DOI: https://doi.org/10.17308/geo.2020.1/2655 ***ISSN 1609-0683***

Prediction of Rare Species Abundance and Distribution on the Basis of Landscape Features, Lipetsk Region Case

D.V. Sarychev[1]✉, J.Vila-Subiros[2], X. Garcia[3], S.A. Kurolap[1]

[1]Voronezh State University, Russian Federation (Universitetskaya pl., Voronezh, 394018)
[2]University of Girona, Spain (Pl. Sant Domenec, Girona, 317004)
[3]Institute of Regional and Metropolitan Studies of Barcelona, Spain
(Cerdanyola del Valles, Campus UAB, Barcelona, 08193)

Received: 20.01.2020
Accepted: 26.02.2020

Abstract: The *objective* of this study is to identify landscape drivers of rare species' distribution, and to predict their abundance in the Lipetsk Region (Russia). *Methods:* we input locations of 1,165 nesting sites of 60 bird species into GIS and applied fishnet analysis with a cell size of 100 km^2. For each of the 220 cells in the region, we computed the number of nesting sites and 13 landscape metrics using cartographic and remote sensing data. We explored interrelation among these variables with Principal Component Analysis (PCA) and Geographically Weighted Poisson Regression (GWPR). *Results:* The PCA grouped landscape metrics into five factors, which explained 84% of the variability and highlighted the four most significant and independent variables (mean altitude, number of water bodies, forest cover, and area of settlements) among those tested. The GWPR model based on these variables explained 68% of variance and simulated bird species abundance across the cells. Comparison of observed and predicted values per cell highlighted under-surveyed areas and biodiversity hotspots. *Conclusions:* We revealed species distribution patterns and their landscape drivers. Additionally, our findings identified target areas of primary conservation attention and provided local wildlife agencies with information and tools for biodiversity monitoring and conservation planning.

Key words: species distribution modeling, landscape metrics, geographically weighted regression, GWR, conservation planning, GIS.

Acknowledgments: we are greateful to all experts who supported us with data on the rare bird species nesting in Lipetsk Region. The reported study was funded by RFBR according to the research projects №18-35-00532 and №19-45-360005.

УДК 591.9+519.876.5

Прогнозирование распространения и численности редких видов по параметрам ландшафта (на примере авифауны в Липецкой области)

Д.В. Сарычев[1]✉, Дж.С. Била[2], Ч.Г. Акоста[3], С.А. Куролап[1]

Аннотация: *Цель* работы заключалась в прогнозировании численности редких видов на основе ландшафтных факторов их распространения. *Методы.* Прогнозное моделирование выполнено на примере всех гнездящихся видов авифауны в Липецкой области, внесенных в Красную книгу региона. Установлено 60 таких видов птиц, координаты 1165 их гнездовых участков мы внесли в ГИС и проанализировали по регулярной сети квадратов 10 х 10 км в рамках исследуемой территории. Для каждого из 220 полученных квадратов вычисляли количество гнездовых участков редких видов, а также 13 характеристик ландшафта – на основе карт и данных дистанционного зондирования. Полученный массив переменных анализировали с помощью метода главных компонент (ГК) и географически взвешенной

✉ E-mail: sarychev.geo@gmail.com

Пуассоновской регрессии (ГВПР). *Результаты.* ГК объединили исследуемые переменные в пять факторов, отражающие 84 % дисперсии, из которых выделены наиболее статистически значимые для предпринятого моделирования предикторы: средняя высота местности, количество водоемов, лесистость и доля площади населенных пунктов на квадрат. Построенная на их основе ГВПР, отразила 68 % варьирования данных и позволила спрогнозировать численность редких видов птиц для слабо обследованных районов. Сравнение прогнозной и учтенной численности по квадратам позволило установить территории высокой природоохранной ценности и перспективные территории для дополнительных орнитологических обследований. *Выводы:* мы установили факторы размещения редких видов птиц и выполнили пространственный прогноз их численности для Липецкой области. Результаты исследования необходимы для мониторинга биоразнообразия и природоохранного планирования в регионе.

Ключевые слова: авифауна, редкие виды, прогноз численности, мониторинг биоразнообразия, ГИС, географически взвешенная регрессия.

Благодарности: авторы выражают глубокую признательность всем специалистам, оказавшим помощь в сборе данных о гнездовании редких видов птиц в Липецкой области. Исследование выполнено при финансовой поддержке РФФИ в рамках научных проектов № 18-35-00532 и № 19-45-360005.

INTRODUCTION

Predicting the distribution of species on the basis of formalized landscape characteristics allow us to preliminary evaluate the effects of a planned human activity on the biodiversity of a given area. Such predictions are especially important in relation to endangered species and have great potential for wildlife conservation research, and human impact assessments [3].

By using field observations, GIS-modelling, and basic statistics for studying patterns of rare avifauna species' distribution in the Lipetsk Region [12, 13], this paper's authors have provided a solid background for further predictive research with new techniques.

Geographically Weighted Regressions have been recently introduced to ecological research in Russia [14] and applied in a few studies of plant and mammal distribution modeling [9, 10, 15]. Zhihai Ma, et al. has previously shown that richness in bird species in relation to landcover diversity can be successfully investigated with spatial Poisson models and particularly with Geographically Weighted Poisson Regression (GWPR) models [7].

In this paper we combine GWPR and Principal Component Analysis (PCA) in order to identify landscape drivers of species' distribution and predict the abundance of rare bird species in under-surveyed areas of the Lipetsk Region.

MATERIALS AND METHODS

The study area, the Lipetsk Region (*Lipetskaya Oblast*), is an agricultural region of approximately 24,000 sq. km, located in forest-steppe of Central Russia (fig. 1).

We used the class Aves as a model taxon because of its high mobility and indicator properties, conservation importance, and sufficient level of surveying in the study area. The primary subject of this study is abundance of 60 nesting bird species enlisted in the regional Red Data Book [11]. We collected 1,165 records on the nesting sites of those species in the region (both from the literature and our own observations) surveyed from 1985 to 2016, and put all related information into a special geodatabase managed with SpatialLite for QGIS 2.18 (summary on the records is provided in table 1) [13].

To that data, we applied fishnet analysis with 10 km x 10 km cells that we laid out in the grid of the European Breeding Birds Atlas [6, 13]. A number of nesting sites was calculated for each of the corresponding 220 cells. Then, terrain characteristics (altitude maximum, minimum, mean, and range) were obtained for the cells using SRTM data (http://srtm.csi.cgiar.org). Characteristics of hydrography (number and total area of bodies of water and lengths of rivers and streams), vegetation (coverage, number, and perimeters of forests), and human impact (number and total area of settlements and lengths of roads) were calculated using vectorized topographical maps of a 1:100 000 scale.

We explored interrelations among the variables of landscapes and the rare bird species abundance with Spearman's rank correlations [13]. To select the most statistically significant and not intercorrelated predictor variables we used the well-established PCA based approach [4, 8]. The set of selected predictors was used in the regression analysis. We applied GWPR as it is one of the most appropriate models for count spatial data [1, 2, 5]. To fit the model and calculate coefficients and performance statistics we used a specialised software “GWR4” version 4.0.9 (https://sgsup.asu.edu/sparc/gwr4).

RESULTS AND DISCUSSION

The Spearman's rank correlation analysis highlighted strongly correlated landscape variables: cover and total perimeter lengths of forests in cells ($r = +0.85$), mean and maximum altitude ($r = +0.93$).

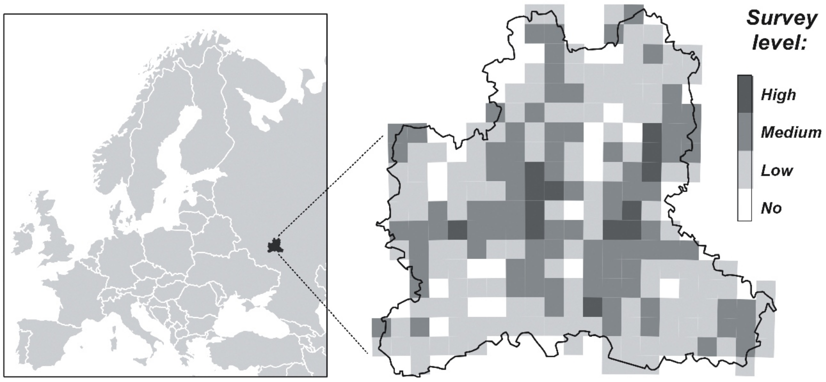

Fig. 1. Location of the Lipetsk Region and its ornythologycal survey level per 10 km x 10 km cells
[*Рис. 1.* Расположение Липецкой области и степень ее орнитологической обследованности по регулярной сети квадратов 10 x 10 км]

Table 1

List of the rare bird species in the Lipetsk Region with quantity of reported nesting sites
[*Таблица 1.* Список редких видов птиц Липецкой области с числом учтенных в регионе гнездовых участков]

No	**Scientific name of a species**	**Nesting sites qty.**
1	2	3
1	*Podiceps ruficollis* (Pallas, 1764)	9
2	*Podiceps auritus* (Linnaues, 1758)	1
3	*Podiceps grisegena* (Boddaert, 1783)	3
4	*Botaurus stellaris* (Linnaues, 1758)	58
5	*Ixobrychus minutus* (Linnaues, 1766)	50
6	*Egretta alba* (Linnaues, 1758)	4
7	*Ardea purpurea* Linnaues, 1766	11
8	*Ciconia ciconia* (Linnaues, 1758)	19
9	*Cygnus olor* (Gmelin, 1789)	17
10	*Anas strepera* Linnaues, 1758	14
11	*Pandion haliaetus* (Linnaues, 1758)	10
12	Pernis apivorus (Linnaeus, 1758)	27
13	*Circus cyaneus* (Linnaues, 1766)	6
14	*Circus macrourus* (S.G. Gmelin, 1771)	5
15	*Buteo rufinus* (Cretzschmar, 1827)	7
16	*Circaetus gallicus* (Gmelin, 1788)	7
17	*Hieraaetus pennatus* (Gmelin, 1788)	34
18	*Aquila clanga* Pallas, 1811	12
19	*Aquila heliaca* Savigny, 1809	4
20	*Haliaeetus albicilla* (Linnaues, 1758)	8
21	*Falco cherrug* Gray, 1834	2
22	*Lyrurus tetrix* (Linnaues, 1758)	7
23	*Grus grus* (Linnaues, 1758)	31
24	*Rallus aquaticus* Linnaues, 1758	17
25	*Porzana parva* (Scop.)	7
26	*Himantopus himantopus* (Linnaues, 1758)	5
27	Haematopus ostralegus Linnaeus, 1758	4
28	*Tringa stagnatilis* (Bechstein, 1803)	22
29	*Xenus cinereus* (Güldenstädt, 1775)	11
30	*Gallinago media* (Latham, 1787)	4
31	*Limosa limosa* (Linnaues, 1758)	31

Table 1 (continued) [Продолжение таблицы 1]

1	2	3
32	*Larus minutus* Pallas, 1776	6
33	*Chlidonias hybrida* (Pallas, 1811)	13
34	Sterna hirundo Linnaeus, 1758	11
35	*Sterna albifrons* Pallas, 1764	4
36	*Columba oenas* Linnaues, 1758	24
37	Bubo bubo (Linnaeus, 1758)	1
38	*Asio flammeus* (Pontoppidan, 1763)	37
39	*Athene noctua* (Scopoli, 1769)	6
40	*Glaucidium passerinum* (Linnaues, 1758)	1
41	*Strix aluco* Linnaues, 1758	35
42	*Caprimulgus europaeus* Linnaues, 1758	16
43	*Upupa epops* Linnaues, 1758	86
44	*Picus canus* Gmelin, 1788	52
45	*Dryocopus martius* (Linnaues, 1758)	71
46	*Dendrocopos medius* (Linnaues, 1758)	43
47	*Dendrocopos leucotos* (Bechstein, 1803)	42
48	*Calandrella cinerea* (Gmelin, 1789)	9
49	*Lullula arborea* (Linnaues, 1758)	44
50	*Lanius minor* Gmelin, 1788	36
51	*Lanius excubitor* Linnaues, 1758	8
52	*Troglodytes troglodytes* (Linnaues, 1758)	14
53	*Locustella naevia* (Boddaert, 1783)	16
54	*Regulus regulus* (Linnaues, 1758)	2
55	*Saxicola torquata* (Linnaues, 1766)	63
56	*Oenanthe isabellina* (Temminck, 1829)	6
57	*Phoenicurus phoenicurus* (Linnaues, 1758)	28
58	*Panurus biarmicus* (Linnaues, 1758)	8
59	*Parus ater* Linnaues, 1758	15
60	*Emberiza calandra* Linnaues, 1758	21
Sum of records in the geodatabase		1165

Such redundant variable couples could lead to multicollinearity in regression models and so, to misleading predictions. Therefore, we left one variable from each couple. The PCA helped to justify variable selection and explore landscape drivers of rare species' distribution.

As a result of using PCA with varimax rotation, the 13 initial variables were grouped into five factors, which all together explained 84 % of the variability (Tab. 2). The number of factors was set according to Kaiser criterion.

Factor 1 explains 27.4 % of variance and expresses terrain conditions in cells. The highest loadings (> 0.7) in the factor included the parameters of relief, particularly mean, maximum and range of altitude. Factor 2 explains 18 % of variance basically supported by parameters of forest coverage: number of fragments, their total area, and lengths of edges. Factor 3 explains 16.2 % of variance and is represented by human impact parameters as total area of settlements and road density in a cell. Factors 4 and 5 each explain about 11 % of variance and are represented by a single parameter: the river density and number of bodies of water, respectively. The river density has a tendency of reduction when the parameter of minimum altitude is increasing across the cells, so, based on that metric, Factor 4 is expressing another feature of relief. At the same time, the number of bodies of water is the premise of Factor 5, which expresses another aspect of human impact because there are mostly artificial water bodies (ponds and reservoirs) in the region.

Overall, the PCA results show that the cells that enclose uplands with well-developed drainage (Factor 1) and have many settlements and roads (Factor 3) have low richness and number of rare bird species. Generally, the opposite results occurs with a combination of large forest fragments with long, complex edges (Factor 2) in broad river valleys with meandering rivers and a plethora of lakes in a cell (Factors 4 and 5).

Table 2

Principal components of environmental variables
[*Таблица 2*. Главные компоненты ландшафтных параметров]

Variables	Principal components				
	1	2	3	4	5
Altitude range (m)	**0.794**	0.385	-0.162	-0.291	-0.209
Maximum altitude (m.a.s.l.)	**0.976**	0.082	0.068	-0.024	-0.011
Mean altitude (m.a.s.l.)	**0.939**	-0.109	0.181	0.143	0.123
Minimum altitude (m.a.s.l.)	0.527	-0.453	0.375	0.409	0.306
Number of forest patches	0.406	**0.718**	-0.014	-0.165	0.272
Forest coverage (%)	-0.424	**0.667**	0.109	0.145	-0.225
Forest edges (m/sq.km)	0.081	**0.961**	0.009	0.031	0.086
Number of settlements	0.473	0.016	0.051	-0.385	0.598
Number of bodies of water	-0.118	0.124	-0.173	0.036	**0.856**
Area of bodies of water (%)	-0.465	0.257	-0.428	0.356	0.119
Area of settlements (%)	-0.137	-0.074	**-0.872**	-0.084	0.184
Road density (km/sq.km)	-0.002	0.017	**-0.951**	0.130	-0.020
River density (m/sq.km)	-0.004	-0.007	0.084	**-0.917**	0.060
Proportion of variance (%)	27.4	18.0	16.2	11.3	11.0
Cumulative proportion (%)	27.4	45.4	61.6	72.9	83.9

In order to build regression models of rare bird species distribution across the cells, we reduced the number of parameters by selecting a single one from each factor. We selected the most correlated parameter with the dependent variable (abundance of the rare bird species nests) among the ones with the highest loadings (> |0.6|) in each factor. The selected parameters were used as a set of independent variables (predictors) in regression modelling. During the model fitting, we left only the predictors with significant coefficients ($p < 0.05$). Thus, the following four predictors were used in modelling the quantity of rare bird nesting sites across the cells: mean altitude in meters above sea level ($X1$), quantity of water bodies ($X2$), percentage of forest coverage ($X3$), and percentage of settlements area ($X4$).

The following global equation of Poisson regression for the study region to predict the quantity of rare bird nesting sites in a cell resulted from the model fitting:

$$Y = e^{(5.942 - 0.026 * X1 + 0.009 * X2 + 0.008 * X3 - 0.026 * X4)},$$

where $X1, \ldots X4$ are the aforementioned predictors and e is Euler's number. The coefficients are significant at $p < 0.01$. The model explaines 57 % of variance, but it does not count spatial nonstationarity in the relationships between species abundance and environmental determinants. The model residuals express spatial autocorrelation (Moran's Index is 0.16, $p = 0.001$).

GWPR takes into account the spatial nonstationarity issue. It does not provide a global equation, but local ones for each cell. The benefits of such approach are well established [1, 2, 5]. Using the same dataset, we fit local GWPR models with the adaptive Gausian kernel and the Golden section bandwidth search [5]. The coeffecients of equations were calculated on the training sample of 82 of the most surveyed cells (fig. 1, “high” and “medium” survey levels), and then were interpolated for the remaining 138 cells of the study region using the default method of GWR4. Statistics on the resulting local coeficients across the study area are summarised in Table 3.

The resulting GWPR model explained up to 68 % of variance and performed better than the global Poisson model according to the Bayesian Information Criterion (BIC), the corrected Akaike Information Criterion (AICc), Residual Mean Square (RMS), and Pearson correlation (r) between observed and predicted values (Table 4). The model residuals distribution showed significantly lower spatial autocorrelation, as well (Moran's $I = 0.07$, $p = 0.001$).

Further calculation of the dependent variables for each cell revealed the general layout of rare bird nesting sites distribution in the Lipetsk region (fig. 2, *A*).

Comparison of the predicted (fig. 2, *A*) and initialy observed (fig. 2, *B*) quantities of nesting sites across all cells highlights the important differences (fig. 2. *A*-*B*). Cells with positive residuals depict mostly undersurveyed areas with a high probability of expect-

Table 3

Descriptive statistics of the local coefficients of GWPR model
[*Таблица 3.* Описательная статистика для локальных коэффициентов ГВПР]

Variable	**Coeficient**		
	Minimum	**Maximum**	**Mean (SD)**
Intercept	-0.138	9.531	6.109 (1.248)
X1 (mean altitude, m.a.s.l.)	-0.048	-0.001	-0.026 (0.007)
X2 (quantity of water bodies)	-0.009	0.049	0.010 (0.010)
X3 (forest cover, %)	-0.083	0.052	0.011 (0.016)
X4 (area of settelments, %)	-0.139	0.121	-0.035 (0.034)

Table 4

Performance statistics of the applied regression models
[*Таблица 4.* Статистические оценки качества регрессионных моделей]

Criteria	**Regression model**	
	Global Poisson	**GWPR**
Explained variance, %	56.7	67.8
AICc	375.6	329.1
BIC	387.8	364.4
RMS	6.993	6.048
Pearson’s *r*	0.766	0.832
Moran’s I	0.164	0.069

ing there would be more nesting sites than those found. The negative residuals, on the other hand, may indicate areas with unique combinations of environmental parameters missed in the model but preferable for these rare species. In both cases, high residual values represent the areas of primary field research and conservation importance (fig. 2, *A-B*).

The produced spatial prediction correlates highly with the factual data and corresponds to theoretical views on rare species' distribution in the region. Thus, the distribution map reflects general shapes of landscape regions: the Central Russian Upland is in the west of the study area and the Oka-Don Lowland is in the east. For the latter, a higher richness and abundance of rare bird species is reported [12, 13]. The natural border between the landscape regions is the Voronezh river valley. It encompasses cells with the highest scores of rare bird species richness (up to 24 of 60) and an abundance of their nesting sites (up to 58 per cell) in the study region. Biodiversity hotspots are also presented in other big river valleys of the region due to the refugium effect. Notably, watersheds have been almost completely deprived of their zonal steppe species due to the complete cultivation of those flat areas.

CONCLUSIONS

We conducted spatial modeling on the abundance of the 60 nesting bird species registered in the Red List of the Lipetsk Region of Russia. The applied methodology based on GIS, PCA, and GWPR provided us with statistically significant modelling results. Our findings revealed distribution patterns of rare avifauna in the region. In general, broad river valley landscapes with numerous lakes and large, intricate forests enrich diversity and abundance of the focus species. In turn, flat uplands occupied by agricultural, human settlements and roads have predictably fewer rare birds. For species distribution modelling across 100 km^2 cells (a grid conventionally used for regional bird atlases), mean altitude, number of water bodies, forest coverage, and total area of settlements turned out to be the most significant landscape variables among those tested. With these predictors, our GWPR model explained 68% of the variance and enabled the prediction of rare bird species abundance across 220 cells of the region. Comparison of observed and predicted values of the abundance showed that cells with high differences indicate areas of conservation interests.

This study not only provides local wildlife agencies with information for biodiversity monitoring and conservation planning, but also has methodological value as it represents one of the first applications of GWPR modeling in Russian biogeography. The tested prediction technique let us foresee the species' distribution shift in response to deforestation, urban

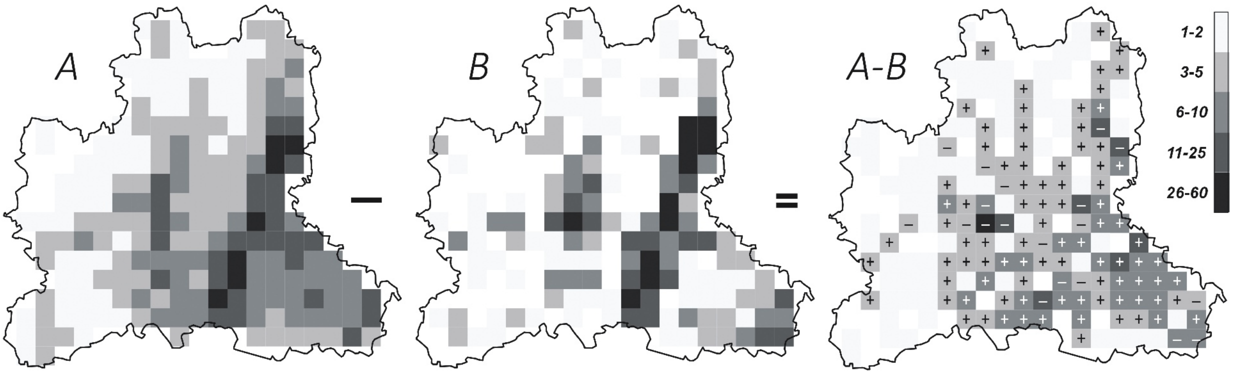

Fig. 2. Distribution of rare bird species' nesting sites in the Lipetsk Region (quantity of the nesting sites is shown with the panchrom ramp): *A*: predicted distribution (modelled by GWPR); *B*: distribution of the initial observation records; *A-B*: difference between the modelled and observed values
[*Рис. 2.* Размещение гнездовых участков редких видов птиц в Липецкой области (шкала отражает число участков на квадрат): *A* – теоретическое распределение (модель ГВПР); *B* – распределение ранее выявленных гнезд; *A-B* – разница между прогнозными и фактическими данными]

sprawl, and other scenarios of future landscape changes and thus is applicable to human impact assessment projects.

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CONFLICT OF INTEREST

The authors declare no information of obvious and potential conflicts of interest related to the publication of this article.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Dmitry V. Sarychev
M. Sc. Assist. Prof. at the Department of Geoecology and Environmental Monitoring, Faculty of Geography, Geoecology and Tourism, Voronezh State University, Voronezh, Russian Federation, ORCID: https://orcid.org/0000-0002-3755-0108, E-mail: sarychev.geo@gmail.com

Сарычев Дмитрий Владимирович
старший преподаватель кафедры геоэкологии и мониторинга окружающей среды, факультет географии, геоэкологии и туризма, Воронежский государственный университет, Российская Федерация, ORCID: https://orcid.org/0000-0002-3755-0108, E-mail: sarychev.geo@gmail.com

Dr. Josep Vila-Subiros
Full Prof. at the Department of Geography, Faculty of Arts and Tourism, University of Girona, Catalonia, Spain, ORCID: https://orcid.org/0000-0001-7746-9227, E-mail: josep.vila@udg.edu

Dr. Xavier Garcia Acosta
Research Fellow at Institute of Regional and Metropolitan Studies of Barcelona, Autonomous University of Barcelona, Catalonia, Spain, ORCID: https://orcid.org/0000-0002-1789-7403, E-mail: xavier.garciaacosta@udg.edu

Dr. Semyon A. Kurolap
Full Prof. at the Department of Geoecology and Environmental Monitoring, Dean of Faculty of Geography, Geoecology and Tourism, Voronezh State University, Voronezh, Russian Federation, ORCID: https://orcid.org/0000-0002-6169-8014, E-mail: skurolap@mail.ru

Джозеп Била Субирос
доктор наук, профессор кафедры географии, факультет искусств и туризма, Университет Жироны, Каталония, Испания, ORCID: https://orcid.org/0000-0001-7746-9227, E-mail: josep.vila@udg.edu

Чавьер Гарсиа Акоста
доктор наук, научный сотрудник Института исследований региона и метрополии Барселоны, Автономного университета Барселоны, Каталония, Испания, ORCID: https://orcid.org/0000-0002-1789-7403, E-mail: xavier.garcia.acosta@uab.cat

Куролап Семен Александрович
доктор географических наук, профессор кафедры геоэкологии и мониторинга окружающей среды, декан факультета географии, геоэкологии и туризма, Воронежский государственный университет, г. Воронеж, Российская Федерация, ORCID: https://orcid.org/0000-0002-6169-8014, E-mail: skurolap@mail.ru