

DOMINANT ENVIRONMENTAL FACTORS SHAPING PLANT DIVERSITY IN THE WESTERN TIEN SHAN TRANSBOUNDARY REGION

Feruz Akbarov*, PhD; **Sardor Po'latov**, PhD; **Ulug'bek Qodirov**, PhD
*Institute of Botany, Academy of Sciences of the Republic of Uzbekistan, Tashkent,
Uzbekistan*

*Corresponding author: **Feruz Akbarov**
(feruzakbar88@gmail.com)

Abstract: *The Western Tien Shan transboundary region is one of the important floristic centers of Central Asia and is distinguished by high environmental heterogeneity and endemism. The aim of this study was to evaluate the relative effects of climatic, edaphic, and topographic factors shaping plant diversity in the region and to identify the dominant ecological drivers. Based on approximately 18,000 herbarium records and 5 × 5 km grid data, Principal Component Analysis (PCA) and Z-score standardization approaches were applied. The results showed that the ecological gradients identified by PCA were mainly structured by terrain complexity and the elevation–temperature axis. Z-score analysis confirmed that topographic factors, particularly elevation and slope gradients, were the dominant ecological drivers across most of the region. While climatic factors defined the broad-scale ecological background, soil factors acted as strong modulators in certain local zones. The obtained results demonstrate that the spatial structure of the Western Tien Shan flora has a multi-factor and mosaic character, providing an important scientific basis for biodiversity monitoring, identification of ecological hotspots, and the designation of priority conservation areas.*

Keywords: *Western Tien Shan, plant diversity, topographic gradient, PCA, Z-score, ecological drivers, hotspots*

Introduction

In recent decades, biodiversity loss has become one of the pressing challenges of global ecology. Climate change, anthropogenic pressure, and unsustainable use of land resources are exerting significant effects on plant diversity (IPCC, 2021). Plant distribution is shaped through the complex interaction of climatic, edaphic, and topographic factors, in which temperature and precipitation act as major ecological drivers at broad scales, whereas terrain complexity, elevation gradients, and soil properties emerge as the principal drivers at local scales (Guisan & Zimmermann, 2000; Hawkins et al., 2003; Stein et al., 2014). In mountain regions, elevation and slope gradients increase ecological niche diversity and play an important role in the spatial distribution of species richness (Körner, 2007).

Multivariate approaches such as Principal Component Analysis (PCA) and Z-score standardization are effective tools for identifying ecological gradients and assessing dominant factors (Jolliffe & Cadima, 2016; Aguirre-Gutiérrez et al., 2022). At the same time, in studies

based on herbarium data, sampling effort represents a source of spatial bias and may modulate the species richness signal more strongly than ecological factors themselves (Beck et al., 2014; Meyer et al., 2016). Therefore, controlling observation intensity is considered an important methodological requirement in ecological analyses.

The Western Tien Shan transboundary region is one of the important floristic centers of Central Asia and is distinguished by high environmental heterogeneity and endemism. The aim of this study was to evaluate the relative effects of climatic, edaphic, and topographic factors shaping plant diversity in this region and to identify the dominant ecological drivers.

2. Materials and Methods

2.1 Floristic data and sampling effort

This study used approximately 18,000 herbarium records collected from the Western Tien Shan transboundary region. All data were initially standardized, taxonomic names were unified, coordinates were converted into numeric format, and the records were assigned to 5 × 5 km grid cells through a spatial join procedure. For each grid cell, species richness (n_{species}), sampling effort based on the number of records (n_{occ}), and spatial coverage (n_{cells}) were calculated. To control for observation intensity, n_{occ} values were transformed as $\log(n_{\text{occ}} + 1)$ and used as a covariate in subsequent analyses (Fithian et al., 2012; Yang et al., 2013).

2.2 Environmental factors and collinearity assessment

Climatic (BIO1–BIO19, WorldClim), topographic (Elevation, slope classes), and edaphic (AWCh1, CECSOL, CRFVOL, SoilGrids) raster layers were used as environmental predictors. Raster values were extracted at herbarium occurrence points, and mean values were calculated for multiple records falling within the same grid cell. Relationships among predictors were evaluated using Pearson correlation, while collinearity was assessed using the Variance Inflation Factor (VIF) (Fig. 1). Variables with $VIF < 5$ were retained for the final analysis (Dormann et al., 2013).

2.3 Assessment of the nonlinear effects of environmental factors on species richness

To identify ecological gradients, Principal Component Analysis (PCA) was applied, while Z-score standardization was used to compare the relative effects of dominant ecological drivers (Aguirre-Gutiérrez et al., 2022; Werden et al., 2018). Nonlinear relationships between species richness and environmental factors were modeled using a Generalized Additive Model (GAM) based on the Negative Binomial family. Sampling effort was included in the model as a covariate, and the results were evaluated using adjusted R^2 , edf, and p-values.

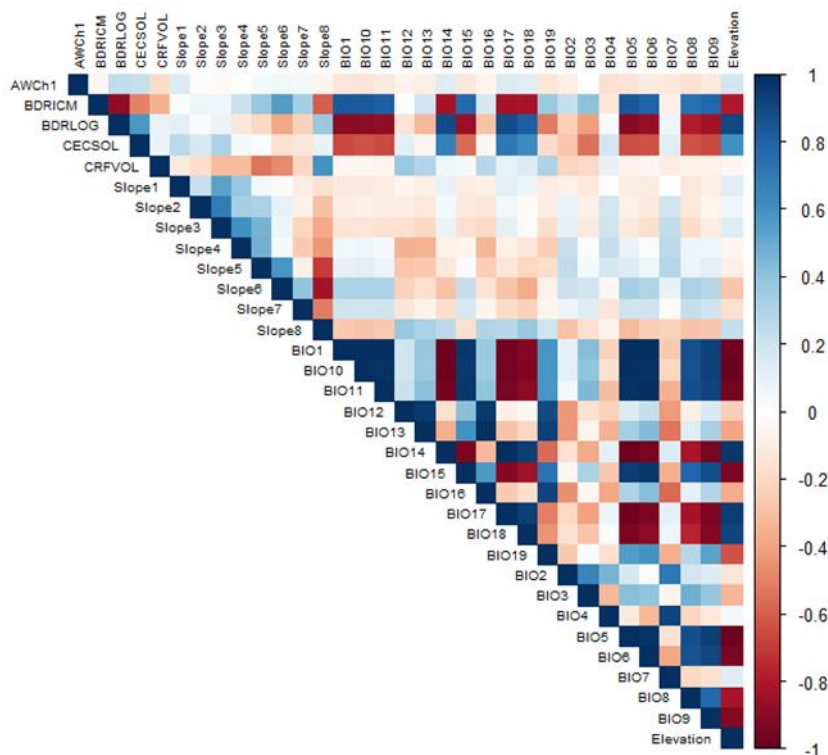


Fig.1. Pearson correlation coefficients among the climatic, edaphic, and topographic factors applied in the Western Tien Shan transboundary region.

3. Results

3.1 PCA results at the grid-cell level

Principal Component Analysis (PCA) was performed to identify the main ecological gradients among environmental factors at the 5 × 5 km grid-cell level. According to the results, the first two principal components explained 47.7% of the total variance (PC1 = 25.6%, PC2 = 22.1%) (Fig. 2).

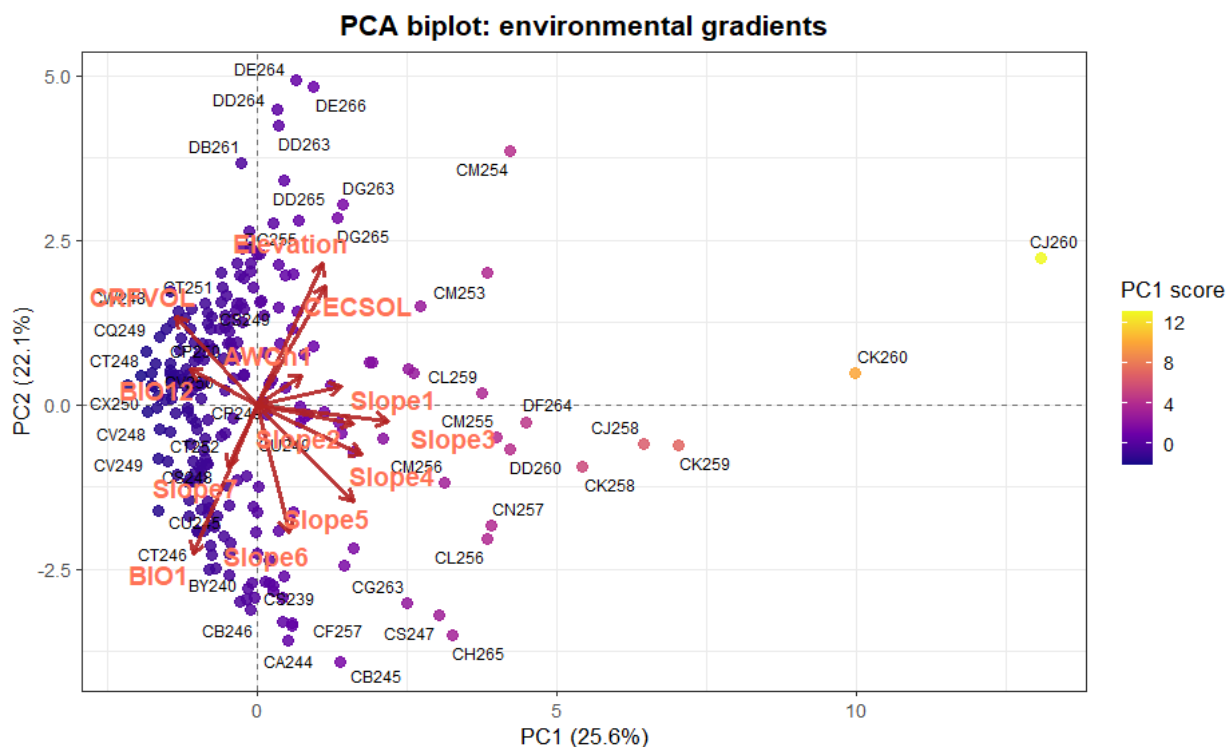


Fig. 2. PCA results at the grid-cell level.

PC1 mainly represented the terrain and topographic complexity gradient. Along this component, Slope3 (0.456), Slope4 (0.367), Slope2 (0.336), Slope5 (0.336), and Slope1 (0.296) showed high positive loadings. At the same time, the negative loadings of CRFVOL (−0.282), BIO1 (−0.224), and BIO12 (−0.233) indicated the contrasting influence of climatic factors along PC1. This suggests the presence of ecological contrasts related to temperature and precipitation regimes under complex terrain conditions. PC2 mainly reflected the elevation–temperature gradient. Elevation (0.450) and CECSOL (0.379) had positive loadings on PC2, whereas BIO1 (−0.474) and Slope6 (−0.403) were represented by negative loadings. This result indicates changes in edaphic conditions through soil cation exchange capacity (CECSOL), together with decreasing temperature as elevation increases in mountain regions. The distribution of grid cells in the PC space showed clear ecological differentiation among areas. Some grid cells with high PC1 values (CK260, CJ260) were characterized by steep terrain and relatively extreme ecological conditions, whereas high values along PC2 corresponded to high-mountain areas.

3.2 Type and effect strength of dominant ecological drivers

Based on the Z-score approach, dominant ecological drivers (Climate, Soil, Topography) and their effect strength ($|Z|$) were assessed at the 5 × 5 km grid-cell level (Fig. 3).

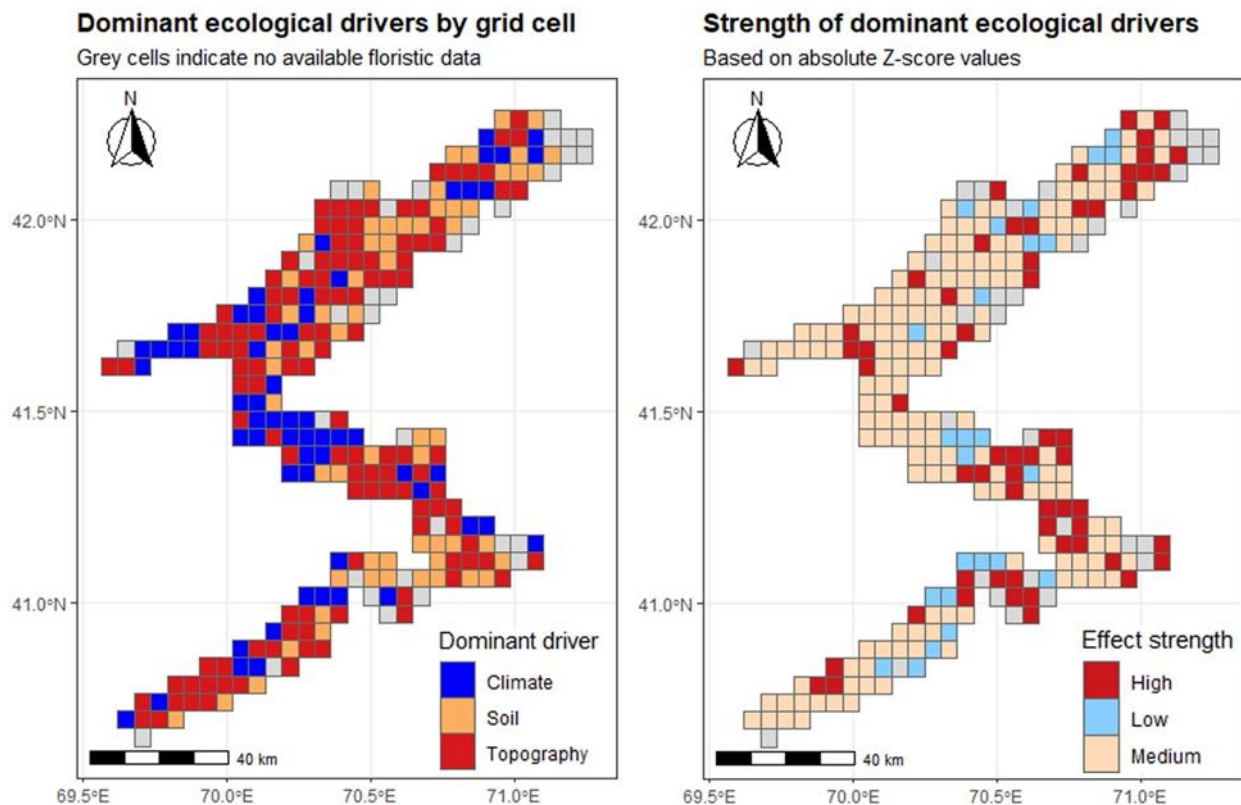


Fig. 3. Type and effect strength of dominant ecological drivers (Z-score).

According to the results, floristic data were available for 239 out of 272 grid cells, while 33 cells (12.1%) were classified as No data (gray) due to insufficient information. In terms of the distribution of dominant drivers, topographic drivers were predominant in 119 grid cells

(43.8%). Climatic and soil drivers had equal shares, each recorded in 60 cells (22.1%). This result indicates that terrain-related factors (elevation and slope classes) are more strongly expressed at the spatial scale in shaping species richness across the region, whereas climatic and soil factors tend to dominate in a more local and mosaic manner.

In terms of effect strength, the majority of grid cells belonged to the Medium class, comprising 154 cells (56.6%), indicating that ecological gradients are mainly expressed at moderate intensity throughout the region. Grid cells with High effect strength accounted for 60 cells (22.1%), representing areas with strong ecological contrasts, such as transition zones or limiting environments. The Low class included 25 cells (9.2%) and corresponded to zones with relatively homogeneous ecological conditions. The 33 cells lacking sufficient data (12.1%) were also not classified by effect strength. Together, the dominant driver map and the effect strength map demonstrate the mosaic and hierarchical character of the regional ecological structure: although terrain factors dominate in a greater number of cells, the effect strength is moderate across most areas, while strong ecological contrasts are concentrated within relatively limited zones.

3.3 Effect strength of dominant ecological drivers

Based on the Z-score approach, the effect strength and direction of dominant ecological drivers were also assessed at the 5 × 5 km grid-cell level (Fig. 4). According to the results, grid cells with moderate (Medium) effect strength were predominant, accounting for 65.0% of all cells. Within this class, positive-direction effects were dominant and were recorded in 95 grid cells (40.1%), whereas negative-direction effects were identified in 59 grid cells (24.9%). Grid cells with high effect strength were relatively fewer, and the majority of them were expressed in the positive direction (57 grid cells; 24.1%), whereas the negative direction was observed at a very limited scale (1 grid cell; 0.4%). Grid cells with low effect strength accounted for a small proportion. Within this class, no significant difference was observed between negative (15 cells; 6.3%) and positive (10 cells; 4.2%) directional effects. These results indicate that the influence of ecological drivers on species richness across the region is expressed mainly in a positive direction and at moderate intensity. At the same time, the very rare occurrence of high-intensity negative effects suggests that ecologically limiting conditions are not sharply distributed across the region but rather have a local and fragmented character.

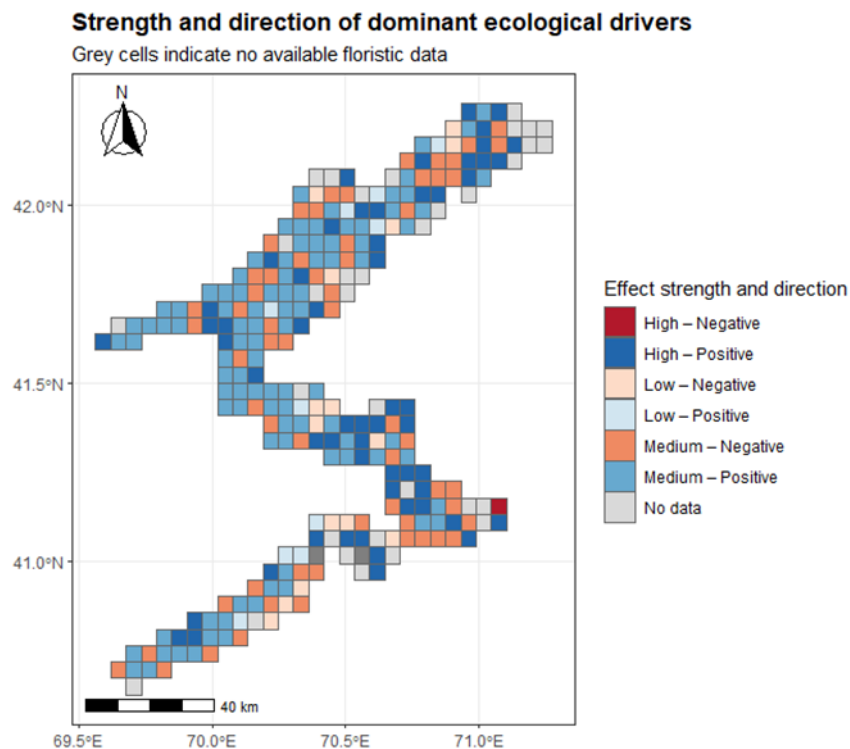


Fig. 4. Effect strength of dominant ecological drivers.

3.4 Type and direction of dominant ecological factors

Based on the Z-score approach, the type, effect strength, and direction of dominant ecological factors were jointly assessed at the 5 × 5 km grid-cell level (Fig. 5). According to the results, topographic factors were predominant among the combined classes, with topographic factors showing moderate positive effect strength representing the largest share (48 grid cells; 17.6%). In addition, topographic factors with high positive effects also accounted for a considerable proportion (33 cells; 12.1%), indicating that terrain-related factors are important ecological drivers in the region.

Climatic factors were mainly characterized by a moderate positive effect (32 grid cells; 11.8%), indicating that they play a more supportive ecological role across the region. Although soil factors were dominant in fewer cells, they stood out with high positive effect strength in certain areas (24 cells; 8.8%), demonstrating that edaphic conditions provide a strong ecological signal at the local scale. Combinations with low effect strength and extreme classes (High–Negative or Low–Positive) represented only a very small proportion of the total number of grid cells, indicating that the regional ecological structure is mainly shaped by ecological gradients of moderate intensity. Grid cells without available floristic data accounted for 12.9% of the total indices and were marked separately on the maps.

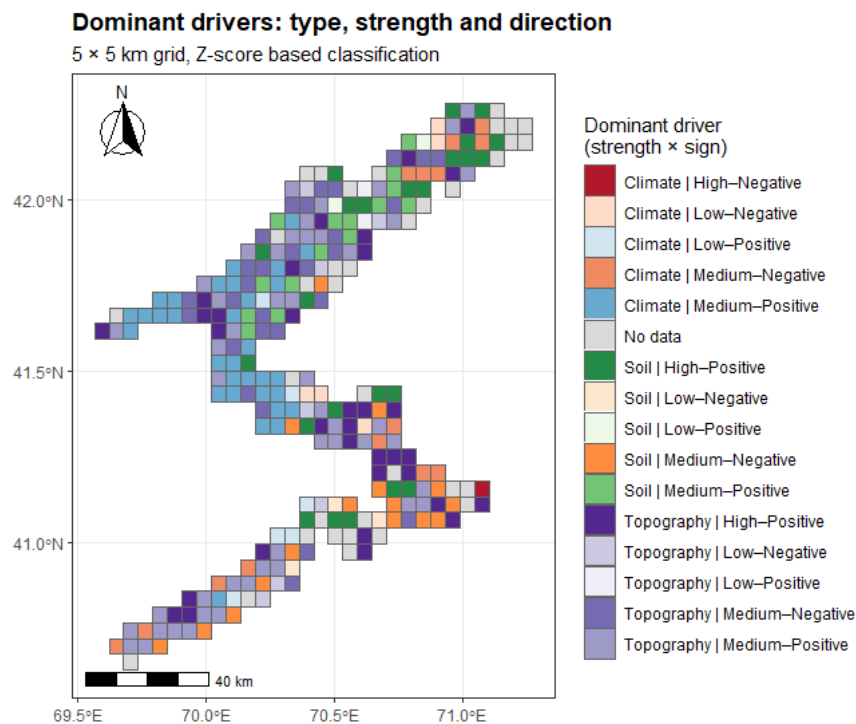


Fig. 5. Type, effect strength, and direction of dominant ecological factors.

4. Discussion

The PCA and Z-score results showed that the ecological factors shaping plant diversity in the Western Tien Shan transboundary region have a hierarchical and spatially mosaic character. The predominance of slope variables in the first PCA component confirms that the heterogeneity of terrain microstructure acts as an important ecological filter for plants. The contrasting loadings of elevation and BIO1 in the second component reflected the classical elevation–temperature gradient typical of mountain regions, while the significant loading of CECSOL indicated that edaphic factors possess an independent ecological signal.

The Z-score analysis confirmed that topographic factors are the dominant ecological drivers across most of the region. This indicates that elevation and slope gradients function as the principal spatial filters shaping floristic structure in the Western Tien Shan. While climatic factors mainly defined the ecological background at the regional scale, soil factors acted as strong modulators in certain local zones. The concentration of grid cells with high effect strength in ecological transition zones indicates that floristic contrasts are particularly strong in these areas.

The consistency between PCA and Z-score results demonstrates that the regional flora is not controlled by a single dominant factor, but rather by the interaction of climatic and edaphic factors within an ecological space structured by terrain. Therefore, the Western Tien Shan flora can be characterized as a spatially mosaic and multi-factor ecological system.

Conclusion

This study showed that the ecological factors shaping plant diversity in the Western Tien Shan transboundary region have a multi-level, hierarchical, and spatially mosaic character. The PCA and Z-score results confirmed that topographic factors, particularly

elevation and slope gradients, act as the dominant ecological drivers across most of the region. While climatic factors mainly defined the broad-scale ecological background, soil factors were identified as strong modulators of floristic differentiation in certain local zones.

The spatial structure of the Western Tien Shan flora is governed by the interaction of climatic and edaphic factors within an ecological space shaped by terrain. The obtained results provide an important scientific basis for biodiversity monitoring, identification of ecological hotspots, and the designation of priority conservation areas in the region.

Acknowledgements

This research was carried out within the framework of the State Program of the Institute of Botany, Academy of Sciences of the Republic of Uzbekistan, entitled “Digital Nature: Development of a Digital Platform for the Flora of Central Uzbekistan” (2025–2029).

The study was also supported by the fundamental research projects “Taxonomic revision of polymorphic families in the flora of Uzbekistan” (A-FA-2021-427) and “Transboundary biodiversity hotspots of Uzbekistan and their current status” (FL-9024093685), as well as applied projects “Bioclimatic and geospatial analysis of medicinal plant resources of the Republic, patterns of adaptation and distribution (on the example of the genus *Ferula* L.)” (FL-9524115063) and “Preparation of the first Uzbek-language edition of the Flora of Uzbekistan” (AL-9224104450).

REFERENCES:

1. Aguirre-Gutiérrez J. et al. Functional susceptibility of tropical forests to climate change // *Nature Ecology & Evolution*. – 2022. – T. 6. – №. 7. – С. 878-889.
2. Beck J. et al. Spatial bias in the GBIF database and its effect on modeling species' geographic distributions // *Ecological Informatics*. – 2014. – T. 19. – С. 10-15.
3. Dormann C. F. et al. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance // *Ecography*. – 2013. – T. 36. – №. 1. – С. 27-46.
4. Fithian W., Hastie T. Finite-sample equivalence in statistical models for presence-only data // *The annals of applied statistics*. – 2012. – T. 7. – №. 4. – С. 1917.
5. Guisan A., Zimmermann N. E. Predictive habitat distribution models in ecology // *Ecological modelling*. – 2000. – T. 135. – №. 2-3. – С. 147-186.
6. Hawkins, B. A., et al. Energy, water, and broad-scale geographic patterns of species richness // *Ecology*. – 2003. – T. 84. – №. 12. – С. 3105-3117.
7. Jolliffe I. T., Cadima J. Principal component analysis: a review and recent developments // *Philosophical transactions of the royal society A: Mathematical, Physical and Engineering Sciences*. – 2016. – T. 374. – №. 2065. – С. 20150202.
8. Körner C. The use of 'altitude' in ecological research // *Trends in ecology & evolution*. – 2007. – T. 22. – №. 11. – С. 569-574.

9. Legg S. IPCC, 2021: Climate change 2021-the physical science basis //Interaction. – 2021. – Т. 49. – №. 4. – С. 44-45.
10. Meyer C., Weigelt P., Kreft H. Multidimensional biases, gaps and uncertainties in global plant occurrence information //Ecology letters. – 2016. – Т. 19. – №. 8. – С. 992-1006.
11. Stein A., Gerstner K., Kreft H. Environmental heterogeneity as a universal driver of species richness across taxa, biomes and spatial scales //Ecology letters. – 2014. – Т. 17. – №. 7. – С. 866-880.
12. Werden L. K., Becknell J. M., Powers J. S. Edaphic factors, successional status and functional traits drive habitat associations of trees in naturally regenerating tropical dry forests //Functional Ecology. – 2018. – Т. 32. – №. 12. – С. 2766-2776.
13. Yang W., Ma K., Kreft H. Geographical sampling bias in a large distributional database and its effects on species richness–environment models //Journal of Biogeography. – 2013. – Т. 40. – №. 8. – С. 1415-1426.