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Monitoring plant diversity in wind farm areas: An approach to early detection of alien plant species

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Abstract

The presence of alien plant species in disturbed habitats is a well-studied subject, however, the contribution of wind farm projects to alien plant invasion is often overlooked in environmental impact assessment. The present study tests a survey method for the assessment of plant diversity and the detection of alien plant invasion in two wind farm areas in Romania. Over 5 years, we recorded plant species incidence data in disturbed and undisturbed plots, making one visit per growing season each year. Using several plant community indicators and methods, such as species richness, beta diversity, non-metric multidimensional scaling, and multinomial species classification, we reliably detected plant species assemblage, including 26 alien plant species among the 608 recorded. Disturbed plots harbor a higher number of alien plant species, supporting the hypothesis that disturbances caused by wind farms reduce habitats' resilience to alien plant invasions. Despite the presence of habitat specialist plant species in certain plots, the community of alien plants did not show a clear preference for disturbed or undisturbed plots. The results underscore the importance of surveying the wind farms beyond the disturbed sites through regular monitoring to accurately assess their impact on plant diversity and detect alien plant invasions. The regular monitoring of all plant species during growing seasons will provide useful data for informing conservation strategies for native plants, including the control and eradication of alien species in early invasion stages.

KEYWORDS

disturbance, plant invasion, recovered vegetation, survey protocol, windmills

1 | INTRODUCTION

The global shift toward renewable energy sources and reduced dependence on fossil fuels and nuclear power has resulted in the widespread construction of wind farms across over 90 countries worldwide (Vella, 2017). Despite the environmental benefits, the impact of wind energy projects on biodiversity is high during the construction phase and can continue to some extent during the operational phase, especially when mitigation measures are lacking or inadequately implemented (Nazir et al., 2020). Furthermore, wind energy projects can negatively affect land use, soil quality, species communities, and wildlife (Bennun et al., 2021; Hamed & Alshare, 2022; Keehn & Feldman, 2018), hence the importance of considering these impacts carefully when planning and designing wind energy projects (Saidur et al., 2011). Therefore, it is essential to prioritize monitoring and mitigation measures to ensure that wind farm projects are developed and operated in an environmentally friendly way (Gartman et al., 2017).

Wind farm development contributes to soil and vegetation disturbance (Denholm et al., 2009), consequently altering the native plant diversity and promoting the invasion of alien plant species (Kumar Rai & Singh, 2020; Root et al., 2020; Sokol et al., 2017). Despite the growing recognition of the risks posed by biological invasions to biodiversity and the increasing research on methods to predict and prevent invasions (Bartz & Kowarik, 2019; Blackburn et al., 2014; Pyšek et al., 2020; Seebens et al., 2017), few studies investigated the contribution of wind farms to the spread of alien and invasive plants. For example, a study to detect alien plant species in a wind farm in the desert bush region of California (USA) showed an increase in their invasion at turbine sites and their spread in surrounding areas (Villarreal et al., 2019). In Europe, a study conducted in Portugal by Passos et al. (2013) found that disturbed areas within wind farms provided optimal conditions for the proliferation of alien plants. However, the study suggested that comprehensive monitoring and early eradication programs could prevent alien plants invasion around the turbine areas. Furthermore, other studies have shown that although soil disturbance is difficult to avoid, early detection and eradication of alien plant species can effectively control their spread (Kumar Rai & Singh, 2020; Qian et al., 2020).

In recent years, Romania has emerged as a significant player in the wind energy sector, ranking 15th in Europe in terms of installed wind power capacity in 2022 (3029 MW) (Costanzo et al., 2022), with some of the largest onshore wind farms in Europe (Vella, 2017). The country's wind power potential is particularly high in the southeastern and southwestern regions, and this has resulted in the installation of over 1200 turbines between 2007 and 2016 (Calota & Stupariu, 2019; Dragomir et al., 2016).

Similar to other countries, in Romania, environmental impact assessments have paid little attention to the study of alien plants in the area of infrastructure projects (Nita et al., 2022; Silva & Passos, 2017). Even though wind farms go through an environmental permitting process (Nita et al., 2022), these tools often fail to produce reliable predictions and to suggest suitable mitigation measures (Gartman et al., 2017; Nita et al., 2022; Smart et al., 2014). When assessing the impact on plant communities and the risk of alien plants invasion, the primary challenge lies in the absence of a standardized protocol for collecting and analyzing species data. This aspect often resulted in different survey protocols applied during ex-ante and post-ante environmental monitoring programs, undersampling or sampling only of disturbed sites without considering the surrounding landscape (Mascarenhas et al., 2018).

Given the increased importance of alien plant species management in wind farms' environmental monitoring programs and the limited data on the efficiency of survey protocols, this paper aims to test the reliability of an easy-to-implement multi-year study in detecting alien species inhabiting wind farm areas and to improve knowledge about the role of wind farms in promoting alien plant invasions. To achieve this, we tested the hypothesis that significant differences exist in plant communities between disturbed sites (i.e., nearby wind turbines) and undisturbed sites (i.e., at least 50 m away from the wind turbines). Our investigation focused on whether a comprehensive survey of the entire wind farm area during the initial assessment phase is advantageous for the rapid detection of the invasion of alien plant species, even when the survey is in the form of species incidence-type data. The hypothesis was tested by comparing plant communities revegetated after construction (disturbed sites) with those that were not directly impacted by the construction (undisturbed sites) in two wind farms in Romania (Sfanta Elena WF located in Banat region and Agighiol WF located in Dobrogea region). Specifically, we (1) contrasted species diversity and community assemblages in disturbed and undisturbed sampling plots to determine if there are significant differences between areas or disturbance types, (2) investigated how alien plant species richness and alien community assemblages varied in the two areas and disturbance types, and (3) analyzed what native and alien plant species are specific to disturbed and undisturbed sites in the two areas. We selected the two wind farms because they (1) are located in two regions with high wind potential but different climates (Agighiol steppe, Sfanta Elena low altitude mountains); (2) are located in protected areas; and (3) were built in the same period. Thus, by exploring the differences between the two wind farms' native and alien plant communities and analyzing the two wind farms together, we were able to formulate more general conclusions and offer guidance for monitoring based on more than one case study.

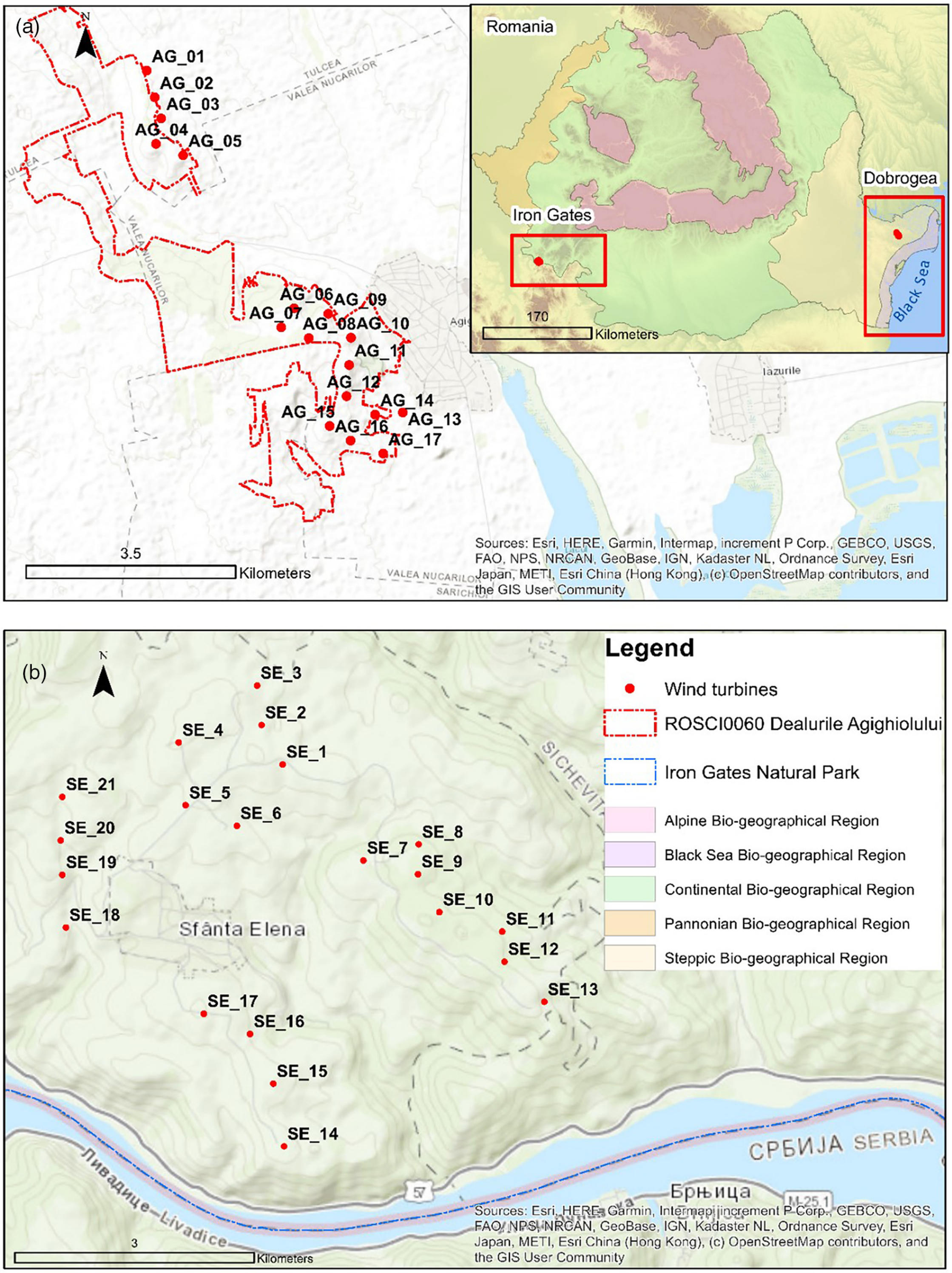


FIGURE 1 Location of the analyzed wind farms in the two regions of Romania (vignette in 1A) and the position of the wind turbines within each wind farm (A = Agighiol WF; B = Sfanta Elena WF).

2 | MATERIALS AND METHODS

2.1 | Study areas

The two analyzed wind farms are located in regions of Romania known for their high biodiversity (Milanovici, 2014; Tupu, 2021) and wind energy potential (Dragomir et al., 2016): Banat in SW Romania and Dobrogea in SE Romania (Figure 1). Sfanta Elena WF comprises 21 wind turbines located in Iron Gates Natural Park, and Agighiol WF comprises 17 wind turbines located in the Agighiol Hill (Dealurile Agighiolului)

Natura 2000 site (Figure 1). The Agighiol WF ranks second in the Dobrogea region in terms of the number of turbines located in a protected area, while the Sfanta Elena WF holds the first position in the Banat region. Both wind farms became operational in 2011 (Urziceanu, 2021).

Differences in environmental conditions between the two wind farm areas are evident in altitude and rainfall, as well as habitat types. Sfanta Elena WF, located at 350 m altitude in the Carpathian Mountains, near the Danube River, has a temperate-continental climate with Mediterranean influences, with an annual average temperature of 11°C and 700 mm/m^2 rainfall (Rozylowicz et al., 2022). The yearly average wind speed is 4 m/s. Agighiol WF, located at 150 m altitude on the hills of Dobrogea, has a temperate-continental climate with sub-Mediterranean influences, with average temperatures of 11°C and 400 mm/m^2 rainfall (Urziceanu et al., 2021). The yearly average wind speed is 6 m/s.

The differences in environmental conditions influence the types of habitats in the two wind farm locations. Sfanta Elena WF hosts significant orchid grasslands and scrub mixed with cultivated lands (Šťastná et al., 2015), while Agighiol WF is well known for the presence of Ponto-Sarmatian steppe grasslands, specific to the Dobrogea region (Urziceanu et al., 2021).

2.2 | Species sampling

The research covered the operational phase of the two wind farms, that is, 5 years after the wind farms became fully operational. To capture all phenological stages, we used a seasonal sampling methodology over a 5-year period (2017–2021), conducted four times annually to align with all growing seasons specific to Romania: (1) prevernal-vernal (March–April), (2) vernal-estival (May–June), (3) estival (July–August), and (4) autumnal (September–October).

In total, we surveyed 76 plots, corresponding to all 38 turbines existing in the two wind farms (42 for Sfanta Elena WF and 34 for Agighiol WF, half disturbed and half undisturbed). Around each turbine, we selected two types of survey plots of 50 × 50 m (2500 m^2): (1) disturbed plot, covering the site that extends near the tower (Figures S1, S2A), and (2) undisturbed plot, at a distance of 50 m measured from the turbine tower, as an example of an area without intensive human interventions during the construction and operation phases of the wind farms (Figures S1, S2B). All turbines have the same configuration of the disturbed sites. The choice of 2500 m^2 plot size matches the size of the disturbance site due to the construction of the wind turbines and incorporates the maneuvering square (Figure S2A). Furthermore, the approach of choosing a distance of 50 m from the turbine was also successfully used by Fraga et al. (2008), who applied the same distance to analyze unimpacted areas by wind farm construction. After construction, vegetation in disturbed sites is rarely mowed, for example, 1 m around the roadsides and maneuvering square (Figure S2A). As the wind turbines are located in protected areas, the use of herbicides is prohibited, and the wind farm operators work to clear vegetation only near access roads and around turbine towers.

In each season, we sampled both types of plots from all wind turbines in a wind farm, for 1 or 2 days, thus maintaining survey effort consistency across seasons and wind farms. In each plot, we recorded presence-only plant species data because we wanted to test if a survey that was easier to implement could provide useful information to environmental authorities and windfarm operators. Data were collected every time by the same botanists (first and last authors of the paper) in both types of plots. When we were unsure about species, we took photos and specimens for identification in the laboratory. Data collected over the 5 years at the wind farm level were converted to incidence matrices and stored for subsequent statistical analysis. A species was considered as present or absent from a plot in comparison with other plots from the same wind farm. The alien status of the recorded plant species was determined following the criteria established by Sirbu et al. (2022) in Romania, in accordance with the terminology employed by Pyšek et al. (2004). At each visit, we took photos of the location of the turbines, including of the vegetation on the disturbed and undisturbed plots (Figure S2).

2.3 | Statistical analyses

First, we calculated the observed species richness for all recorded species and separately for alien species for each plot type (disturbed and undisturbed) and study area (Sfanta Elena WF and Agighiol WF). Then, we used Wilcoxon rank-sum test (Zar, 2010) to compare disturbed vs. undisturbed plots in terms of observed species richness, grouped by study area or not. We also used Wilcoxon signed-rank test for analyzing the differences between undisturbed and disturbed plots at the same wind turbine (paired data). These analyses were conducted using R *base* package (R Core Team, 2020). To estimate the species richness while accounting for potential undersampling of the plant communities, we calculated Hill numbers for $q = 0$, representing estimated species richness. For this analysis, we used a sample-size-based rarefaction and extrapolation approach implemented in the *iNext* R package (Hsieh et al., 2016). Hill numbers were calculated to estimate the number of species with the same abundance needed to achieve the same level of diversity as in the studied plant community, in our case, species diversity (Chao et al., 2014). By extending the estimated number of species through extrapolation to simulate species richness as if we would sample more plots (e.g., 40 plots in each area), we could uncover some differences between the two areas and/or disturbance types in terms of species richness (Chao et al., 2014; Urziceanu et al., 2021). Graphs were plotted using R *ggpubr* package (Kassambara, 2020).

To assess the dissimilarity between the investigated plant communities and the position of alien species in undisturbed and disturbed plots, we employed Non-metric Multidimensional Scaling (NMDS) using the Jaccard dissimilarity index provided by the R *vegan* package (Oksanen et al., 2020). NMDS provides a low-dimensional rank-based ordination of pairwise species and site differences. The first two dimensions were selected based on Shepard's stress value, with a value below 0.2 indicating a strong correspondence in the ordination diagram (Oksanen et al., 2020).

In addition, we employed a multinomial species classification (CLAM) analysis (Chao & Lin, 2011) to categorize the plant species as generalists, undisturbed specialists, disturbed specialists, or too rare to confidently classify (Chazdon et al., 2011). CLAM is a multinomial model that considers estimated relative species abundance (presence in our case) in two sites (undisturbed or disturbed) and minimizes the bias resulting from differences in sampling intensities between the two sites and insufficient sampling within each site. Rare species are not excluded a priori in this approach (Chazdon et al., 2011; Oksanen et al., 2020). We applied a specialization threshold of $K = 0.667$ (2/3 specialization supermajority threshold) and $\alpha = .05$ (Chazdon et al., 2011).

Finally, we explored the ecological processes influencing the dissimilarity between the two compared sites (undisturbed/disturbed). This involved disentangling the beta diversity into total beta diversity, spatial turnover, and nestedness. Beta diversity, measured as the Jaccard dissimilarity of all site pairs, was calculated using the R package *betapart* (Baselga et al., 2023; Baselga & Leprieur, 2015). The beta. pair function provided information on total beta diversity, spatial turnover, and nestedness (Baselga & Leprieur, 2015). We tested total beta diversity, spatial turnover, and nestedness differences for dissimilarities within and between areas using the non-parametric Kruskal–Wallis test (Zar, 2010). Specifically, we evaluated differences in undisturbed plots (comparing undisturbed plots to each other), in disturbed plots (comparing disturbed plots to each other), and between undisturbed and disturbed plots (comparing disturbed plots to undisturbed plots) (Urziceanu et al., 2021). Corresponding graphs were plotted using R *ggpubr* package (Kassambara, 2020). Maps were created using ArcGIS Pro 3 (Esri, Redlands, CA, USA).

3 | RESULTS

3.1 | Observed plant species richness

The observed species richness in both wind farms was 608 plant species, with Sfanta Elena WF having a higher number of observed species (415 species) than Agighiol WF (362 species) (Data S1). A total of 169 species were found in both wind farms. The median number of observed species per sampling plot was higher in Sfanta Elena WF (median = 103.5 species, IQR = 87–113) than in Agighiol WF (median = 83 species, IQR = 73–107). Wilcoxon rank-sum test shows a statistically significant difference between the two wind farms ($W = 456$, p-value = .007).

When we analyzed observed species richness per type of plot (undisturbed vs. disturbed), the results indicated that undisturbed plots included 540 species, while disturbed plots only 466 species. However, the median number of observed species per plot was significantly higher in disturbed plots (median = 110 species, IQR = 89–117) compared to undisturbed plots (median = 86.5, IQR = 75–103; Wilcoxon rank sum test $W = 1077$; p-value = .00023) (Figure 2a). When analyzing the data by area and type of plots, we recorded 371 species in undisturbed plots at Sfanta Elena WF, 299 species in Agighiol WF undisturbed plots, 328 species in disturbed plots at Sfanta Elena WF, and 275 species in disturbed plots at Agighiol WF. When testing if the observed number of plant species is the same in the undisturbed and disturbed plots (matched paired test at plot level), it resulted that the species richness observed at the plot level is also higher in disturbed plots than in undisturbed ones (Wilcoxon signed rank test $V = 87$, p-value <.001), a pattern which is also observed when the paired analysis is done at area level (Figure S3).

3.2 | Observed number of alien plant species

We recorded 26 alien plant species, of which 18 were recorded in Sfanta Elena WF and 13 in Agighiol WF (five species were common for the two wind farms) (Data S1). The median number of observed alien species per plot was higher in Sfanta Elena WF (median = 3, IQR = 2–4)

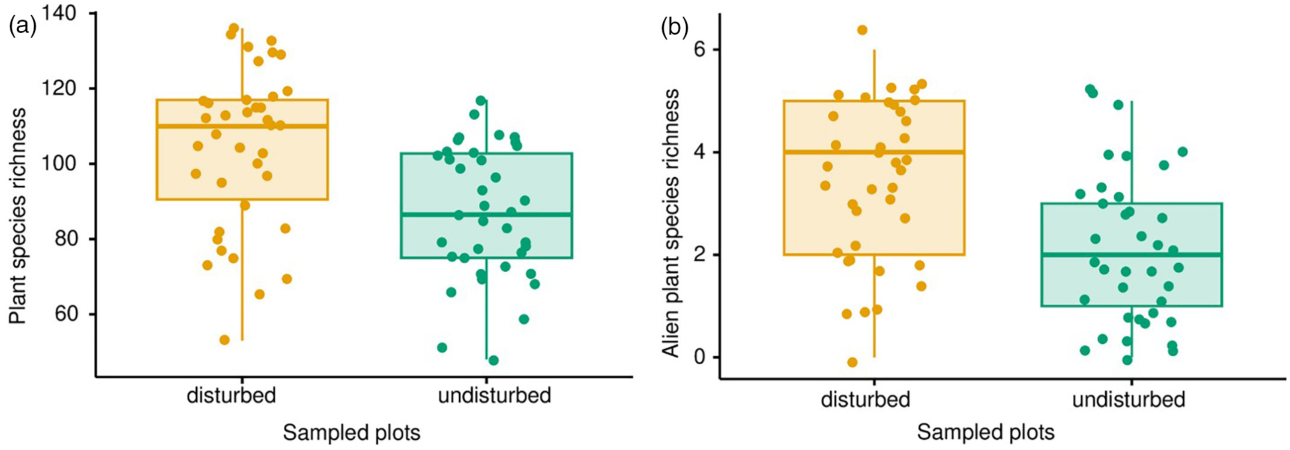


FIGURE 2 Observed plant species richness (a) and observed number of alien plant species (b) per plot type within the two wind farms (Agighiol and Sfanta Elena).

than in Agighiol WF (median = 2, IQR = 1–3) (Wilcoxon rank sum test $W = 431$, p-value = .0027). Of all 76 investigated plots, 69 include alien plant species. Sampling plots free of alien plant species were found mostly in undisturbed sites from Agighiol WF (6 out of 7 alien-free plots).

When we compared disturbed and undisturbed plots, we found that disturbed plots had more observed alien plant species than undisturbed plots. Specifically, we recorded 22 alien plant species in disturbed plots (15 in Sfanta Elena WF and 12 in Agighiol WF), while we observed 18 species in undisturbed plots (13 in Sfanta Elena WF and 7 in Agighiol WF). The median number of alien species per plot was higher in disturbed sites (4, IQR = 2–5) than in undisturbed sites (2, IQR = 1–3) (Wilcoxon rank sum test $W = 1058$, p-value = .0004) (Figure 2b). Moreover, when we analyzed plots as pairs (undisturbed vs. disturbed) in the two wind farm areas, we noticed that observed alien plant species richness was significantly higher in disturbed than in undisturbed plots (Wilcoxon signed-rank test $V = 26$, p-value <.001) (Figure S4).

3.3 | The effective number of plant species

We found high sampling completeness when calculating rarefaction and extrapolation with Hill numbers per plot type and per wind farm × plot type. For example, sampling completeness per wind farm × plot type was 96% for disturbed Agighiol WF, 94% for undisturbed Agighiol WF, 97% for disturbed Sfanta Elena WF, and 95% for undisturbed Sfanta Elena WF (Figures S5, S6). Rarefaction and extrapolation with Hill numbers for $q = 0$ also indicated that there were actually a higher number of species in undisturbed plots than in the disturbed plots, with an asymptotic estimation of species richness of 666.75 (CI95% = 617.79–715.71) for undisturbed plots and 584.74 (CI95% = 535.360–634.12) for disturbed plots. The overall asymptotic estimation of species richness was 715.49 (CI95% = 669.97–761.01) (Figure 3a), following a pattern similar to that recorded in the observed richness analysis.

Regarding the effective number of plant species per plot type in the two wind farm areas, the asymptotic estimation of species richness was higher in undisturbed plots (452.27, CI95% = 419.39–507.49) than in disturbed plots (405.14, CI95% = 370.15–469.18) from Sfanta Elena WF. However, there was no significant difference observed in the species richness between the plots from Agighiol WF, with an asymptotic estimation of species richness of 389.68 (CI95% = 351.92–454.20) for undisturbed plots and 345.42 (CI95% = 312.67–406.68) for disturbed plots (Figure S7).

3.4 | The effective number of alien plant species

The effective number of alien plant species in both areas, calculated using rarefaction and Hill number extrapolation for $q = 0$, is 28.63 (CI95% = 26.00–40.07), slightly lower in undisturbed plots (asymptotic estimation of species richness = 19.94, CI95% = 18.00–31.76) than in disturbed plots (asymptotic estimation of species richness = 24.59, CI95% = 22.00–39.57). However, the difference is not statistically significant due to the large range of CI95%, indicating a less precise estimation of the effective number of species (Figures 3b, S8).

Sampling completeness for alien plant species per area and disturbance type is unbalanced (Figure S9), and

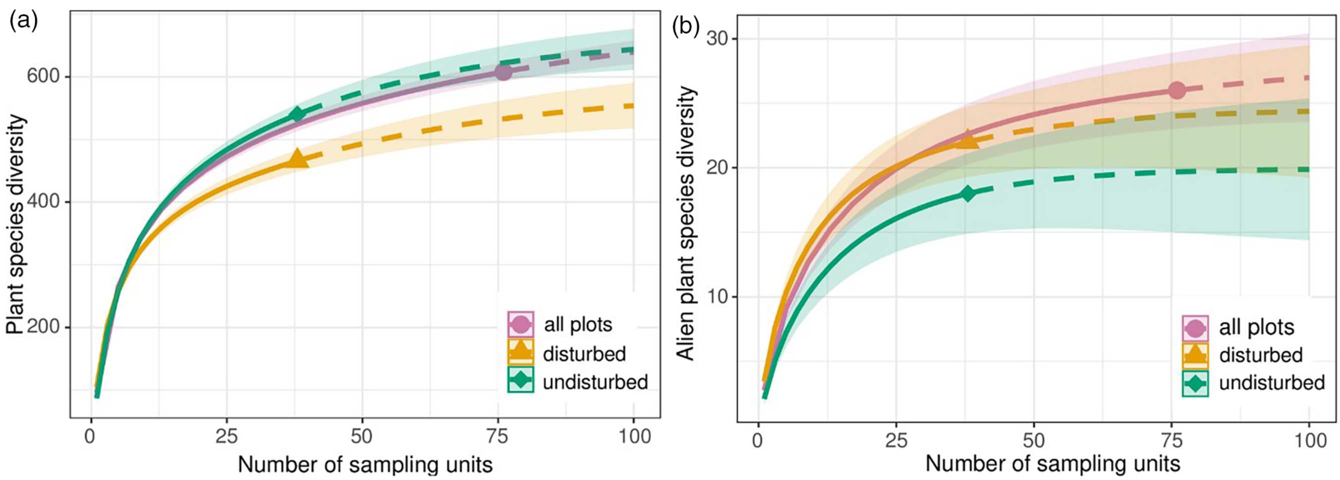
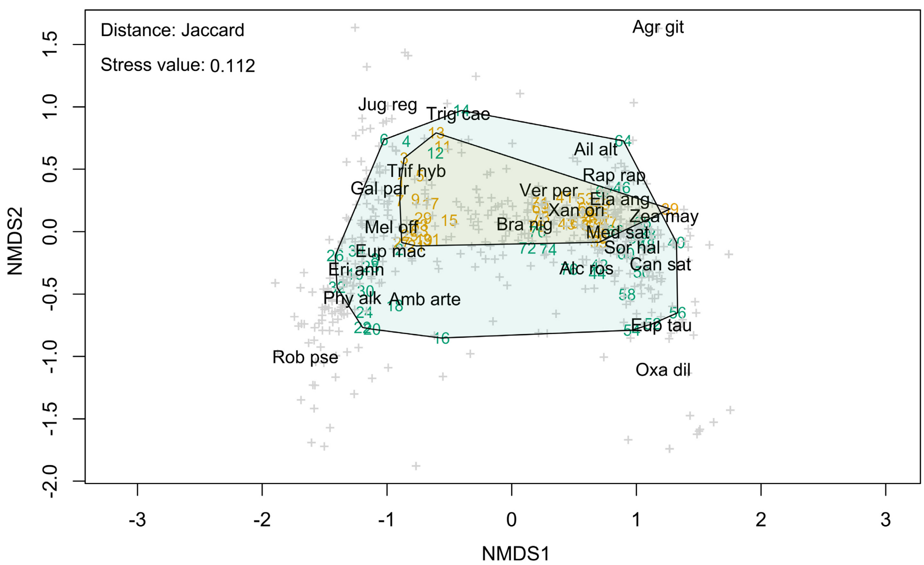


FIGURE 3 (a) Estimation of plant species richness, (b) and of alien plant richness in undisturbed, disturbed plots and all investigated plots within the two wind farms (line = rarefaction, dotted line = extrapolation, shaded area = lower and upper 95% confidence limits for the diversity of $q = 0$).

FIGURE 4 NMDS ordination showing the position of plant species communities from disturbed and undisturbed sampling plots within Agighiol and Sfanta Elena WFs (numbers in colors = id of survey plots, gray crosses = plant species, species acronyms = alien species, green area = undisturbed sites, yellow area = disturbed sites).



rarefaction and extrapolation analysis indicate that only undisturbed plots in Agighiol WF had a lower estimated diversity of alien species; however, the results are not statistically significant due to the large range of CI95% of the effective number of species (Figure S10). The upper 95% confidence levels for the four analyzed sites are between 11.53 alien species (undisturbed plots within Agighiol WF) and 42.47 alien species (disturbed plots within Sfanta Elena WF).

3.5 | Dissimilarity of communities and characterization of alien plant species

NMDS analysis for both wind farm areas indicates that plant communities from disturbed plots are similar to those from undisturbed plots (ANOSIM test = 0.72, $p < .001$), but communities from undisturbed plots are more variable than those from disturbed plots (Figures 4, S11). Plant communities from the two sites that share similarities (overlapped polygons in Figure 4) include alien species such as *Brassica nigra*, *Veronica persica*, *Xanthium orientale* subsp. *italicum*, *Erigeron canadensis*, *Elaeagnus angustifolia*, *Medicago sativa*. Moreover, alien species such as *Agrostemma githago*, *Oxalis dillenii*, *Juglans regia*, and *Robinia pseudoacacia* are the most dissimilar alien species from the analyzed plant communities.

NMDS analysis for each wind farm area further validates that alien plant communities from disturbed plots overlap alien plant communities from undisturbed plots, and disturbed plots show less variability (ANOSIM test

Agighiol WF = 0.37, p <.001, Figures S12, S13; ANOSIM test Sfanta Elena WF = 0.22, p <.001, Figures S14, S15). Moreover, the analysis indicates that species such as *Brassica nigra*, *Euphorbia taurinensis*, and *Alcea rosea* are the most dissimilar alien species from Agighiol WF (Figure S12). In Sfanta Elena WF, there are no species clearly linked to disturbed or undisturbed sites, all of them being common to disturbed and nearby undisturbed sites (Figure S14).

The multinomial species classification method (CLAM) classifies the recorded plant species into habitat generalist (specific to both disturbed and undisturbed habitats), habitat specialist (specific to disturbed or undisturbed habitats), and scarce species (too rare to be classified with confidence) (Figure S16). When analyzing the recorded species in both wind farm areas, most species were too rare to classify (348 species, including 20 alien species). The second largest group is habitat generalist plant species (234 species), including six alien species (*Ailanthus altissima*, *Ambrosia artemisiifolia*, *Erigeron annuus*, *Erigeron canadensis*, *Medicago sativa*, and *Xanthium orientale* subsp. *italicum*). Fourteen species were identified as undisturbed specialists (*Adonis vernalis*, *Clinopodium vulgare*, *Crocus danubensis*, *Cruciata laevipes*, *Galium octonarium*, *Glechoma hirsuta*, *Hyacinthella leucophaea*, *Inula oculus-christi*, *Ligustrum vulgare*, *Ornithogalum orthophyllum* subsp. *kochii*, *Ornithogalum refractum*, *Quercus pubescens*, *Potentilla recta*, and *Stellaria graminea*), and 12 species are disturbed specialists (*Agrostis stolonifera*, *Alyssum alyssoides*, *Artemisia campestris*, *Asperula tenella*, *Cerastium brachypetalum*, *Cerastium pumilum*, *Lactuca serriola*, *Matricaria chamomilla*, *Polygonum aviculare*, *Scleranthus annuus*, *Sonchus asper* subsp. *asper*, and *Vulpia myuros*), none of them being alien plant species.

3.6 | Processes driving sampling plots differentiation

In both wind farm areas, the heterogeneity in the distribution of plant communities, as assessed by the total Jaccard beta dissimilarity (Figure 5) is significantly higher in undisturbed plots and between disturbed and undisturbed plots (Kruskal–Wallis test = 21.12, p-value <.001), due to greater turnover in species composition (Kruskal–Wallis test = 90.42, p-value <.001), that is, the replacement of species by new ones. Dissimilarity of disturbed sites is driven by nestedness-resultant components (Kruskal–Wallis test = 16.11, p-value <.001), that is, species recorded in low-richness disturbed plots are a subset of the assemblages in more species-rich disturbed plots.

4 | DISCUSSION

Monitoring plant species within wind farms using presence-only data obtained from pairs of undisturbed and disturbed sampling plots placed around wind turbines confidently detected species assemblages, including alien plant species. Distinct plant species richness observed between the two areas, with Sfanta Elena WF showing a higher number of species than Agighiol WF, may be attributed to more favorable environmental conditions in Sfanta Elena WF (SW Romania), including higher rainfall and elevation, as well as a mix of habitats, mainly mountain grasslands and low-intensity agriculture.

Data from Agighiol WF (SE Romania) and Sfanta Elena WF (SW Romania) indicate that, at the wind farm level, disturbed sites include significantly fewer species, even though at the sampling plot level, the median number of plant species is higher in disturbed sites. The higher observed richness at the disturbed plot level may result in particular habitat conditions that arise after the initial disturbance (Deutschewitz et al., 2003). These conditions reduce the resilience of native plant communities to the invasion of alien species (Chambers et al., 2014; Davis et al., 2000; Lazzaro et al., 2020). Thus, our findings are aligned with other studies (Lazzaro et al., 2020) suggesting that the recovery of plant communities in disturbed sites depends on input from adjacent plant communities. Moreover, studies conducted by Hemming (2022), Stohlgren et al. (2003), and Trotta et al. (2023) demonstrate a positive correlation between native and alien species, highlighting an increased vulnerability to invasion in open-field areas. These outcomes emphasize the urgency of implementing measures to detect and control alien plant species, starting with the planning stages of wind farms (Trotta et al., 2023).

The NMDS analysis indicates that disturbed and undisturbed alien plant communities are not significantly differentiated, a pattern valid for both wind farms. Hence, 10 years after the construction of the two wind farms, alien plant species, as a community, are not preferentially linked to either disturbed or undisturbed sampling plots, even though several species were recorded only in particular plots (e.g., only in disturbed sites). Although it is known that areas disturbed by wind turbines construction provide better conditions for alien plant invasion (Fraga et al., 2008; Silva & Passos, 2017), our study matches the observations of Villarreal et al. (2019) that not all alien plants arrived in these plots due to construction activities. For example, in the case of the two studied wind farms, previous data (Goia et al., 2014; Tupu, 2021) show that species such as *Ailanthus altissima* and *Elaeagnus angustifolia* were formerly introduced to stabilize the land, and their expansion in the plant

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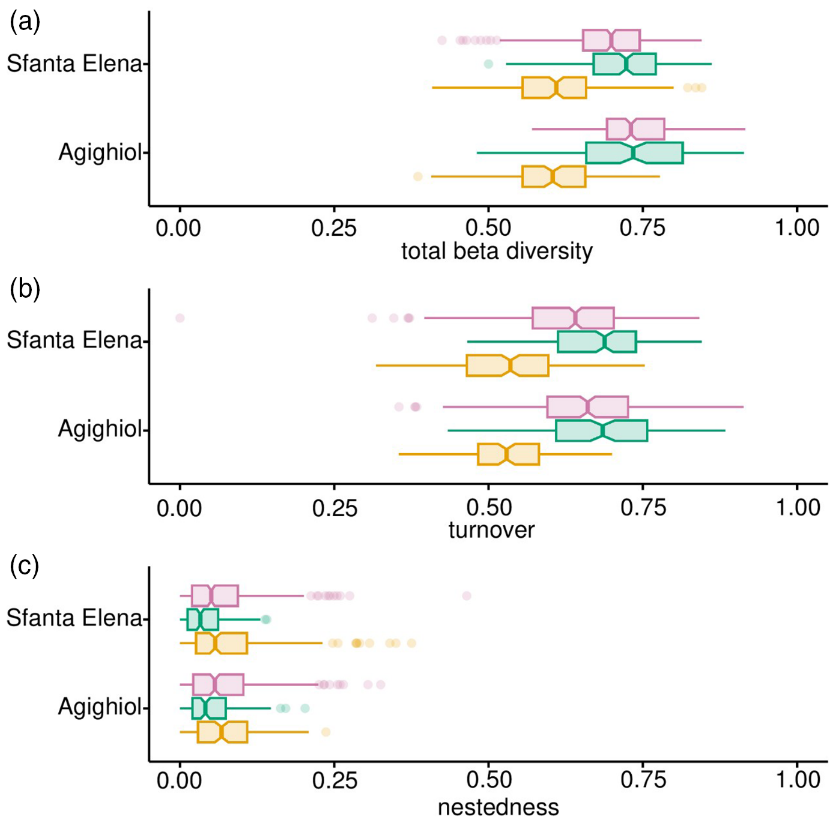

FIGURE 5 Beta diversity of disturbed and undisturbed sites within the two wind farms. Yellow = disturbed plots, green = undisturbed plots, lilac = undisturbed and disturbed plots.

communities was observed before the construction of the wind farms. However, the lack of ex-ante studies from the planning phase limited us in detecting new arrivals and increases in the abundance of already existing alien species, confirming the usefulness of high-quality environmental impact assessments (Nita et al., 2022).

The presence of habitat generalist plant species in both disturbed and undisturbed sites suggests their adaptability to various environmental conditions (Büchi & Vuilleumier, 2014); however, we cannot neglect that alien plants are better adapted to disturbed landscapes than native plants (Catford et al., 2012). Additionally, the presence of alien plant species as habitat generalists in undisturbed habitats may indicate past anthropogenic disturbances nearby or within wind farms, underscoring the importance of considering the disturbance history of wind farm siting areas. Understanding and managing plant diversity post-construction requires acknowledging complex interactions between impact factors. For instance, in the Agighiol Hills area, the powerful invader *Ambrosia artemisiifolia* is absent, both from past reports and our survey of the Agighiol WF area. In contrast, in the Sfanta Elena WF area, this species has an older history (Goia et al., 2014; Mataca, 2005); therefore, it is common around wind turbines.

The presence of habitat specialist plant species in undisturbed and disturbed sites highlights the importance of monitoring the entire plant community in a wind farm area, as focusing solely on alien species or disturbed sites does not provide a comprehensive understanding of wind farm impact on plant diversity. Undisturbed specialist native plant species, such as *Adonis vernalis*, *Crocus danubensis*, and *Hyacinthella leucophaea* act as indicators of the conservation value of grasslands in Dobrogea (Mountford et al., 2008), while disturbed specialist native plant species, such as *Artemisia campestris* and *Polygonum aviculare*, indicate anthropogenic disturbance in Romania (Sarbu et al., 2013). Despite wind farm construction disturbances, the presence of habitat specialist plant species in our study areas also highlights the necessity for conservation measures focused on enhancing habitat resilience and promoting native diversity during vegetation recovery for long-term survival.

Beta diversity assesses community differentiation processes (Carlos-Júnior et al., 2019), indicating how species composition changes due to anthropogenic influences (Socolar et al., 2016). In our study, lower beta diversity in disturbed sites suggests repeated species in these areas, creating homogeneous plant communities. Similar trends occur in wind turbines within desert vegetation (Keehn & Feldman, 2018). Conversely, turbines in homogeneous areas (e.g., bogs, peatlands, farmlands) foster heterogeneous microhabitats, supporting greater plant diversity (Fraga et al., 2008; Pustkowiak et al., 2018).

Thus, surveying the entire plant diversity pool is crucial for evaluating plant diversity in wind farms' disturbed plots and for early detection of alien species. If aliens are present, eradicating them from a larger area should be prioritized to prevent further invasion (Silva & Passos, 2017).

While presence-only data may not reveal the size of areas occupied by alien plants, our focus on species composition and diversity, particularly species richness, provides relevant indicators of the source of plant diversity in both site types. Still, species richness stands out as one of the most significant indicators of plant diversity in a given area (Chiarucci et al., 2003; Côté et al., 2021; Poudyal et al., 2019). Although a more sophisticated approach, e.g., integrating abundance data and functional traits, could offer additional insights, our methodology prioritizes early detection of alien species with the aim of rapid and efficient eradication.

While monitoring measures are in place in many countries, the control of alien plants invasion is frequently inadequate (Nita et al., 2022). Successful restoration of native plant diversity requires a more structured approach involving clear targets in terms of plant community structure and early eradication of alien plant species.

5 | CONCLUSIONS

Inappropriately located and operated wind turbines could have a significant impact on biodiversity, leading to disturbance and habitat damage. That is why the environmental permitting process is key to minimizing environmental impacts and achieving desired environmental, social, and economic benefits. Although the establishment of alien species in disturbed habitats is a well-studied subject, so far, few studies have investigated the contribution of wind farms to their spread around wind turbines. To fill this knowledge gap, we conducted a multi-year presence-only survey of plant communities from wind farms located within two Romanian protected areas to test the potential to detect alien species, including when they are in their early stage of invasion. The survey provides a comprehensive picture of plant diversity in the proximity of wind turbines and nearby undisturbed sites and can serve as a model for biodiversity monitoring in the post-construction and operating phases of wind farms. This approach allows early detection of alien plant species, and at a later stage, it can be completed with a wide range of variables that can be explored to assess environmental damages and identify effective mitigation measures. Such a plant species monitoring program should be introduced as early as possible, for example, from the planning phase during environmental permitting processes, and, if the human and financial resources allow, it can be extended to a coverage-based survey (e.g., in the biodiversity-rich areas or when the wind farms include few turbines).

AUTHOR CONTRIBUTIONS

Conceptualization: M.U., L.R., P.A. *Methodology*: M.U., L.R., P.A. *Data collection*: M.U., P.A. *Data analysis*: M.U., L.R., D.M.S. *Investigation*: M.U., L.R., D.M.S., P.A. *Data Curation*: M.U., L.R. D.M.S., P.A. *Writing—original draft preparation*: M.U., L.R. *Writing—Review & Editing*: M.U., L.R., D.M.S., P.A. *Visualization*: M.U., L.R.; M.U., and L.R. contributed equally to this work.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding this article. This work is an original contribution carried out by the authors. Any funding or support received in relation to this work has been disclosed within the manuscript.

DATA AVAILABILITY STATEMENT

Data that formed the basis of this study are included in the article and its Supporting Information.

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