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Environmental Preferences of an Invasive Plant Species, *Bidens frondosa* (Asteraceae), in European Russia and Western Siberia

Anatoliy A. Khapugin [1,2,*], Igor V. Kuzmin [1], Leonid A. Ivanov [1,3], Dina A. Ronzhina [1,3] and Larissa A. Ivanova [1,3]

[1] Institute of Environmental and Agricultural Biology (X-BIO), Tyumen State University, 625003 Tyumen, Russia; ivkuzmintgu@yandex.ru (I.V.K.); l.a.ivanov@utmn.ru (L.A.I.); dar03@mail.ru (D.A.R.); ivanova.larissa@list.ru (L.A.I.)
[2] Joint Directorate of the Mordovia State Nature Reserve and National Park "Smolny", 430007 Saransk, Russia
[3] Institute Botanical Garden, Ural Branch of RAS, 620144 Yekaterinburg, Russia
* Correspondence: hapugin88@yandex.ru

Abstract: To identify habitat conditions, indirect ordination methods on the basis of environmental scales are used widely in Europe. However, many alien plants are absent from those scales. *Bidens frondosa* (Asteraceae) is an invasive alien species distributed widely in Europe. It is becoming a significant part of natural plant communities, sometimes forming monospecific stands. This study aimed to empirically determine environmental factor values using analysis of the flora accompanying *B. frondosa* in 22 regions of European Russia collected in a 34-year time span. In European Russia, Tsyganov environmental scales are widely used for such analyses. We determined intervals of values for each environmental factor according to Tsyganov environmental scales, namely thermoclimatic scale (TM: 7.3–9.4), climate continentality (KN: 6.0–9.4), climate aridity/humidity (OM: 6.1–8.6), cryoclimatic scale (CR: 5.3–8.8), soil moisture (HD: 9.9–17.6), scale of the soil salt regimen (TR: 5.1–10.7), soil nitrogen availability (NT: 4.4–8.5), soil pH (RC: 4.8–8.8), habitat shading (LC: 2.0–4.5), and soil-moisture variability (FH: 0.7–5.9). These data on environmental factor values can be further used in ordination analyses of plant communities where *B. frondosa* appears in the subzone of coniferous-deciduous forests of Eastern Europe. Results of this study demonstrate the ecological preferences of this species and can be used to determine conditions of habitats invaded by *B. frondosa*.

Keywords: alien species; biological invasions; Eastern Europe; environmental preferences; floristic list; habitat conditions

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Citation: Khapugin, A.A.; Kuzmin, I.V.; Ivanov, L.A.; Ronzhina, D.A.; Ivanova, L.A. Environmental Preferences of an Invasive Plant Species, *Bidens frondosa* (Asteraceae), in European Russia and Western Siberia. *Diversity* **2022**, *14*, 598. https://doi.org/10.3390/d14080598

Academic Editor: Michael Wink

Received: 20 June 2022
Accepted: 25 July 2022
Published: 27 July 2022

1. Introduction

Direct measures and analysis of environmental conditions of plant habitats are difficult because long-term measurement of many ecological factors is highly labor-intensive. As an alternative, methods of indirect ordination based on vegetation character are widely applicable to determine the values and variation of the environment in the site under consideration. To this end, habitat assessment using environmental scales is of wide interest and application. Among such studies in East Europe, the most popular environmental scales were developed by Landolt et al. [1], Ellenberg et al. [2], and Tsyganov [3]. Among them, the scales of Landolt et al. [1] and Ellenberg et al. [2] were developed for Central Europe, while, for Eastern Europe and other Eurasian regions, certain correction coefficients may be needed for accurate assessment.

In European Russia, the use of Tsyganov [3] scales is the most promising for indirect analysis of environmental characteristics of current habitats [4,5] because it was developed specifically for the sub-zone of coniferous-deciduous forests of European Russia. However, new challenges have arisen in the use of environmental scales successfully developed decades ago. Owing to intensive biological invasions, many new alien species are missing from the phytoindication scales, particularly in the scales of Tsyganov [3]. Some alien species such as *Cyclachaena xanthiifolia* Nutt., *Bidens frondosa* L., *Echinocystis lobata* (Michx.) Torr. & A. Gray form stable plant communities [6], some of which are widely distributed. In turn, this makes it difficult to conduct an indirect ordination analysis of vegetation plots inhabited by unlisted alien plants.

In Russia, one of the widely distributed invasive alien plants is *Bidens frondosa* [7]. In various European-Russian and West-Siberian regions, *B. frondosa*-dominated plant communities were recently described [6,8]. In some regions, this alien plant has recently been found for the first time [9,10], highlighting the need to identify ranges of environmental factor values for Tsyganov [3] scales. As an initial attempt, this study aimed to determine the score intervals for *B. frondosa* in the sub-zone of coniferous-deciduous forests of European Russia. To test the applicability of Tsyganov [3] scales to the West-Siberian flora, the analysis included data from West-Siberian regions, namely, Kurgan and Tyumen.

2. Materials and Methods

By following the scheme of ecoregions proposed by Dinerstein et al. [11], we selected all regions covered by the biome of temperate broadleaf and mixed forests, including ecoregions of East-European forest steppe, Central European mixed forests, and Sarmatic mixed forests (Figure 1).

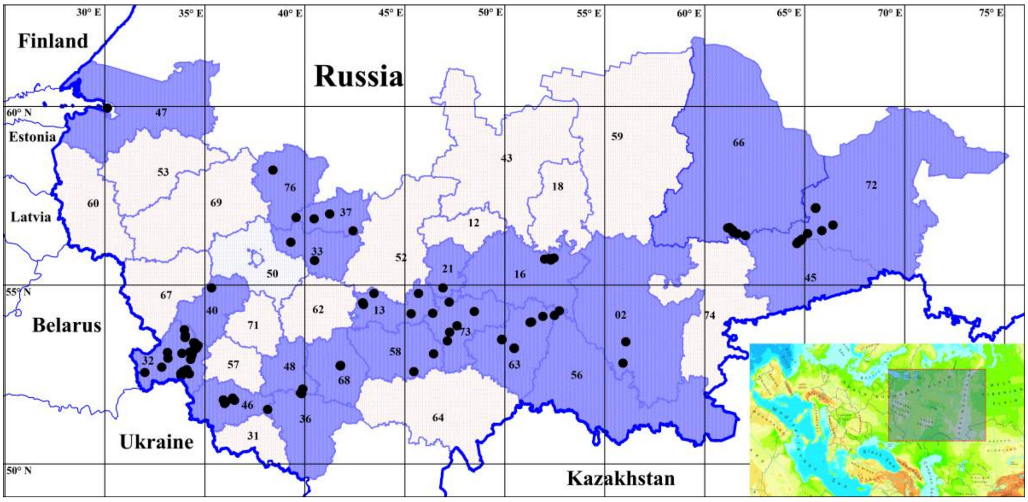

Figure 1. Map of the study areas. Regions of European Russia from where we used data (black dots) on floras accompanying *Bidens frondosa* are colored in blue. Designations of regions of European Russia and Western Siberia based on the state system of region numeration: 02—Republic of Bashkiria, 12—Republic of Mari El, 13—Republic of Mordovia, 16—Republic of Tatarstan, 18—Republic of Udmurtia, 21—Chuvash Republic, 31—Belgorod Region, 32—Bryansk Region, 33—Vladimir Region, 36—Voronezh Region, 37—Ivanovo Region, 40—Kaluga Region, 43—Kirov Region, 45—Kurgan Region, 46—Kursk Region, 47—Leningrad Region, 48—Lipetsk Region, 50—Moscow Region, 52—Nizhnii Novgorod Region, 53—Novgorod Region, 56—Orenburg Region, 57—Orel Region, 58—Penza Region, 59—Permsky Krai, 60—Pskov Region, 62—Ryazan Region, 63—Samara Region, 64—Saratov Region, 66—Sverdlovsk Region, 67—Smolensk Region, 68—Tambov Region, 69—Tver Region, 71—Tula Region, 72—Tyumen Region, 73—Ulyanovsk Region, 74—Chelyabinsk Region, 76—Yaroslavl Region. Borders of Russian regions, Russia, and other adjacent countries are colored in blue.

To determine the score intervals of *B. frondosa*, we used data about the composition of the flora accompanying this species. Data were extracted from three source types: (i) our field data obtained in the Republic of Mordovia, Kurgan Region, and Tyumen Region; (ii) published data (Table S1), and (iii) field data kindly provided by our colleagues (see Acknowledgements). In total, these data cover a 34-year time span, including 1984, 1985, 1990, 2000, 2001, 2004–2021. Our data were obtained by floristic surveys of habitats invaded by *B. frondosa*. Floristic lists included all plant species found on 10 × 10 m plots where *B. frondosa* was observed. Notably, the lack of data on the flora accompanying *B. frondosa* from some regions in our analysis does not mean that this alien species is absent from these regional floras. It just reflects the absence of data on the flora accompanying the invasive plant, which actually occurs in these regions, including the Volgograd, Saratov [12], and Moscow Regions [13].

Calculations of environmental score values were performed using the following formula (see [14]), taking into account environmental factor values (EFVs) of all species found in each floristic list determined in the studied regions:

$$mEFV = \frac{(x_1^{\min} + x_2^{\min} + \ldots + x_n^{\min}) + (x_1^{\max} + x_2^{\max} + \ldots + x_n^{\max})}{2n} \quad (1)$$

where $mEFV$ = average environmental factor value, $x_n^{\min}$= the minimal score value of a certain factor for n plant species, $x_n^{\max}$= the maximal score value of a certain factor for n plant species, n = the number of certain plant species in the floristic list obtained in each location. For this purpose, we used the algorithm published by Buzuk and Sozinov [15].

To characterize the environmental preferences of *B. frondosa*, we used designations of environmental factors based on Tsyganov [3] (see Table S2). Among them, there are macroscales (climatic factors) (thermoclimatic scale, TM; climate continentality, KN; climate aridity/humidity, OM; cryoclimatic scale, CR) and microscales (plot scales) (soil moisture, HD; scale of the soil salt regimen, TR; soil nitrogen availability, NT; soil pH, RC; habitat shading, LC; soil-moisture variability, FH). Minimal and maximal EFVs may reflect the environmental survival limits of the plant. We used the 25th and 75th percentiles of data as limits of the most reliable survival of *B. frondosa* in the study area, where this alien plant should express the highest fitness to the environment. Calculations were performed by MS Excel 2010 and PAST 4.09 [16].

3. Results and Discussion

For these analyses, we were able to comply 191 pertinent floristic lists which have been found from 22 regions of European Russia and Western Siberia (Table S1), with results presented in Figure 2 and Table 1. A principal component analysis of these data (Table 1) identified three principal components (PC1, PC2, PC3) with eigenvalues > 0.9, accounting for 83.0% of the total variability of environmental factors.

Figure 2 demonstrates that data from Western Siberia (Tyumen Region, Kurgan Region) and the Urals (Sverdlovsk Region) are not outliers within the large set of data collected across European Russia. Although the Tsyganov [3] scales were developed for European Russia (sub-zone of coniferous-deciduous forests), this approach seems to work well in Western Siberia.

Based on the thermoclimatic scale, the highest fitness of *B. frondosa* is found in boreal-nemoral areas with effective radiation at about 40 Kcal/cm^2 × year (see Tsyganov [3], p. 58). At the same time, minimal (TM: 7.3) and maximal (TM: 9.4) values indicate that this species can survive under conditions from ca. 35 Kcal/cm^2 × year (e.g., river sandbanks) to ca. 45 Kcal/cm^2 × year of effective radiation (e.g., edges of the burnt swamps). This parameter is characterized by low variability (CV = 4.7).

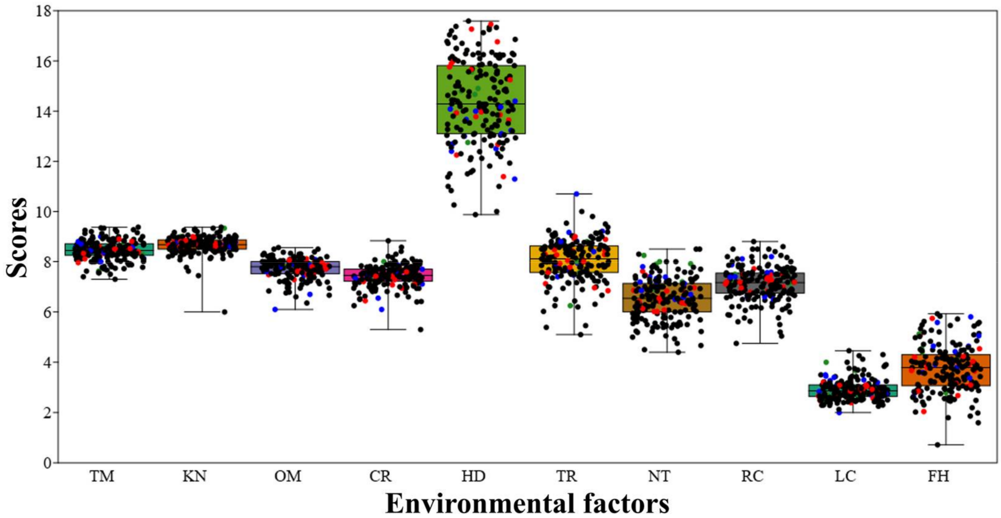

Figure 2. Scores of environmental factors of the Tsyganov [3] scales empirically found for *Bidens frondosa* based on data from European Russia and Western Siberia. Designations: dots indicate floristic data from European Russia (black), Tyumen Region (blue), Kurgan Region (red), and Sverdlovsk Region (green); the boundaries of the box plots indicate the 25th and 75th percentiles; whiskers above and below indicate the minimum and maximum values; TM—thermoclimatic scale, KN—climate continentality, OM—climate aridity/humidity, CR—cryoclimatic scale, HD—soil moisture, TR—scale of the soil salt regimen, NT—soil nitrogen availability, RC—soil pH, LC—habitat shading, FH—soil-moisture variability. Quantitative data are presented in Table 1.

Table 1. The summary statistics of environmental factors of the Tsyganov [3] scales empirically found for *Bidens frondosa* based on data from European Russia and Western Siberia, and factor weightings derived from principal components (PCs) analysis.

Parameters	TM	KN	OM	CR	HD	TR	NT	RC	LC	FH
Mean	8.4	8.7	7.7	7.4	14.4	8.1	6.5	7.1	2.9	3.8
Standard deviation	0.4	0.3	0.4	0.4	1.7	0.8	0.8	0.7	0.4	0.9
Min	7.3	6.0	6.1	5.3	9.9	5.1	4.4	4.8	2.0	0.7
Max	9.4	9.4	8.6	8.8	17.6	10.7	8.5	8.8	4.5	5.9
CV	4.7	4.0	5.3	6.0	11.7	10.3	12.3	9.5	14.4	24.9
25th percentile	8.3	8.5	7.5	7.2	13.1	7.6	6.0	6.8	2.6	3.1
75th percentile	8.7	8.9	8.0	7.7	15.8	8.6	7.1	7.5	3.1	4.3
PC 1	−0.091	−0.079	0.092	−0.094	0.968	−0.137	0.050	0.073	0.068	0.004
PC 2	0.162	−0.045	0.030	0.134	0.053	0.583	0.591	0.465	−0.203	0.048
PC 3	−0.123	−0.002	0.058	−0.040	0.000	0.148	−0.150	−0.014	0.069	0.965

Note: TM—thermoclimatic scale, KN—climate continentality, OM—climate aridity/humidity, CR—cryoclimatic scale, HD—soil moisture, TR—scale of the soil salt regimen, NT—soil nitrogen availability, RC—soil pH, LC—habitat shading, FH—soil-moisture variability.

Climate continentality is a second environmental factor with low variability (CV = 4.0). Based on phytoindication data, we expectedly found that the highest fitness of *B. frondosa* corresponds to mainland/sub-continental climate, which corresponds well to the locations of our analyzed relevés.

Analysis based on the scale of climate aridity/humidity characterizes *B. frondosa* as a sub-aridophyte (sub-arid climate) confined to areas with P-E (evaporation minus precipitation) of ca. 0–400 mm/year. The minimal and maximal limits indicate more arid and humid areas respectively, but deviations from the mean value are not considerable. They are most probably related to differences in the flora accompanying *B. frondosa* in invaded habitats.

Based on the cryoclimatic scale, the highest fitness of *B. frondosa* is related to areas with moderate winters (i.e., average temperature of the coldest month is from –8 °C to –16 °C). This is typical for the whole study area, including Western Siberia and the west of European Russia.

Based on the soil moisture scale, *B. frondosa* inhabits a wide range of conditions. The highest fitness of *B. frondosa* occurs in moist (HD: 13.1) to wet (HD: 15.8) meadows and forests with other mesophytes or permesophytes, respectively. However, minimal (HD: 9.9) and maximal (HD: 17.6) EFVs reflected a wide range of potential habitats, ranging from meadow-steppes (sub-mesophytic) to palustrine forest-meadows (sub-hygrophytic).

Based on the scale of the soil salt regimen, *B. frondosa* is best adapted to moderately rich soils to rich soils (HD: 7.6–8.6) based on Tsyganov [3]. However, considering the minimal and maximal EFVs, *B. frondosa* can inhabit sites ranging from salt-poor soils (HD: 5.1) to salt-rich/slightly-saline soils (HD: 10.7).

Based on the scale of soil nitrogen availability, *B. frondosa* prefers sub-nitrophilic soils, which are quite well-supplied with nitrogen. At the same time, the high CV (12.3) for this parameter demonstrates its wide range of tolerance. So, *B. frondosa* inhabits very nitrogen-poor (hemi-nitrophilic group) to sufficiently nitrogen-rich (nitrophilic group) soils.

According to the scale of soil pH, the highest fitness of *B. frondosa* is related to slightly acidic soils, corresponding to pH of ca. 5.2–5.7 based on scaling in Tsyganov [3]. Taking into account the range of EFVs, *B. frondosa* can survive on acidic (RC: 4.8) to slightly alkaline (RC: 8.8) soils.

Based on the habitat-shading scale, shrub vegetation (semi-open habitats) has the most favorable lighting conditions for *B. frondosa*. Taking into account minimal and maximal EFVs, *B. frondosa* can grow in a wide range of lighting conditions, from open glade habitats (LC: 2.0) to light forest habitats (LC: 4.5). This characterizes *B. frondosa* as a heliophyte, more rarely a sub-heliophyte in the study area.

Based on the scale of the soil-moisture variability, the highest fitness of *B. frondosa* is related to relatively constant soil moisture with a reliable range of EFVs of 3.1–4.3. Nevertheless, data about the EFV range indicate the wide diversity of habitats suitable for *B. frondosa* in terms of soil-moisture variability. For instance, it is present in habitats with constant, relatively constant, or slightly variable soil moisture.

By summarizing these parameters, one can see that *B. frondosa* is a mesophyte to hygromesophyte growing on somewhat acidic (pH $\approx$ 5.2–5.7 $\pm$ 0.7), nitrogen-poor to nitrogen-rich soils. It prefers predominantly semi-open habitats (e.g., shrub vegetation, such as *Salix* thickets), rarely open (e.g., open riverbanks, roadsides) or slightly-shaded ones (e.g., roads in thin forests) with constant to slightly-variable soil moisture. We should note here that mean EFVs may not always be optimal values for a species. However, mean EFVs and extreme (minimal and maximal) values are needed to calculate mean EFVs of plant communities where *B. frondosa* is present. At the same time, the optimal EFVs are required to assess overall habitat suitability for *B. frondosa*. For this purpose, we need additional, extensive research beyond the scope of this paper.

Our data from European Russia and Western Siberia are similar to data from this species' native range in Canada [17], where it grows on sand, loamy or clay soils under wet-mesic to mesic conditions. Although *B. frondosa* does not form the backbone of naturally occurring prairies and meadows [17], it inhabits generally the same habitats, namely moist forests, meadows, thickets, fields, roadsides, railroads, borders of streams, ponds, sloughs, swamps, ditches [18] as in the invaded range [19,20]. Unfortunately, we have not found publications with detailed information about environmental preferences of *B. frondosa* in North America. Therefore, this comparison is somewhat superficial without additional studies from Canada or the northern USA.

Our principal components analysis of EFVs demonstrated that soil moisture (HD), soil nitrogen availability (NT), soil pH (RC), scale of the soil-salt regimen (TR), and habitat shading (LC) are the most important environmental factors determining habitat suitability for *B. frondosa*. These results coincide with data presented in other studies. In garden [21] and field [22] experiments in China, it was demonstrated that nitrogen and water availability increase the growth and competitive ability of *B. frondosa* in comparison with its native congeners. Although in our study, the habitat shading (LC) has been a less important factor than others, *B. frondosa* was found to be more sensitive to photoperiod and less macrothermal than its European congener, *B. tripartita* L. [23]. These three studies [21–23] showed that *B. frondosa* has more plastic responses to environmental factors than other congeners, in accordance with the high coefficients of variation we obtained for microscale factors (Table 1). The range of environmental conditions of habitats invaded by *B. frondosa* in Eastern Europe and Siberia do need further study. Establishment of EFVs of Tsyganov scales for *B. frondosa* will facilitate the characterization of its habitats in Northern Eurasia using phytoindication methods.

4. Conclusions

Now that we have empirically obtained limits for all EFVs in the Tsyganov [3] environmental scales, this allows researchers to use these data to calculate mean EFVs for floristic lists of plant communities where *Bidens frondosa* occurs. This is especially relevant because, at present, there are now plant communities of low species diversity dominated by *B. frondosa* in various parts of the invaded range, e.g., [24,25]. Besides *B. frondosa*, many other widespread invasive species (e.g., *Echinocystis lobata*, *Ambrosia trifida*) are absent in the Tsyganov [3] scales, which highlights a need to perform similar studies to establish EFVs for these alien plants required for phytoindication analysis.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d14080598/s1, Table S1: Characteristics of the sources used to determine flora accompanying *Bidens frondosa* in the study area. Table S2: Designations of environmental factor scores based on Tsyganov (1983). References [6,26–51] cited in the Supplementary Materials.

Author Contributions: Conceptualization, A.A.K.; methodology, A.A.K.; validation, A.A.K.; formal analysis, A.A.K.; investigation, A.A.K., I.V.K., L.A.I. (Leonid A. Ivanov), D.A.R. and L.A.I. (Larissa A. Ivanova); data curation, A.A.K.; writing—original draft preparation, A.A.K.; writing—review and editing, A.A.K., L.A.I. (Leonid A. Ivanov), D.A.R. and L.A.I. (Larissa A. Ivanova); visualization, A.A.K. and L.A.I. (Leonid A. Ivanov). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the state assignment FEWZ-2020-0009 from Ministry of Education and Science of the Russian Federation, and by RFBR, project number 20-44-720006.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are available upon request from the corresponding author.

Acknowledgments: We cordially thank Elena A. Starodubtseva (Voronezh State Nature Reserve, Russia), Vadim E. Prokhorov (Kazan Federal University, Russia), Vladimir M. Vasjukov (Institute of Ecology of the Volga River basin of RAS, Russia), Yury A. Semenishchenkov (Bryansk State University, Russia), Irina G. Esina (Joint Directorate of the Mordovia State Nature Reserve and National Park "Smolny", Russia), and Olga A. Kapitonova (Tobolsk Complex Scientific Station, Ural Branch of RAS, Russia) for graciously providing data for our study, and other helpful contributions.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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