Changes in species richness of vascular plants under climate and solar radiation in the Middle Volga River region (Russia)

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Abstract. Specially protected natural conservation areas in the Middle Volga River region serve to preserve both rare and endangered species and the entire biotic complex, including typical floristic communities of vascular plants. We have identified 25 sites, 100 km² each, where the flora is represented in full the most. We studied the relationships between the general species richness (SR) and the richness of particular life forms (LF) of vascular plants with climate and relief using multiple regression methods. Our study shows that the special function of March precipitation is the factor that influences the most the spatial change of the SR and LF. When increasing the precipitation in the model by only 1 mm, this leads to a decrease in the number of species by 7.1%. Winter precipitation and temperature are important factors as well; together they are responsible for 70–82% of the SR variation. These close links made it possible to develop the maps of the species richness of the study area. The SR model did not include solar radiation, one of the most important environmental factors, as a significant predictor. This factor was omitted due to the analysis of the number of species of particular LF, which showed the maximum illumination of the slopes as a highly significant factor for number of them. The two dominant LFs (hemicryptophytes and therophytes), which account for 73% of the total number of species, depend oppositely on the illumination. This fact indicates a decrease in competition between LFs due to their separation in space, since hemicryptophytes, in contrast to therophytes, predominate on well-illuminated slopes. In addition, opposite LF responses lead to omitting of illumination factor from the SR model for all species in the region.

1. Introduction

The regularities of the spatial distribution of the species richness (SR) of vascular plants were studied mainly on a global and continental scale with a resolution of ~100 km. Although the current understanding of the regularities is far from complete [1], SR is associated with climate and energy required for photosynthesis, which explains more than 80% of SR dispersion in a global scale. At the regional level, the relationships between SR and environmental factors are usually weaker due to a narrower range of environmental conditions [2, 3]. The ecological and morphological characteristics of the floristic composition of the study area are often described using the spectrum of life forms (LF) [4]. We study the regularities of the influence of environmental factors on the species richness in general and on the species richness of various life forms in a region with relatively weak climatic gradients.
2. Materials and Methods

The studies were carried out on the territory of the Samara Oblast and the eastern part of Ulyanovsk Oblast. The southeastern part of the study area is presented by steppes; the forest-steppe zone stretches northwards. The soils vary from chernozems in the southern part, through gray forest soils in the central part, to sod-podzolic soils in the northern part. The average annual temperature is $4.5 \pm 0.5 \, ^\circ C$, the annual precipitation is $514 \pm 30 \, mm$. The highest precipitation is usual in June and July, the lowest, in February and March. The coldest months are January and February. Such a distribution is unfavorable for vegetation since a decrease in temperature corresponds to a decrease in precipitation.

The SR of vascular plants was assessed at 25 plots, each of an area of 100 km$^2$ (figure 1). The floristic descriptions were carried out in 2004–2018 [5]. The SR at the study sites varied from 394 to 690 species, on average, $512 \pm 80$. The LF of the plant species was defined according to the system of K. Raunkiaer. The monthly temperatures and precipitation and bioclimatic characteristics were obtained from the WorldClim database [6]; these were the averaged values for the 50-year period (1950–2000) presented with a 900-m resolution. The relief heterogeneity was estimated using a matrix of heights (600-m resolution). In order to obtain such pattern, 100 quadrate plots with a side of 600 m were taken into account within each 100-km$^2$ site. The relative illumination of the slopes $F$ was calculated as the perpendicularity of the incidence of sunlight on the surface: $F = 100\%$ for the perpendicular incidence of rays and 0% on the shadow slopes. The maximum $F_s$, minimum $F_n$, and average $F_{av}$ illumination was calculated for 100 plots similarly to that for relief heterogeneity.

Multiple regression model was a basis for comparing SR with environmental factors [7, 8]. The original statistical methods described in detail in earlier publications have been applied [9].

3. Results and Discussion

The closest relationship between average monthly precipitation and temperatures was observed for July ($R^2 = 0.759$), in the month of the highest precipitation and high temperatures. This relationship is negative for all the other months; in winter, such a close relationship may have a positive effect on the SR of plants, since low temperatures often correspond to abundant precipitation which prevents the heat loss by the soil. However, the air temperature and precipitation are practically unrelated in March, which determines the climatic influence, i.e. from harsh conditions with low precipitation and low temperatures to favorable otherwise. Therefore, precipitation in March plays a special role in this region; this is confirmed by the closest relationship between SR and this factor. This relationship is characterized by a sharp nonlinearity with a peak at average $P_{Mar} = 26.65 \, mm$. A closer relationship is obtained if one uses the function $P_{Mar} = 26.65$, which corresponds to the deviation from the March precipitation norm. The larger the function, the lower SR. The sensitivity of SR to this factor is high; in particular, a 1-mm difference leads to an average decrease in the number of species by 36.3, which is 7.1% of their total number. Meantime, a 1-mm absolute difference in precipitation in March would change SR by 12.9 (by 2.5%) at a linear relationship. Regard must be paid that this modulus is associated with changes in the values of some climatic norms of precipitation in the region; particularly, as the former increases, the latter decrease. In other words, an increase of the deviation from the optimum of precipitation in March accompanied by the decrease in SR is coherent with a decrease of other important ecological indicators, which are annual precipitation and precipitation of the driest season.

A multiple regression model using March precipitation and other climatic indicators as a predictor of this function has been developed. This model describes the spatial variation in the total number of species in the region and explains 74% of the variance of the dependent variable ($R^2 = 0.742$; equation (1) in the Table). Regard must be paid to the model (1), which includes in addition to the modulus winter precipitation and climatic characteristics of the margin months (March and October), when the air temperature in the neighboring months is shifting from negative to positive and vice versa, but climatic indicators of the growing season are absent. The SR matrix was calculated using equation (1), and a map for the region was developed (figure 1). Transect, which has been used to estimate the
change in the calculated SR model from south to north, is shown on the map. There is a decrease in SR in this direction and a close relationship between SR and distance to the north \( R^2 = 0.792 \).

![Map of the spatial distribution of SR according to the model (1).](image)

**Figure 1.** Map of the spatial distribution of SR according to the model (1). 1 - centers of observation sites, 2 - boundaries of administrative regions, 3 - water bodies, 4 - transect

### Table. Factors of species spatial distribution

| Species / Factors | The significance of the factor in explaining the variance of the number of species (%) | \( R^2 \) | Other factors of regression |
|-------------------|------------------------------------------|----------|--------------------------|
| Total species number (1) | 40 | 0 | 19 | 41 | 0.742 | \( T_{Mar}, T_{Oct} \) |
| Hemicryptophytes (2) | 32 | 25 | 23 | 20 | 0.751 | \( P_{Oct} \) |
| Theophytes (3) | 33 | 20 | 20 | 27 | 0.699 | \( P_{Jan} \) |
| Phanerophytes (4) | 30 | 27 | 27 | 24 | 0.738 | \( P_{Dec} \) |
| Geophytes (5) | 34 | 21 | 0 | 45 | 0.816 | \( T_{win}, dT \) |
| Chamaephytes (6) | 31 | 34 | 24 | 11 | 0.705 | \( T_{win} \) |

\( a \) modulus of the difference between precipitation in March and its mean value \( P_{Mar-26.5} \) in all equations with a minus sign,

\( b \) maximum illumination of slopes on sites \( F_x \) in the equation with a minus sign,

\( c \) abbreviations: \( P_{win} \) – winter precipitation; \( P_{Oct} \) – October, \( P_{Jan} \) – January, \( P_{Dec} \) – December; \( T_{Mar} \) – temperature in March, \( T_{Oct} \) – in October, \( T_{win} \) – in winter, \( dT \) – the difference between the maximum and minimum temperatures of a year

The list of predictors for species richness (equation (1)) does not include any radiation characteristics, although this seems to be expected. The reason for this becomes obvious, when SR of different LFs were examined separately. For LF, the modulus of the difference in precipitation in March is still one of the leading predictors, as observed for the general SR; however, the maximum illumination \( F_x \) shows up in the models (Table). The two dominants in the LF region,
hemicryptophytes and therophytes (73% of all species), have different signs of connections with $F_x$ (equations (2) and (3)). This results as elimination of illumination factor from the regression equation (1) for the general SR. The opposite nature of the relationships for these LFs leads to a decrease in competition between them due to spatial differentiation; i.e. some species prevail on well-illuminated slopes, while the others, on shady ones. The maps based on the models of hemicryptophytes and therophytes have been developed (figure 2).

![Figure 2](image.png)

**Figure 2.** Maps of the SR of hemicryptophytes (a) and SR of therophytes (b) according to the models (2) and (3) of the Table.

4. **Conclusion**

Two major outcomes may be underlined:

- it makes sense to use the average long-term values of monthly precipitation and temperature and their derivatives in the analysis of the spatial distribution of species richness at the regional level due to the fine relationship of the SR with local climatic conditions;
- it is more correct to use subsets (life forms) of SR to identify the relationship of the plant species richness with radiation due to their various responses to solar radiation, which may be even opposite.

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