMS distribution across the GNSS network stations. Source: authors' processing based on the results of the 3D network adjustment

The GIS component of the study was structured as a basis for spatial analysis of GNSS data. In the current version, it includes the placement of GNSS points on a coordinate-based map and the preparation of a spatial-data logic for subsequent comparison with natural and anthropogenic factors.

The most important factors for subsequent analysis are the proximity of GNSS points to tectonic and fault structures, the elevation and slope characteristics derived from a digital elevation model, engineering-geological conditions, urban density, the presence of transport and underground infrastructure, and zones of deformation previously identified using remote sensing or engineering surveys.

The prepared GIS structure makes it possible to move from a point-based representation of GNSS measurements to the spatial interpretation of monitoring results. However, in the present study, GIS analysis is not used for final geodynamic hazard zoning because such zoning requires repeated measurements, calculation of displacement vectors, and comparison with independent data, including InSAR, engineering-geological materials, and seismic monitoring results.

4 Discussion

The obtained results show that the established GNSS network provides sufficient accuracy for use as an initial coordinate basis. RMS values from 0.004 to 0.010 m correspond to the accuracy level required for high-precision geodetic work and for subsequent monitoring of changes in the position of points. This is an important practical result because future displacements cannot be reliably estimated without a stable initial network.

At the same time, the results of one observation campaign do not allow conclusions to be drawn about actual modern deformations of the ground surface. Full geodynamic monitoring requires repeated GNSS campaigns carried out according to a unified methodology, in the same reference frame, and under comparable observation conditions (Hamit et al., 2025). Only with two or more epochs is it possible to determine horizontal and vertical displacements, calculate deformation rates, and assess their statistical significance (Bock & Melgar, 2016; Altamimi et al., 2023).

Comparison with recent studies shows that, for the territory of Almaty, it is especially important to combine GNSS observations with remote sensing and GIS methods. SBAS-InSAR studies of Almaty demonstrate the possibility of identifying spatial patterns of deformation and their relationships with faults and urban infrastructure (Bayramov et al., 2024). However, InSAR results require ground validation. In this respect, the ALMA-CHIL-ESIK-FABR-KGAI GNSS network can be used as a reference basis for verifying and refining remote sensing results.

One limitation of the study is the small number of observation points. A five-station network makes it possible to establish an initial coordinate basis, but it is insufficient for a complete assessment of the geodynamic state of the entire Almaty agglomeration. To improve monitoring reliability, the network should be expanded by adding points near fault zones, on foothill slopes, in areas of dense urban development, and near critical infrastructure.

Another limitation is the preparatory character of the GIS component. In the present version, it performs the function of cartographic representation and data structuring. Future studies should include full GIS layers, including a digital elevation model, active faults, engineering-geological conditions, infrastructure objects, and remote sensing results. With such data, it will be possible to perform preliminary zoning of the territory according to the priority of geodynamic control.

Thus, the results of the study should be interpreted as the first stage in establishing a geodynamic monitoring system rather than as completed identification of geodynamic regularities. The scientifically correct conclusion is that a high-precision GNSS/GIS basis has been created. This basis can be used for subsequent observation cycles, calculation of actual deformation parameters, and mapping of the spatial distribution of displacements.

5 Conclusion

This study established an initial GNSS/GIS basis for subsequent geodynamic monitoring of Almaty city. The GNSS network includes the ALMA reference station and the CHIL, ESIK, FABR, and KGAI observation points. Processing of static GNSS observations and three-dimensional adjustment produced coordinate solutions with RMS values ranging from 0.004 to 0.010 m for the observation points. These results confirm the suitability of the network for high-precision geodetic observations and its use as an initial coordinate basis.

The scientific significance of the study lies in clarifying the methodological approach to forming a GNSS/GIS basis for an urbanized and seismically active territory. The practical significance is that the

obtained network can be used for subsequent repeated measurements, control of the stability of engineering-developed areas, and integration with GIS layers representing natural and anthropogenic factors.

The study also has important limitations. Based on one GNSS observation epoch, it is not possible to reliably calculate displacement vectors, deformation rates, or temporal trends. Therefore, the present study does not formulate a new geodynamic law or a completed deformation model for Almaty. The results should be considered the first stage required for organizing long-term monitoring.

Further development of the study requires repeated GNSS campaigns, calculation of horizontal and vertical displacements between epochs, mapping of displacement vectors and deformation rates, expansion of the observation network in areas of faults and dense urban development, and integration of GNSS results with InSAR data, a digital elevation model, and engineering-geological materials.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Gulnar Jangulova	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		
Gulban Baidauletova	✓						✓	✓	✓	✓				
Olzhas Kurmanbayev		✓	✓	✓			✓		✓	✓	✓			
Nurzhan Khamit	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

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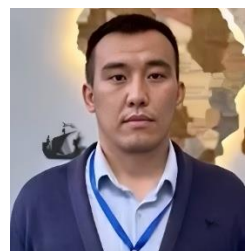
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Article

Methods for improving cartographic competence of schoolchildren

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SECTION

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Map-related knowledge; mapping skills; map-based activity; cognitive skills; analytical thinking.

Abstract: The development of cartographic competence is an important objective of contemporary geography education, as it enables students to interpret spatial information, analyze geographical phenomena, and apply higher-order thinking skills through map-based learning. This study aims to evaluate the effectiveness of methods for improving the cartographic competence of secondary school students using learning tasks structured according to Bloom's taxonomy. A quasi-experimental research design was conducted with 94 students aged 13–14 from Secondary School No. 167 in Almaty, Kazakhstan. Participants were divided into experimental and control groups. Three levels of cartographic tasks aligned with Bloom's taxonomy were developed to assess students' map-reading, analytical, synthesis, and evaluation skills. The experimental group received structured instruction based on taxonomy-oriented map activities and project-based learning, while the control group followed conventional geography instruction. Comparative analysis of the results showed that the experimental group achieved higher performance across all cognitive levels. The largest difference between the groups was observed at the synthesis and evaluation level, where the experimental group outperformed the control group by 34 percentage points. The findings indicate that the systematic integration of Bloom's taxonomy into cartographic instruction effectively enhances higher-order thinking skills, including analysis, synthesis, evaluation, and independent problem-solving. In addition, project-based cartographic activities contribute to the development of practical mapping skills and cartographic literacy. The study demonstrates the pedagogical value of taxonomy-based instruction within the updated geography curriculum of Kazakhstan and highlights its potential to strengthen students' critical thinking and spatial reasoning. The proposed approach provides a practical methodological framework for improving cartographic competence and promoting more effective geography learning in secondary schools.

* * * * *

1 Introduction

As one of the most critical social institutions, education is continually evolving to align with shifting societal goals and needs, driven by the development and integration of advanced technologies. This reality calls for ongoing exploration, analysis, and tracking of both broader civilizational processes and the operational dynamics of educational systems, aiming to synchronize their key features with social transformations and the primary directions of scientific, technological, and social advancement (Whittaker, 2012). Simultaneously, modernization must target the content of education itself, since the core curriculum lays the groundwork and potential for refining secondary school training programs, while also shaping the standards and quality of higher education (Kyriacou, 2010). The content of contemporary

education influences how society's productive forces develop and are utilized, as well as its material and spiritual culture and the overall well-being of its people (Ahtee et al., 2011).

Today, numerous perspectives exist for outlining the trends shaping 21st-century education. The following major trends can be identified:

- *humanization* of education as a fundamental turn from its technocratic goal (providing production with staff, their adaptation to the needs of production) to the humanistic goals of becoming and developing a personality, creating conditions for its self-realization;

- *democratization* of education as a transition from a rigid centralized and uniform system of organization of education to the creation of conditions and opportunities for every educational institution, every teacher, lecturer and student to fully reveal their potential and abilities;

- *leading development* of general and professional education of individuals in line with the evolving levels of production, equipment, and technology.

In today's educational world of secondary and higher education institutions, not only knowledge is transferred, but also the process of educating motivated, enterprising personality of students is going on. It is necessary to replace the formula "education for life" with the formula "education through whole life". Like other social fields, education requires constant updating, that is, using new methods and forms of organizing education that will help students learn new material, strive for a goal, learn how to work independently, be able to analyze information, learn how to apply skills in practice.

In recent years, the education system of the Republic of Kazakhstan has undergone fundamentally new transformations. The large-scale implementation of the updated curriculum in secondary schools marks the initial phase of reforming the educational institution as a whole. Revising the curriculum is a necessity driven by the demands of the present era. The renewed content of the curriculum will enable the development and enhancement of knowledge and skills for both students and teachers.

The education reform strategy is designed to shift the education system toward a new model, with the aim of making it competitive in the global education arena (Parker & Hurry, 2007; Kaldybekova et al., 2021). It focuses on developing a generation of young people who are both protected and adaptable in the labor market, equipped with the knowledge, skills, and competencies needed to integrate into society at various levels, and capable of lifelong learning.

A map is a source of information that, in the context of information technology (Harrow, 1972; Simpson, 1971) can be viewed as a specific information product resulting from the application of cartographic methods to the study of specific territories. The current curriculum prioritizes tasks that align with the higher levels of Bloom's taxonomy of thinking. This is because the revised Bloom's taxonomy (Anderson & Krathwohl, 2001) places special emphasis on developing the learner's abilities that lead to the formation of creative skills. Nevertheless, teachers remain uninterested in developing mapping skills—an integral component of geography - through such tasks (Marzano, 2006; Costa, 1985).

Given the rapid pace of technological advancement today, individuals need to be able to adjust to any situation. Continuous learning is essential, because knowledge evolves every four to five years, making self-improvement a necessity. Accordingly, education should equip students with practical skills and abilities that serve them in real life, rather than overwhelming their minds with vast amounts of information that has little everyday use. The modern educational system bears the responsibility of raising a generation that is intelligent, multilingual, and eager to keep learning throughout life - one capable of adapting to the conditions of a fast-changing world. Despite the growing international recognition of Bloom's taxonomy as an effective framework for developing higher-order thinking skills, its systematic application through map-based tasks at the secondary school level in Kazakhstan has not been empirically investigated. This study therefore addresses an existing research gap by examining how structured cartographic tasks, designed across all six levels of Bloom's revised taxonomy, can enhance students' cartographic competence and geographic thinking skills within the context of Kazakhstan's updated secondary school curriculum.

2 Materials and methods

The revised content and organization of the geography curriculum are shaped by the unique characteristics of the discipline (Lambert & Balderstone, 2012). Whereas geography was once a science focused on describing new territories and countries through exploration, its current role now encompasses the following objectives:

- assessing the impact of human activity on the environment;
- examining the integrity of ecosystems;
- preventing the detrimental effects of human actions on nature;
- exploring methods to conserve mineral resources;
- identifying causal relationships within natural processes;
- analyzing political, demographic, and economic developments occurring globally.

The purpose of studying this subject is to cultivate specific skills. These skills are categorized according to Bloom's taxonomy.

Table 1. Verbs used in Bloom's Taxonomy

Creating	Create new, design an innovation.
Evaluation	Argue, defend a point of view, validate, predict.
Analyzing	Analyze, check, conduct an experiment, organize, compare, and differentiate.
Applying	Apply, illustrate, solve
Understanding	Describe, explain, identify signs, formulate differently.
Remembering	Make a list, highlight, tell, show, name.

In the course of the study, the methods of mastering new knowledge, methods of forming skills and abilities, practical, visual techniques and methods were used. A feature of these methods is that students are given the opportunity of oral presentation, the formation of mental activity, the use of knowledge through action.

For instance, engage with diverse origins of geographical understanding - such as recounting and appraising the impact of explorers and scholars on the advancement of geography as a discipline. Fulfilling these assessment aims cultivates a range of hands-on competencies in learners, illustrating how theoretical insights can be applied in real-world scenarios. Concurrently, the outlined evaluation objectives and abilities are tailored to the developmental stage of the students.

Working with the updated curriculum shows that students become more autonomous and better at regulating their own learning process. This happens because they can see the final result of their efforts and develop practical skills they can actually use. In this context, the teacher's role is to teach how to learn - rather than handing out ready-made knowledge, they provide guidance and adjust the learning process in the classroom. Today, people need to build skills and acquire knowledge that are essential for real life. The updated geography curriculum is designed to help students grow into independent and responsible individuals, guided by strong moral and spiritual values.

In the present day, it is impossible to study geography without relying on cartographic data. A map is no longer just a familiar depiction of the Earth's surface; it is now viewed as a source of information that, through the lens of information technology, can be considered a distinct informational product derived from cartographic methods used to analyze specific areas. In contemporary society, there is a growing emphasis on the importance of cartographic science. Without maps, it would be extremely challenging to form a representation of the place we inhabit (Beard et al., 1993; Wood & Fels, 1992).

Becoming familiar with a map involves the following steps:

- developing cartographic knowledge;
- learning practical techniques for using the map;
- grasping the meaning of the map;
- forming spatial perceptions.

In today's world, a shift in perspective is essential across numerous aspects of existence. The cognitive process involves organizing information, progressing from fundamental concepts to increasingly complex ones. This concept is linked to the creation and application of innovative teaching methods within the learning experience. Advanced cognitive abilities in geography pertain to the subsequent intellectual exercise:

- ability to work with geographic concepts and terms;
- transformation of geographic material from one form of expression to another;
- application of knowledge and skills in research activities;
- analyze geographic information;
- make logical conclusions;
- critically process facts;
- correctly present the results of completed studies in academic forms (in the form of a poster presentation, etc.).

Bloom's Taxonomy is an effective hierarchical system in education that enables the efficient use of time while ensuring a systematic approach to learning and facilitating student self-assessment. In the course of research aimed at evaluating academic performance, the aforementioned group of scholars identified several factors influencing the learning process of schoolchildren, both within the educational institution and outside it. One key factor identified was the lack of choice in the learning process.

In particular, teachers used a one-size-fits-all curriculum that did not meet the needs of every student. To address this issue, Bloom and his colleagues concluded that student performance would improve if each teacher worked with an individualized curriculum. This hypothesis formed the basis of Bloom's "Mastery Learning" method—a system in which teachers are trained in specific skills and concepts through a weekly cycle of lessons. At the end of each section, students' knowledge is assessed through reflective tasks and review questions. The assessment of learning outcomes identifies areas requiring additional support, after which students are offered remedial tasks to ensure full mastery of the material. Drawing on Bloom's taxonomy, educators have concluded that students can successfully master a subject if they use a curriculum suited to their needs and set specific learning goals for themselves.

3 Results

The objective of this research is to foster students' advanced cognitive abilities by integrating map literacy into geography instruction. Each task contributes to the development of a distinct array of subject-specific competencies. The cultivation of these competencies, in turn, is linked to hands-on abilities in utilizing diverse information sources, including cartographic ones. A map serves as a tool through which the complete spectrum of information can be accessed.

The study was carried out with 13- and 14-year-old students at Secondary School No. 167 in Almaty. Its purpose was to assess the higher-order thinking skills of learners through cartographic exercises during geography classes. The study was conducted during the 2025–2026 academic year over a period of six months (September 2025 to February 2026). A total of 94 students were divided into two groups: the experimental group (n=47) and the control group (n=47). The groups were formed using purposive sampling, ensuring comparable baseline performance levels as verified by prior geography test scores. The experimental group received instruction using Bloom's taxonomy-based cartographic tasks, while the control group followed the standard curriculum without additional map-literacy interventions. For the experiment, we designed three levels of questions based on Bloom's taxonomy. At the first level - covering knowledge and comprehension - the students answered four questions. These questions were crafted to evaluate their foundational cartographic understanding. On this first level, the experimental group's performance was 7.8 percentage points lower than that of the control group (Figures 1 and 2). The difference between the two groups was not substantial. Consequently, we determined that their general cartographic foundational knowledge is adequate. A chi-square test of independence was applied to compare the proportions of correct responses between groups. At the first level, the difference was not

statistically significant ($\chi^2 = 2.14, p > 0.05$), confirming comparable baseline cartographic knowledge across groups. The results are presented in the table below (Table 2).

Table 2. Outcomes of the experiment

First-level (knowledge and comprehension)				
Questions	Total	Group	Yes (%)	No (%)
Can you read the map using the legends?	94	Experimental	86 (91.4)	8 (8.6)
		Control	76 (80.8)	18 (19.2)
Is there a distortion on the globe?	94	Experimental	90 (95.7)	4 (4.3)
		Control	73 (77.6)	21 (22.4)
Can you show the location of the main meridian and equator on the map?	94	Experimental	91 (96.8)	3 (3.2)
		Control	88 (96.6)	6 (3.4)
Do you think that cartographic knowledge is needed in everyday life?	94	Experimental	89 (94.6)	5 (5.4)
		Control	87 (92.5)	7 (7.5)
Average median	94	Experimental	94.6 %	5.4 %
		Control	86.8 %	13.2 %

The second-tier questions (focused on application) we developed were more complex than those at the first level; their purpose was to assess skills in using maps, atlases, puzzles, and the ability to differentiate between types of scales. In this case, the experimental group's performance was 16.7 percent lower than that of the control group. This experiment revealed that students require greater emphasis on hands-on map-related activities. Statistical analysis at the second level revealed a significant difference between groups ($\chi^2 = 8.73, p < 0.01$), indicating that the experimental group demonstrated significantly stronger application and analysis skills. The experimental outcomes are presented in the table below (Table 3).

Table 3. Findings of the experimental study

Second-level (application and analysis)				
Questions	Total	Group	Yes (%)	No (%)
Can you work with a contour map using atlas?	94	Experimental	88 (93.6)	6 (6.4)
		Control	69 (73.4)	25 (26.6)
If geographic puzzles are given, can you lay down the contour of the mainland?	94	Experimental	89 (94.6)	5 (5.4)
		Control	82 (87.2)	12 (12.8)
Can you distinguish the map by scale?	94	Experimental	79 (84.0)	15 (16.0)
		Control	66 (70.2)	28 (29.8)
Can you determine the location of countries on the contour map?	94	Experimental	83 (88.2)	11 (11.8)
		Control	59 (62.7)	35 (37.3)
Average median	94	Experimental	90.1%	9.9%
		Control	73.4%	26.6%

The questions at the third level of the experiment pertain to analysis and evaluation. The geography-related questions presented here are intricate, demonstrating the capacity to carry out creative assignments. At the same time, they are designed to assess mental, emotional, and social development, as well as traits related to self-expression and research curiosity. Furthermore, they reveal the ability to independently choose geographic data, draw reasoned conclusions, and create presentations and projects that incorporate geographic maps in the course of research. The indicators for the experimental group were notably lower than those for the control group. Specifically, the difference amounted to 34 percent. This experiment highlighted the necessity of strengthening research and creative efforts among students. The third-level difference was the most pronounced and highly significant ($\chi^2 = 18.45, p < 0.001$), suggesting that Bloom's taxonomy-based instruction has the greatest impact on higher-order synthesis and evaluation skills. These findings are consistent with international studies such as Aksoy (2019), who

reported similar patterns of improvement in map literacy following structured cognitive-level interventions. The monitoring outcomes are displayed in the table below (Table 4).

Table 4. Results obtained from the experiment

Third-level (synthesis and evaluation)				
Questions	Total	Group	Yes (%)	No (%)
Can you select geographic data (official and unofficial) when conducting research?	94	Experimental	76 (80.8)	18 (19.2)
		Control	43 (45.7)	51 (54.3)
If a geographic text is given, can you make a logical inference from it?	94	Experimental	65 (69.1)	29 (30.2)
		Control	41 (43.6)	53 (56.4)
Will you be able to prepare a presentation on the topic: "Discover the world using map!"?	94	Experimental	61 (64.8)	33 (35.2)
		Control	31 (32.9)	63 (67.1)
Can you prepare a small project on the topic: "Native Land"?	94	Experimental	59 (62.7)	35 (37.3)
		Control	18 (19.1)	75 (90.9)
Average median	94	Experimental	69.3%	30.7%
		Control	35.3%	64.7%

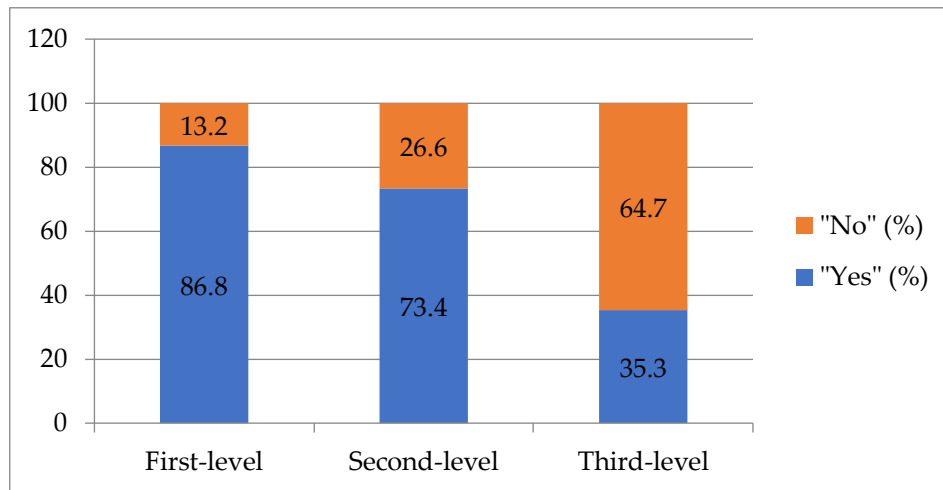


Figure 1. The results of experimental group

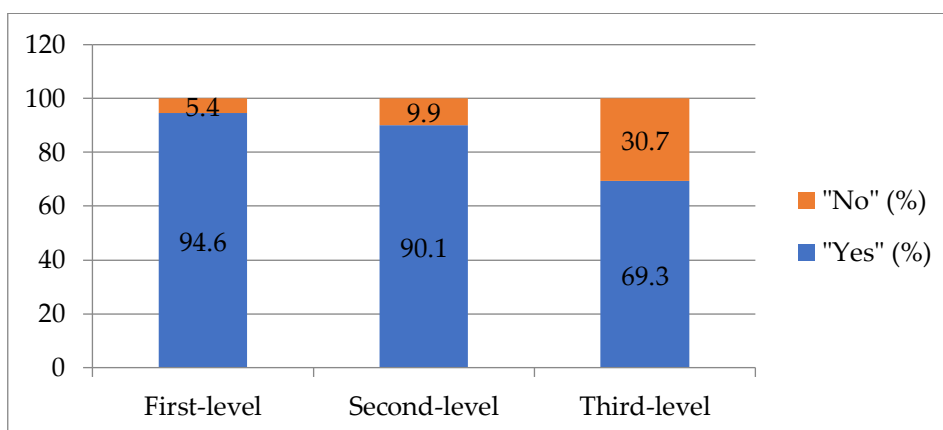


Figure 2. The results of control group

After the results of the experiment were determined, we focused on the correct formulation of questions according to Bloom's taxonomy in geography lessons in order to improve students' cartographic activity through thinking skills.

In the pedagogical environment there are already such concepts as "high-order thinking", "critical thinking". The study of this problem from the point of view of philosophy, psychology and pedagogy was

studied by foreign scientists E. de Bono, J. Dewey, M. Lipman, D. Halpern, D. Klooster, R.K. Johnson, P. Freire, J. Steel, D. Spiro, K. Meridith, Ch. Temple.

The correct formulation of the question is the most powerful tool for the formation of thinking skills (Anderson & Krathwohl, 2001; Bloom, 1956). There is a direct link between the questions we ask students and the answers. Bloom's taxonomy helps broaden higher-order thinking skills. The formulation of higher-order questions is interrelated and interdependent with thought processes. Higher-order questions are built using specific verbal structures, such as: "If I've understood you correctly, does that mean...?" or "What would you do if you were in...?" The ability to craft these types of questions enables you to engage in conversations at various levels, including cumulative discussions, debates, and research-oriented dialogues.

Examples of the correct formulation of questions on geography are given in the following table (Table 5).

Table 5. Examples of correct questions on the subject of geography

Types	Sample questions that can be asked students
Remembering	<ul style="list-style-type: none"> - List the types of geographic maps? - Remember the types of scales? - What are the meridians and parallels? - How are geographic coordinates determined? - What are the geographical coordinates of the 5 largest cities (London, Canberra, New York, Buenos Aires, Tokyo) of the world? - Mark on the contour map the location of these cities?
Comprehension	<ul style="list-style-type: none"> - Explain the differences between parallels and meridians? - Compare the length of the equator and the initial meridian. - Give the definition in your own terms: geographical latitude and longitude? - Tell us about the geographical value of the 180 ° meridian. - Give synonyms of the initial meridian. - Distinctive features of the equator from other parallels?
Applying	<ul style="list-style-type: none"> - What is the significance of geographic coordinates in daily life? - In what ways can cartographic skills be used to explore the geography of one's homeland? - Identify five major world cities (London, Canberra, New York, Buenos Aires, Tokyo) on a hemisphere map, arranging them from north to south. - In a notebook, draw a schematic representation of the globe. Label the equator, the tropics, and the polar circles. Indicate the North and South Poles. - List these seas from west to east: Yellow Sea, Mediterranean Sea, Black Sea, Arabian Sea, Bering Sea.
Analyzing	<ul style="list-style-type: none"> - What is the role of the map when studying geography? - Analyze the similarities and differences between the globe and the map? - Determine the distance of your settlement from the equator and the initial meridian? - How to measure the distance on the degree grid? - Prove the equality of the lengths of the arc meridians?
Evaluation	<ul style="list-style-type: none"> - Discuss the meaning and use of maps for science and practice. - Evaluate the role of the map in the study of geography. - Prove that the map is a source of geographic knowledge. - Compare ancient and modern geographical maps.
Creating	<ul style="list-style-type: none"> - Compose images of continents using geographic puzzles? - Place the names of geographical objects according to their location on the map of the hemispheres (Amazon, Maracaibo, Himalayas, Vancouver, Adriatic) - Prepare a presentation on the topic: "Discover the world using a map".

The questions listed above were compiled in accordance with Bloom's taxonomy. This has shown that it is useful for students to correctly represent geographic knowledge in a systematic sequence, from their understanding to evaluation. These questions are gradually promoting students from answers to easy questions to answers to difficult questions. Having received enough answers to the questions asked above,

we asked to perform the following tasks. These tasks include cartographic actions that are performed using the map.

Using the map data, students are asked to answer the following questions:

- 1) What is the territory depicted on the map (world map, map of hemispheres, continents, their parts, states, their parts, etc.)?
- 2) What is the frame of the map (round, rectangular, elliptical)?
- 3) What lines are the meridians (straight lines, curves) and parallels (straight lines, curves, circles, arcs concentric or eccentric circles)?
- 4) How do the intervals between the parallels and the meridians change (they do not change, change slightly, increase or decrease and how many times)?
- 5) What additional features of the projection are depicted on the map (the equator is a straight line or a curve, not shown; the pole is not shown, shown as a dot)?
- 6) Give a classification of the projection according to the character of the auxiliary geometric figure (azimuthal, cylindrical, conical, their varieties).

Thus, according to the tasks we proposed, the students, working with the map, were able to develop higher-order thinking skills. Thinking skills teach to memorize, apply acquired knowledge, independently make conclusions.

4 Discussion

On knowledge and comprehension, students were able to form terms and concepts that are the basis of geographical knowledge. They learned to distinguish between symbols on geographical maps, identify differences between the globe and the map, and they realized that when the Earth's surface was transferred onto a map, there were more distortions than on the globe. They formed the concept of the importance of the elements of a geographic map - the initial meridian, equator, 180⁰ meridian. They also learned how to determine geographic coordinates using meridians, parallels, and a degree grid. These skills have shown that a high level skills are especially among those students who work well with atlas. They understood the need for cartographic knowledge in everyday life, for example, learned to find a place of residence on the world map.

On application and analysis, skills of working with a contour map using an atlas were formed. Skills for shaping the contours of the continents with the help of geographic puzzles were improved. They understand the map, distinguishing types of scales. They can determine the location of states on the contour map. They can give a definition of the importance of geographic coordinates in everyday life. They can use cartographic knowledge in a timely manner when studying the geography of their native land. Note in their dissertation research that new pedagogical technologies facilitate the development of an individual's system of thinking and foster the ability to make specific decisions in various situations (Harrow, 1972). Pedagogical principles form the foundation of educational modernization. One of the key tasks at the current stage of development is the technologization of the educational process within the school system. Consequently, various educational technologies are being developed and implemented in school practice. Implementing long-term projects aimed at developing cartographic skills requires a significant amount of time. For instance, in the seventh grade, students spend the entire year creating a model of a hypothetical (imaginary) continent: they map out various thematic features, invent new countries and cities, and construct a history of the continent's discovery and exploration. Work on such a project continues throughout the academic year.

In the first stage, children locate the future continent on the map. While studying the topic of "Geographic Coordinates" they determine its geographic location and the coordinates of its extreme points, noting the parallels and meridians between which it lies. They also identify the oceans that wash its shores and the other continents with which it shares borders. Thus, a new continent is "registered" on the world map. Subsequently, as each new topic is studied, various geographical features appear on the continent.

When studying the "Lithosphere" topic, the children create a physical map of the continent. They mark major landforms on it, drawing upon maps showing the Earth's crustal structure as well as maps of earthquake and volcanic activity zones.

When studying the "Hydrosphere" topic, students identify river systems, examine their flow regimes and feeding patterns, locate major lakes on a map, and analyze their origins. As with the study of other continents, students mark the natural zones of their continent on a map. Furthermore, they determine which animals and plants can inhabit specific natural environments, taking into account the adaptation strategies of living organisms.

5 Conclusion

The necessary skills for determining the placement direction of geographical objects on a map were developed. Students learned how to use geographic maps and scales to calculate the distance of an object from the equator and the prime meridian. The scientific novelty of this study lies in the systematic application of Bloom's revised taxonomy as a structuring framework for cartographic competence development within the Kazakhstani secondary education context, where such an approach had not previously been tested empirically. Unlike general studies on Bloom's taxonomy in education, the present work specifically operationalizes all six cognitive levels through map-based tasks and validates them against measurable student performance outcomes. A critical analysis of the results reveals that while the experimental group demonstrated consistent advantages across all three cognitive tiers, the gains were most pronounced at the higher-order levels (synthesis and evaluation: +34 percentage points), suggesting that structured cartographic tasks are particularly effective for developing complex reasoning skills. However, the absence of long-term follow-up assessment remains a limitation: future studies should examine whether these gains are sustained beyond the intervention period. Additionally, comparison with international benchmarks, such as those established by Aksoy (2019) and Koc & Cifci (2016), indicates that Kazakhstani students in the experimental group reached performance levels comparable to their Turkish counterparts following similar map-literacy interventions, which underscores the cross-cultural applicability of Bloom's taxonomy-based approaches in geography education.

The implementation of new technologies requires a specialist with a creative mindset—someone capable of bringing fresh substance to professional and social life, as well as defining and addressing forward-looking challenges. In recent years, school teachers have been conducting short sessions (lasting 3–5 minutes) to help students develop the necessary skills. Such exercises, aimed at developing map-reading skills, will undoubtedly boost students' self-confidence and teach them to take responsibility for their actions.

For synthesis and evaluation, they were given the chance to build skills for independently selecting geographic data during research, such as distinguishing between official and unofficial data. While working with geographic texts, they learned to draw conclusions based on the main idea. It turned out that some students were able to summarize research findings and present them in the form of a presentation. It was observed that a few gifted students could carry out small research projects. We believe that it is important to adequately emphasize the application and analysis of knowledge among students in the control group as compared to those in the experimental group. To achieve this, we think it would be more effective to hold additional lessons focused on practical tasks. Additionally, in order to enhance students' creative abilities, more attention should be given to fostering their creative potential.

Modern pedagogical and psychological research shows that students not only understand the learning material but also consciously organize their own learning activities. Therefore, a student should ask themselves: "How did I do this? Why did I do this?" Why did I do this? Did I reach any conclusion? Which option is more effective for answering the review questions? Students ask themselves questions, become aware of their actions, and are capable of reflection. Reflection during the learning process fosters a different kind of relationship between teacher and student.

With the teacher's guidance, the student masters new material independently and develops the skill of creative inquiry. Reflection boosts the student's engagement in learning: they begin to recognize their learning goals and, drawing on self-assessment, are able to consciously organize each stage of the learning process. Reflection can take place not only at the end of a lesson but also in various situations or at specific stages, gradually evolving into a continuous internal reflective process as the topic is explored.

Active participation in the learning process is a didactic principle that fosters students' interest in learning and lays the groundwork for independent inquiry, task completion, deep mastery of the material, the acquisition of competence, the ability to formulate and substantiate ideas and explain concepts, and the development of creative abilities. To make such active engagement a habit, the educator must ensure a high level of preparation for every lesson. Consequently, thanks to the skills developed in this way, students will be able to apply the knowledge gained in class to real-life situations. Active learning methods are among the most effective techniques for encouraging students not merely to listen to the teacher, but to participate in the lesson with interest. During every class, active students quickly and correctly complete tasks and exercises, while other students - in contrast - gather around their active peers, striving to grasp new concepts.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Razia Kaldybekova	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		
Albina Beikitova	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓		

- C : Conceptualization
- M : Methodology
- So : Software
- Va : Validation
- Fo : Formal analysis
- I : Investigation
- R : Resources
- D : Data Curation
- O : Writing - Original Draft
- E : Writing - Review & Editing
- Vi : Visualization
- Su : Supervision
- P : Project administration
- Fu : Funding acquisition

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Review

Biodiversity loss in steppe ecosystems: a comprehensive review of conservation strategies

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SECTION

Geocology and Environmental Protection

KEYWORDS

Biodiversity loss; steppe ecosystem; grassland conservation; habitat loss; empirical field study; systematic review; PRISMA.

Abstract: Steppe and grassland ecosystems are among the most biologically diverse yet increasingly threatened terrestrial biomes, supporting unique biodiversity and providing essential ecosystem services. However, these ecosystems are experiencing rapid biodiversity loss due to agricultural expansion, overgrazing, habitat fragmentation, land-use change, invasive species, and climate change. Understanding recent advances in conservation research is therefore essential for developing effective management strategies and evidence-based environmental policies. This study presents a systematic bibliometric review of empirical research on biodiversity loss and conservation strategies in steppe ecosystems published between 2020 and 2025. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, 65 peer-reviewed articles were identified from the Scopus database through a structured Boolean search and a multi-stage screening process. The selected studies represent research conducted in 25 countries, with the highest publication output from the United States (n = 11), Germany (n = 6), and China (n = 6). Field surveys and field-based ecological studies were the dominant research methods (n = 39), followed by remote sensing and GIS approaches (n = 13), long-term ecological monitoring (n = 4), and species distribution modelling (n = 3). The review identified five major research themes: grazing impacts on plant diversity, habitat fragmentation, protected area effectiveness, ecological restoration, and climate-driven shifts in species distributions. The findings reveal considerable geographical gaps in conservation research, particularly in Central Asia and Kazakhstan, despite the extensive distribution and ecological significance of their steppe ecosystems. This review synthesises current empirical evidence, identifies methodological trends and research gaps, and provides recommendations for future interdisciplinary studies and policy development to strengthen biodiversity conservation and promote the long-term sustainable management of steppe ecosystems.

* * * * *

1 Introduction

Steppe and temperate grassland ecosystems cover approximately 40 percent of Earth's terrestrial surface and support extraordinary biological diversity across all trophic levels. These biomes provide critical ecosystem services including carbon sequestration, water regulation, and the livelihoods of pastoralist communities on every inhabited continent. Despite their global significance, temperate grasslands have experienced disproportionate rates of conversion, fragmentation, and degradation, with native grassland losses in some regions exceeding 80 to 95 percent of historical extents (Fogarty et al., 2020). Agricultural expansion, urban development, overgrazing, fire suppression, and climate change

have collectively driven declines in plant, invertebrate, and vertebrate diversity across steppe systems worldwide (Ambrósio et al., 2024; Luo et al., 2025).

The escalating pace of biodiversity loss has galvanised international conservation commitments. The Kunming-Montreal Global Biodiversity Framework adopted in December 2022 set the 30x30 target of protecting 30 percent of terrestrial and marine areas by 2030, with specific attention to ecosystems under severe threat. However, policy implementation remains uneven, and steppe biomes frequently receive less attention than forest systems in national biodiversity strategies. A growing body of empirical research is now addressing these gaps, spanning topics from livestock grazing management (Dong et al., 2025) to protected area effectiveness (Gameiro et al., 2020), restoration ecology (Watkinson et al., 2025), and climate-driven range shifts (Gao et al., 2025).

Despite this growing research activity, no comprehensive synthesis of post-2020 empirical literature on steppe biodiversity exists. The present systematic review addresses this gap by synthesising 65 empirical studies identified through a structured PRISMA-compliant search of the Scopus database. The objectives are: (1) to map the geographic and temporal distribution of steppe biodiversity research; (2) to identify and synthesise evidence on the principal drivers of biodiversity loss; (3) to evaluate conservation and restoration strategies examined in empirical studies; and (4) to identify critical research gaps and priorities for future investigation.

2 Materials and methods

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines adapted for bibliometric studies. The Scopus database was selected as the primary source owing to its comprehensive coverage of peer-reviewed scientific literature in the environmental and ecological sciences. A Boolean search was conducted using the following query: TITLE-ABS-KEY (("biodiversity loss" OR "biodiversity decline" OR "species loss" OR "habitat loss") AND ("steppe*" OR "grassland*" OR "dryland*" OR "semi-arid*") AND ("conservation strateg*" OR "conservation plan*" OR "protected area*" OR "ecosystem management" OR "restoration strateg*")). The search was conducted in June 2025 and returned an initial set of 397 records.

Records were screened in sequential stages, as illustrated in Figure 1. A publication year filter was applied first, restricting results to 2020 to 2025 and reducing the pool to 185 records. The document type filter, limiting results to original research articles, reduced this further to 166 records. Removal of duplicate entries yielded 161 records, and application of the open access filter produced 108 records. Title and abstract screening for relevance to steppe or grassland ecosystems reduced the pool to 82 records. Finally, full-text assessment of each article for empirical content excluded a further 17 records that were found to be systematic reviews, meta-analyses, or purely theoretical studies, resulting in a final corpus of 65 articles included in the analysis.

Articles were included if they: (1) reported original empirical data collected through field surveys, field experiments, remote sensing analyses, or long-term monitoring programmes; (2) focused on steppe, temperate grassland, semi-arid, or dryland ecosystems; (3) addressed biodiversity metrics such as species richness, abundance, community composition, or habitat quality; and (4) were published in English in Scopus-indexed, peer-reviewed journals between January 2020 and December 2025. Articles were excluded if they were systematic reviews or meta-analyses without new empirical data, purely theoretical or modelling studies without field validation, or studies focused solely on non-steppe ecosystems such as forests or aquatic habitats.

For each included article, the following variables were extracted: authors and year of publication, article title, journal name, country of study identified from author affiliations, methodological approach, and key thematic content based on author keywords and abstracts. Methodological approaches were categorised into six types: field survey, field experiment, remote sensing and GIS analysis, long-term monitoring, species distribution modelling, and statistical analysis. Thematic coding was performed inductively based on author keywords and abstract content, and articles were assigned to one primary thematic cluster.

Descriptive statistics and frequency analyses were performed to characterise the distribution of studies across geographic, temporal, and methodological dimensions.

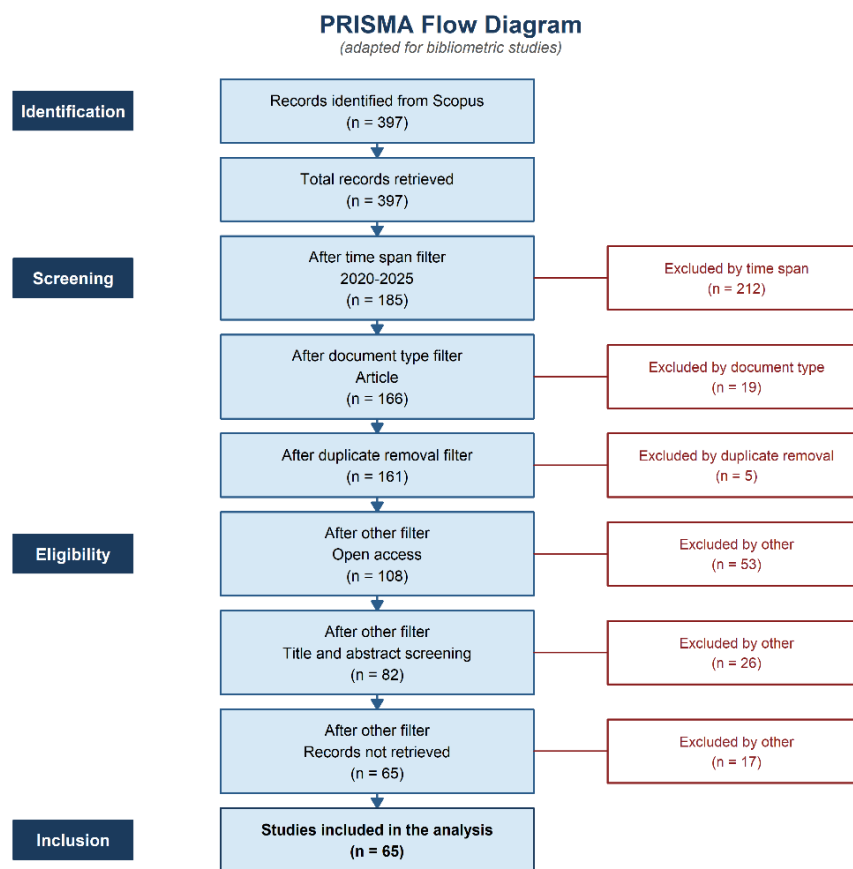


Figure 1. PRISMA 2020 flow diagram illustrating the article selection process from initial Scopus search (n = 397) to final included studies (n = 65).

3 Results

3.1 Overview and temporal trends

The 65 included studies (Table 1) were published across the period 2020 to 2025, with a pronounced upward trend: 3 articles in 2020, 6 in 2021, 10 in 2022, 9 in 2023, 11 in 2024, and 26 in 2025. This acceleration likely reflects growing policy urgency following the adoption of the Kunming-Montreal Global Biodiversity Framework. Studies were published across 40 journals, most frequently in Biological Conservation (n = 5), Ecological Indicators (n = 4), and Landscape Ecology (n = 4).

Table 1. Distribution of 65 included studies by journal (n = number of articles; % = percentage of total).

No.	Journal	n	%
1	Biological Conservation	5	7.7
2	Ecological Indicators	4	6.2
3	Landscape Ecology	4	6.2
4	Diversity	3	4.6
5	Global Ecology and Conservation	3	4.6
6	Restoration Ecology	3	4.6
7	Ecological Processes	2	3.1
8	Ecosphere	2	3.1
9	Ecology and Evolution	2	3.1
10	American Journal of Primatology	1	1.5

Table 1. (Continued)

No.	Journal	n	%
11	Animals	1	1.5
12	Applied Vegetation Science	1	1.5
13	Austral Ecology	1	1.5
14	Biology	1	1.5
15	Birds	1	1.5
16	Biosystems Diversity	1	1.5
17	Catena	1	1.5
18	Desenvolvimento e Meio Ambiente	1	1.5
19	Diversity and Distributions	1	1.5
20	Ecological Applications	1	1.5
21	Ecology	1	1.5
22	Endangered Species Research	1	1.5
23	Environmental Monitoring and Assessment	1	1.5
24	Environmental Problems	1	1.5
25	Environmental Research Letters	1	1.5
26	Forest Ecology and Management	1	1.5
27	Genome Biology	1	1.5
28	Global Change Biology	1	1.5
29	Insect Conservation and Diversity	1	1.5
30	Journal of Animal Ecology	1	1.5
31	Journal of Applied Ecology	1	1.5
32	Journal of Ecology	1	1.5
33	Journal of Environmental Management	1	1.5
34	Journal of Insect Conservation	1	1.5
35	Land	1	1.5
36	Land Degradation and Development	1	1.5
37	Land Use Policy	1	1.5
38	Ornis Hungarica	1	1.5
39	ORYX	1	1.5
40	Perspectives in Ecology and Conservation	1	1.5
41	Remote Sensing	1	1.5
42	Revista de Biología Tropical	1	1.5
43	Scientific Reports	1	1.5
44	Sustainability	1	1.5
45	Wildlife Society Bulletin	1	1.5
	Total	65	100.0

3.2 Geographic distribution

The included studies originated from 25 countries, as shown in Figure 2, with the highest output from the United States ($n = 11$), Germany ($n = 6$), and China ($n = 6$), followed by Brazil ($n = 4$), and the United Kingdom, Canada, Argentina, South Africa, and Italy ($n = 3$ each). Studies from Austria (Schwaiger, 2022; Probst, 2025), France (Ghasemi et al., 2025; Chenot-Lescure et al., 2022), Spain (Parengal et al., 2025; Muñoz-Reinoso, 2023), Switzerland (Achury et al., 2025; Perrin et al., 2025), Ukraine (Dubyna et al., 2023; Uvaieva et al., 2025), India (Dutta & Jhala, 2021; Jhala et al., 2021), and Australia (Stoudmann et al., 2024; Lee et al., 2023) each contributed two articles. Single studies originated from the Netherlands (Ambrósio et al., 2024), New Zealand (Pedley et al., 2023), Czech Republic (Segrestin et al., 2025), Slovenia (Gazoulis et al., 2022), Tanzania (Rija, 2022), South Korea (Abedin et al., 2024), Thailand (Jahan et al., 2022), Portugal (Crispim-Mendes et al., 2024), and Sweden (Narváez-Torres et al., 2025).

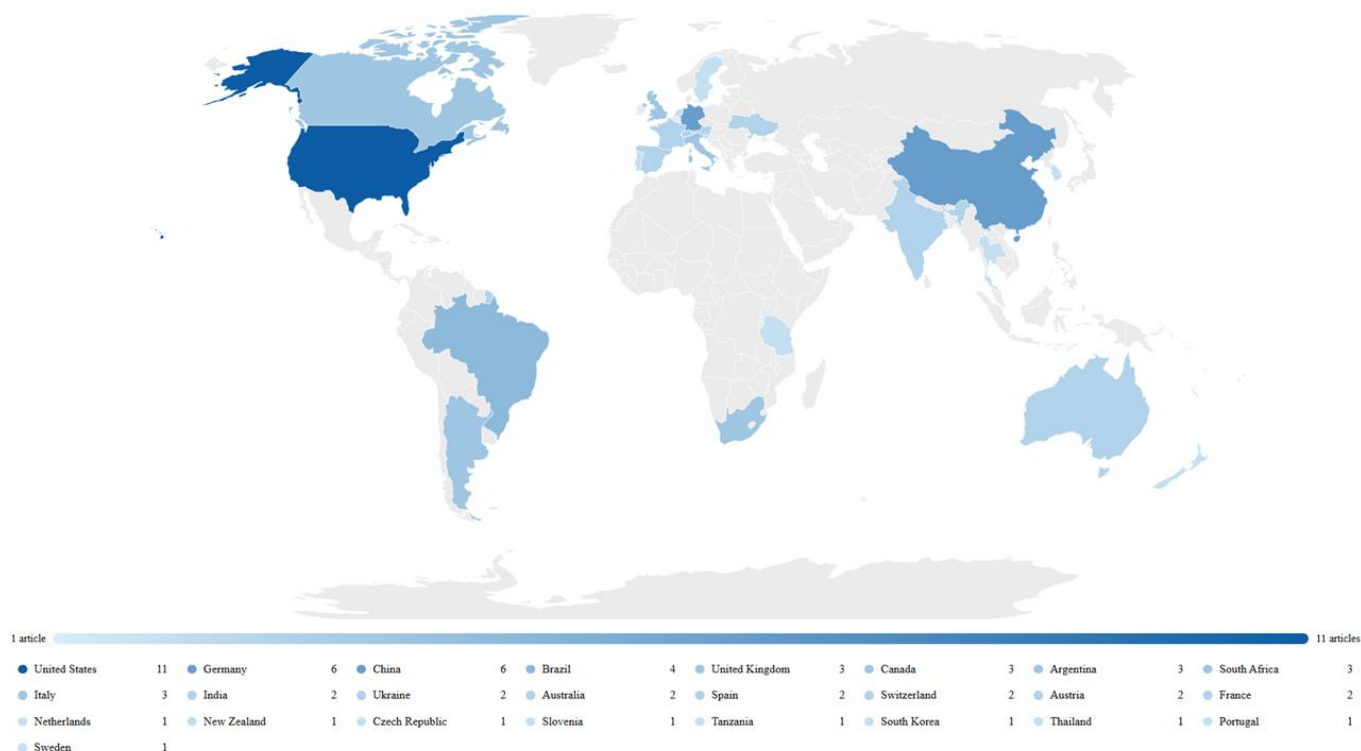


Figure 2. Geographic distribution of the 65 included empirical studies across 25 countries. Colour intensity (light to dark blue) corresponds to number of publications per country (range: 1 to 11 articles).

A critical geographic gap was identified in Central Asia. No empirical open-access studies from Kazakhstan, Uzbekistan, Mongolia, or other Central Asian countries met the inclusion criteria, despite these regions containing the largest remaining contiguous steppe areas on Earth. This underrepresentation has significant implications for global conservation planning, as evidence-based management frameworks cannot be developed without locally-grounded empirical data.

3.3 Keyword co-occurrence analysis

Figure 3 presents the keyword co-occurrence network generated using VOSviewer based on the author keywords of the 65 included studies. Six thematic clusters were identified, reflecting the dominant research foci in the literature: (1) nature conservation and policy (red cluster); (2) climate change and environmental factors (orange/yellow cluster); (3) conservation planning and species distribution (green cluster); (4) ecological restoration and landscape connectivity (blue cluster); (5) pasture and agroecosystem management (purple cluster); and (6) grassland ecosystem and dryland dynamics (pink cluster). The most frequently co-occurring keywords were nature, conservation planning, environmental factor, and ecological restoration, indicating that these concepts form the conceptual core of current steppe biodiversity research.

3.4 Methodological profile

Field surveys and observational field studies were the dominant methodological approach (n = 39). Remote sensing and GIS analyses were employed in 13 studies, including vegetation change monitoring (Lu et al., 2022), land cover mapping (Rodrigues et al., 2025; Pavlacky et al., 2022), and habitat suitability assessment (Fowler et al., 2024; Paterson et al., 2024). Long-term monitoring programmes were the basis of four studies (Bernath-Plaisted et al., 2025; Ogan et al., 2022; Richiardi et al., 2025; Deutsch et al., 2024). Species distribution modelling was used in three studies (Jhala et al., 2021; Crispim-Mendes et al., 2024; Luo et al., 2025). Field experiments examining the effects of specific management interventions were

conducted in four studies (Segrestin et al., 2025; Watkinson et al., 2025; Nascimento et al., 2025; Chenot-Lescure et al., 2022).

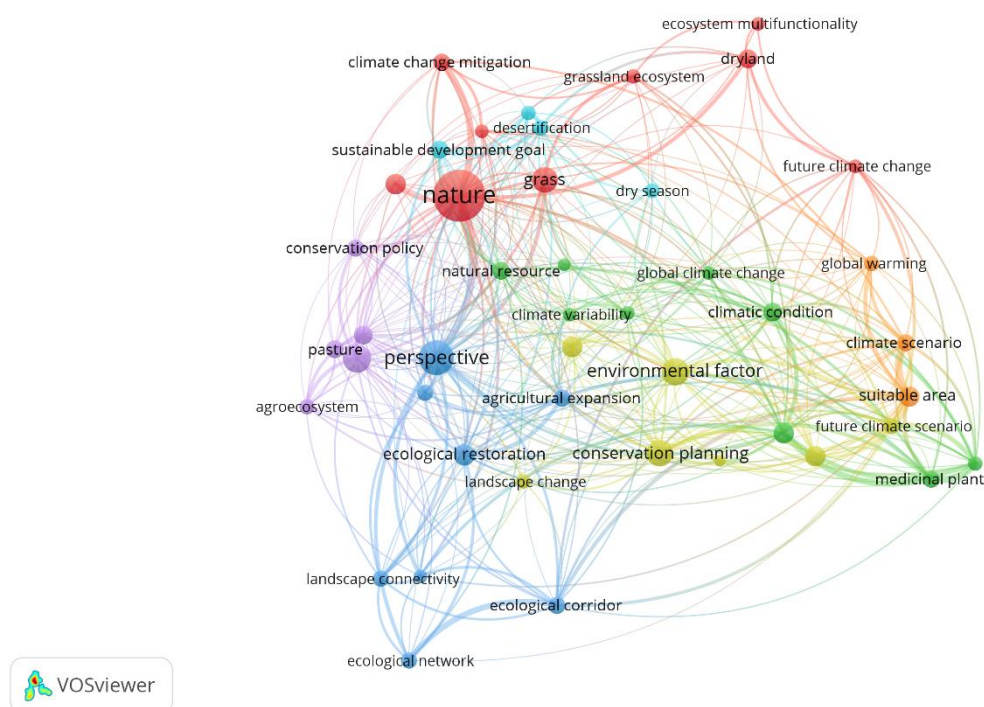


Figure 3. Keyword co-occurrence network of included studies generated using VOSviewer (n = 65).

3.5 Theme 1: Grazing impacts on steppe biodiversity

Grazing by domestic livestock is the most pervasive anthropogenic influence on steppe ecosystems. Dong et al. (2025) demonstrated that expansion of native poisonous plants in degraded Tibetan pastures was mediated by soil processes altered by overgrazing, paradoxically increasing plant diversity in degraded sites through facilitation mechanisms. Igl et al. (2023) found that conversion of Conservation Reserve Program grasslands to cropland in the northern Great Plains resulted in significant loss of grassland-dependent bird species, with the removal of grassland cover eliminating habitat for both obligate and facultative grassland species. These contrasting findings highlight the complexity of grazing effects and the importance of spatially and taxonomically explicit empirical approaches.

3.6 Theme 2: Habitat loss and land use change

Fogarty et al. (2020) documented progressive encroachment of woody vegetation into native Nebraska grasslands associated with fire suppression and altered grazing regimes. Fernandes et al. (2025) assessed extinction risk in South American pampas grasslands, finding that endemic Cactaceae were disproportionately threatened by habitat conversion. Pedley et al. (2023) examined natural regeneration of woody vegetation into New Zealand grasslands, reporting significant reductions in open-habitat specialist species. Niemuth et al. (2021) showed that grassland bird conservation in the United States was strongly linked to maintenance of large unfragmented grassland patches, with Conservation Reserve Program enrolment directly predicting population recovery. Stoudmann et al. (2024) evaluated conservation outcomes in Australian agricultural landscapes, demonstrating that targeted on-farm conservation agreements significantly improved vegetation structural complexity.

Lakner et al. (2020) found that combining management plans with payment for ecosystem services schemes in German calcareous grasslands achieved higher plant species richness targets than either instrument alone. Perrin et al. (2025) examined habitat fragmentation effects on insect diversity in Swiss

grasslands, showing that fragment size and connectivity were the strongest predictors of species richness. Ivey et al. (2025) documented ongoing decline in landcover suitability for sandhill crane habitat in United States grasslands driven by agricultural conversion. Deutsch et al. (2024) used long-term monitoring in Argentine Patagonian steppes to show substantial reductions in small mammal diversity linked to grazing intensity and land tenure changes. Probst and Probst (2025) investigated winter ecology of the hen harrier in Austrian steppe systems, finding that landscape-level grassland cover predicted foraging success and survival. Begosh et al. (2022) demonstrated that semi-natural grassland edges maintained significantly higher floral diversity than cropland-dominated landscapes in United States dryland systems.

Ding et al. (2022) assessed probable extirpation of the hog deer from Chinese steppe regions, attributing local extinction to habitat loss through conversion of floodplain grasslands to rice cultivation. Ramírez and Säumel (2023) used betadiversity analysis to demonstrate that land use change in South American grasslands drove replacement of grassland specialist communities by generalist species. Pavlacky et al. (2022) applied remote sensing and field data to evaluate the effectiveness of United States grassland conservation programmes for migratory shorebirds.

3.7 Theme 3: Protected area effectiveness

Gameiro et al. (2020) found mixed effectiveness of European Natura 2000 special protection areas for steppe birds in Portugal, with some species recovering within protected zones while others continued declining due to inadequate internal management. Abedin et al. (2024) modelled the distribution of a globally threatened steppe bird in South Korea and identified critical gaps in the protected area network relative to the species' habitat requirements. Frenzel et al. (2025) demonstrated that higher bee species richness in German grassland-cropland mosaics was associated with the proximity and area of semi-natural habitats within 500 m, supporting landscape-scale conservation. Schwaiger et al. (2022) documented pronounced species turnover without net species loss in Austrian grasslands over 30 years, attributing change to management intensification within and outside protected areas.

Barros et al. (2023) evaluated community structure and conservation value of steppe bird assemblages in Ecuadorian grasslands, finding that traditionally managed grasslands supported higher diversity than intensively managed sites. Rodrigues et al. (2025) applied machine learning to Cerrado grassland land cover mapping in Brazil, improving precision of habitat change detection for conservation planning. Ghasemi et al. (2025) modelled ecosystem services in French Mediterranean grasslands, finding significant co-benefits for biodiversity and carbon storage from agricultural extensification policies. Richiardi et al. (2025) used remote sensing combined with long-term monitoring in Italian Natura 2000 grasslands to document progressive shrub encroachment despite protected status. Uvaieva et al. (2025) assessed the impact of military operations on natural vegetation in Ukrainian steppe using remote sensing, documenting widespread destruction of steppe plant communities. Hawkes et al. (2025) found that coordinated agri-environment scheme management at landscape scales significantly improved farmland bird outcomes in United Kingdom grasslands. Nunes et al. (2021) identified spatial mismatches between conservation area networks and grassland-dependent bird species ranges in the United States, highlighting the need for dynamic protected area planning. Smit et al. (2024) demonstrated that South African protected area boundaries were largely effective in preventing conversion but less effective in controlling internal shrub encroachment.

3.8 Theme 4: Ecological restoration

Dutta and Jhala (2021) investigated habitat requirements of the critically endangered great Indian bustard, providing detailed data essential for restoration site selection. Watkinson et al. (2025) demonstrated that greater sage-grouse habitat restoration through targeted native grass seeding in Canadian steppe significantly improved vegetation structural complexity within two growing seasons. Nascimento et al. (2025) evaluated the effectiveness of targeted habitat restoration for a threatened grassland raptor in South America, showing that vegetation structure restoration was the most important

intervention. Narváez-Torres et al. (2025) assessed grassland restoration outcomes across Madagascar and other island steppe systems, identifying vegetation connectivity as the key metric for restoration success. Paterson et al. (2024) applied species distribution modelling combined with remote sensing to predict effects of targeted grassland restoration on a threatened shorebird in Canadian prairies. Luo et al. (2025) demonstrated that combined climate and land use change effects on North American grassland plant communities exceeded the impacts of either driver alone, with strong implications for climate-adaptive restoration design. Chenot-Lescure et al. (2022) compared multiple artificial seed sources for grassland restoration in Mediterranean France, identifying locally sourced seed mixes as most effective and cautioning against use of commercial non-local provenance mixtures.

3.9 Theme 5: Climate change responses

Ambrósio et al. (2024) modelled global sustainability scenarios and found that steppe and dryland systems were among the most sensitive to climate-driven habitat change. Parengal et al. (2025) documented distribution shifts and habitat contractions in an endangered grassland bird in India linked to temperature and precipitation trends over three decades. Gao et al. (2025) projected substantial climate-driven redistribution of steppe bird species in Inner Mongolia, with implications for the adequacy of existing protected area networks. Ogan et al. (2022) used long-term resurvey data from German grasslands to demonstrate pronounced species turnover linked to climate warming, with thermophilous species expanding at the expense of cold-adapted specialists.

3.10 Theme 6: Species distribution and community ecology

The largest thematic cluster (n = 26) comprised studies examining species distributions, community composition, and ecological interactions in steppe and grassland systems. Mills et al. (2023) quantified avian biodiversity responses to habitat heterogeneity across Brazilian grasslands. Han et al. (2025) examined niche overlap between two sympatric steppe raptor species in China, providing evidence for competitive exclusion as a driver of local distribution. Germain et al. (2025) investigated geomorphic impacts of fossorial mammals in Canadian steppe, revealing important roles of burrowing species in soil turnover and vegetation patchiness. Menezes et al. (2025) assessed distribution and conservation status of endemic Cactaceae in Brazilian pampa grasslands, identifying in situ conservation priorities. Bernath-Plaisted et al. (2025) applied long-term monitoring to assess population trends for migratory grassland birds across United States steppe regions, finding significant declines in species dependent on native grassland structure. Rosas et al. (2021) characterised plant community composition across Argentine steppe using field surveys combined with remote sensing. Pretorius et al. (2023) demonstrated that preservation of large tracts of natural grassland in South Africa promoted significantly higher mammal diversity and biomass compared to smaller fragments.

Dubyna et al. (2023) documented plant community changes in Ukrainian steppe associated with management abandonment, showing progressive decline in steppe specialists and expansion of ruderal generalists. Jhala et al. (2021) modelled feasibility of reintroducing grassland megaherbivores in Indian steppe, identifying suitable areas currently outside the protected area network. Medina et al. (2021) demonstrated that burrowing mammal communities in Argentine pampas were strong predictors of plant community composition. Achury et al. (2025) showed that semi-natural habitat area within landscapes was the strongest determinant of arthropod species richness in Swiss grasslands. Gazoulis et al. (2022) quantified displacement of native grassland species by invasive *Ailanthus altissima* in Slovenian steppe margins. Tang et al. (2025) showed that climatic seasonality shaped insect community composition across Chinese steppe, with precipitation variability driving annual arthropod turnover. Rija (2022) demonstrated that local habitat characteristics, particularly vegetation density and flowering plant diversity, were stronger predictors of butterfly richness than landscape context in Tanzanian grasslands.

Meißner et al. (2025) applied genomic approaches to elucidate population structure of a threatened large mammal in South African grasslands, providing data for translocation planning. Muñoz-Reinoso

(2023) tracked directional vegetation transitions in Spanish grassland systems, demonstrating replacement of steppe grass communities by scrub under reduced grazing pressure. Jahan et al. (2022) identified grass height and litter depth as the most critical microhabitat parameters for grassland bird nest site selection in Thai savanna-grassland mosaics. Lu et al. (2022) revealed significant vegetation degradation hotspots in Chinese semi-arid steppe using multi-temporal satellite imagery. Fowler et al. (2024) demonstrated that grassland patch size and connectivity were stronger predictors of bird occurrence than local vegetation characteristics in United States steppe systems. Crispim-Mendes et al. (2024) projected habitat requirements for a threatened steppe bird in Portugal under multiple land use and climate scenarios, identifying critical conservation areas outside the existing protected area network. Meschini et al. (2024) demonstrated strong associations between breeding site selection and extensive cereal farming practices for a declining migratory grassland bird in Italian steppe. Anderle et al. (2024) found that targeted agri-environment measures significantly outperformed general extensification payments for maintaining multi-species grassland bird assemblages in Alpine foothills of Italy.

Lee et al. (2023) identified fire management as the key conservation intervention for a threatened grassland ant in Hong Kong shrub-grassland mosaics, using remotely sensed habitat suitability modelling. He et al. (2025) developed a scalable framework for large-scale analysis of ecosystem integrity in Chinese steppe using multi-source remote sensing data. Schöpke et al. (2024) demonstrated that semi-natural grassland strips significantly enhanced local plant diversity even under intensive farming regimes in German agricultural landscapes.

4 Discussion

This systematic review synthesises empirical evidence from 65 studies and provides a comprehensive overview of the current state of knowledge on biodiversity loss and conservation in steppe ecosystems. Several cross-cutting findings emerge from this synthesis.

The accelerating trajectory of publication output, culminating in 26 articles in 2025 alone, reflects growing scientific and policy recognition of the conservation crisis facing temperate grasslands. The adoption of the Kunming-Montreal Global Biodiversity Framework in 2022 has catalysed substantial new research examining the adequacy of existing protected area networks and the most effective strategies for expanding conservation coverage in grassland biomes. This momentum is encouraging, yet the absolute volume of research on steppe ecosystems remains far below that dedicated to forest systems, highlighting a persistent imbalance in conservation attention.

The geographic concentration of research in North America and Western Europe (Figure 2) reflects longstanding structural inequalities in global research investment. This is particularly consequential given that Kazakhstan alone harbours approximately 100 million hectares of steppe, representing the largest remaining block of near-natural temperate grassland on Earth, yet no empirical open-access studies from the region met inclusion criteria in this review. Addressing this gap requires sustained international investment in research infrastructure, open-access publication support, and collaborative programmes linking Central Asian scientists with international research networks.

The dominance of observational field studies and remote sensing approaches reflects the practical constraints of steppe research across large, often remote landscapes. However, the relative scarcity of manipulative field experiments limits causal inference regarding conservation intervention effectiveness. The experimental studies identified here (Segrestin et al., 2025; Watkinson et al., 2025; Nascimento et al., 2025; Chenot-Lescure et al., 2022) demonstrate the feasibility and scientific value of randomised management experiments in steppe systems. Long-term monitoring programmes (Bernath-Plaisted et al., 2025; Ogan et al., 2022; Richiardi et al., 2025; Deutsch et al., 2024) provide essential temporal context but require sustained institutional commitment.

The finding that protected areas frequently fail to fully protect steppe biodiversity, documented across multiple continents (Gameiro et al., 2020; Schwaiger et al., 2022; Richiardi et al., 2025; Smit et al., 2024), points to the need for landscape-scale conservation approaches. Agri-environment schemes (Lakner et al.,

2020; Anderle et al., 2024; Hawkes et al., 2025), payments for ecosystem services (Stoudmann et al., 2024; Ghasemi et al., 2025), and collaborative agreements with private landowners provide consistent empirical support for complementary conservation tools when accompanied by appropriate monitoring and adaptive management.

Climate change emerges as a cross-cutting threat interacting with land use pressures to produce compound effects on steppe biodiversity (Ambrósio et al., 2024; Parengal et al., 2025; Gao et al., 2025; Ogan et al., 2022). Climate-adaptive conservation strategies, including dynamic protected area planning and climate-informed restoration site selection (Paterson et al., 2024; Luo et al., 2025), are urgently needed to maintain the long-term viability of steppe conservation investments.

5 Conclusion

This systematic bibliometric review synthesises empirical evidence from 65 peer-reviewed studies published between 2020 and 2025 on biodiversity loss and conservation strategies in steppe and grassland ecosystems worldwide. The analysis reveals a rapidly accelerating research output, a geographic concentration in North America and Western Europe, and a persistent underrepresentation of Central Asian steppe systems despite their global ecological significance. Together, these findings point to both the progress and the limitations of the current international conservation research landscape.

The five thematic clusters identified — grazing impacts, habitat fragmentation, protected area effectiveness, ecological restoration, and climate change responses — reflect the principal drivers and management levers currently documented in empirical literature. The consistent finding that protected areas alone are insufficient to halt biodiversity decline, observed across multiple continents, underscores the need for landscape-scale approaches that integrate agri-environment schemes, payments for ecosystem services, and collaborative governance with private landowners. Experimental restoration studies demonstrate that targeted interventions, including native seed mixes and managed grazing regimes, can produce measurable ecological recovery within short timeframes.

A critical gap identified by this review is the near-total absence of open-access empirical research from Kazakhstan and Central Asia in internationally indexed databases, despite the region harbouring the largest contiguous block of near-natural temperate grassland on Earth. Addressing this gap requires sustained investment in research infrastructure, capacity building, and open-access publication support for scientists working in the region. Future research priorities include long-term experimental studies on restoration effectiveness, dynamic conservation planning under climate change scenarios, and the development of region-specific biodiversity monitoring frameworks aligned with the Kunming-Montreal Global Biodiversity Framework targets.

Author contributions statement:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Zhuldyz Zhanassova	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

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