Assessing the impact of wind farms on the plant diversity of blanket bogs in the Xistral Mountains (NW Spain)

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SUMMARY

The work reported in this paper explored the effects of wind farms on the plant species and vegetation diversity of summits and slopes in the Xistral Mountains, where priority habitats occur (EU Habitats Directive, code 7130 blanket bog). Quantitatively, our results showed significantly lower α diversity and higher β diversity in impacted areas when compared to non-impacted areas. These findings indicated a link between the spread of invasive species and wind farms. The relationship was confirmed, from a qualitative perspective, by the greater community heterogeneity found in altered patches. The surveyed area was mainly covered by the *Carici durieui-Eriophoretum angustifolii* community, which is endemic to the Xistral Mountains and usually forms very homogenous vegetation. However, where it was altered by the building of wind farms, we observed new communities (wet meadows) or substitution by wet heath or humid grassland.

KEY WORDS: biodiversity, vegetation, endangered species, Galicia.

INTRODUCTION

Wind power receives strong public support as a “clean” alternative energy source which does not emit greenhouse gases and produces little or no air pollution (Kuvlesky *et al.* 2007). Wind farms have also reduced the cost of energy production (de Lucas *et al.* 2005). For these reasons, wind has been rapidly developed as a renewable energy source in Galicia (northwest Spain), which was one of the six regions of the world with high concentrations of wind farms (1,287 MW) at the end of 2002. Even though Galicia (5.84% of the Spanish territory) already hosted more than 22% of the Spanish wind energy generation capacity (2,603 MW) in 2007, the current Galician Wind Energy Plan sets a more ambitious target of 6,500 MW by 2012, which is five times the wind power figure in the 2002 Plan.

Despite the benefits provided by wind power, the construction of large wind farms potentially threatens natural habitats, especially if the developments are sited carelessly or negligently. Perhaps much of the perception of wind power as "clean" energy is due to the fact that scientific literature about the impacts of wind farms on the environment is scarce (Kuvlesky *et al*. 2007). Most of the research on this subject is presented as reports with restricted access, which usually remain unpublished because of the confidentiality agreements between researchers and the companies that finance the majority of the work. Most of the published surveys focus on effects on fauna, especially studying mortality or stress in birds, bats or small mammals (e.g. de Lucas *et al.* 2005). To the best of our knowledge, the only published paper that deals with the impact of wind farms on local plant biodiversity is the one by Fagúndez (2008), although there have been comprehensive studies of the impacts of wind farms on blanket bog (e.g. Lindsay & Bragg 2004).

Ombrotrophic mires are very stable ecosystems for which little or no change in floristic composition over time (centuries or even millennia) has been documented (Backeus 1972, Barber 1981, Rydin & Barber 2001, Gunnarsson *et al.* 2002 *etc*.). However, disturbance such as that caused by wind farm construction may alter the vegetation within a very short time (Topić & Stančić 2006, Walker & Preston 2006). Landscape devaluation and destruction of plant cover are patent impacts that can easily be detected during and after construction; and the infrastructure that is required to support an array of turbines (e.g. roads and transmission lines) represents an even larger potential threat to wildlife than the turbines themselves (Kuvlesky *et al*. 2007). In the particular case of peatlands, changes in hydrological status and trophic equilibrium (by increasing nitrogen or other nutrients), habitat fragmentation (due to tracks and roads), peat slides and encroachment by invasive plant species are especially harmful to vegetation. In terms of plant biology, another relevant impact related to restoration activities is the genetic pollution produced by re-vegetation with commercial varieties of species like *Agrostis capillaris* L., *Agrostis stolonifera* L. and *Festuca rubra* L. The resulting hybridisation alters the gene pools of native populations. All of these changes and their consequences should be monitored on both a short-term and a long-term basis. Unfortunately this is not usually achieved because the impacts often outlast the period covered by the EIA (Environmental Impact Assessment) or Management Plan.

The Xistral Mountains host the highest concentration and best examples of mire ecosystems in Galicia (80% of its peatland area); and Galicia is where these habitats are best represented within the Iberian Peninsula (Pontevedra-Pombal *et al.* 2006). Thus the Xistral Mountains are the major Iberian refuge for mire ecosystems, but the presence of blanket bogs was practically ignored until recent years and little is known about their vegetation, which contains many characteristic, endemic and threatened species. To preserve this valuable biodiversity, the procedure to include the Xistral Mountains in the European Union (EU) Natura 2000 network as a Special Area of Conservation (SAC) was initiated in 1999 (Consellería de Medio Ambiente 1999). Meanwhile, the ongoing rapid development of wind energy led to the construction of 23 wind farms (25% of the Galician Wind Plan) in the Xistral Mountains regardless of the concomitant SAC status of this area.

As a result of the installation of wind farms in the Xistral Mountains since 1999, the surfaces of the mires have been dissected by roads. Further engineering works such as the digging of trenches and the construction of turbine foundations, as well as other linked environmental impacts, have resulted in changes to plant species distributions and vegetation composition. These modifications have disturbed not only blanket bogs (where most of the wind farms are located) but also minerotrophic mires, and thus have affected the mire complex of the Serra do Xistral SAC.

In the work described here we analysed the effects of the wind farms on plant biodiversity nine years after wind farm installation began. We tested the null hypothesis that wind farms do not affect plant α and β diversity using a quantitative approach. We also investigated whether or not there were qualitative changes in vegetation composition. We aimed to: (a) comparatively establish the biodiversity status of areas directly affected by wind farms and unaffected areas; (b) identify vegetation changes produced by wind farm installation; and (c) analyse the consequences of these impacts.

METHODS

Site description

The Xistral Mountains are the northernmost of the Galician mountains, being the western spur of the Cantabric Mountain Range (Figure 1). Mean altitude is around 1,000 m a.s.l. and the mountains form a natural barrier to moist air masses moving inland from the coast. The climate is Atlantic European and ranges from very humid to hyperhumid. Annual rainfall is between 1,400 and 2,000 mm, and mean annual temperature is 7–10ºC with an average annual temperature range of 14.5–15.5ºC. The lithology is mainly Precambrian quartzitic rocks, which form the main axis of the mountain range (Pontevedra-Pombal *et al.* 2006).

Sampling

A total of 100 floristic relevés (1 m^2 square plots) were recorded using the Braun-Blanquet semi-quantitative scale. The sampling plots were stratified in ten blanket bog areas within the Serra do Xistral SAC which were affected by wind farm installations (Figure 1). For each area (considered as a block or homogeneous subgroup), five relevés were placed at sites with impact and five in putatively unaffected sites. The criteria employed to select these sites were: (i) within 50 metres of a windmill (impacted) and (ii) more than 50 metres from the closest windmill and without visible signs of anthropic effects (unimpacted). For two of the ten areas, it was impossible to find five clearly undisturbed sites. Therefore the relevés were divided unevenly between impacted (55) and non-impacted (45) sites.

Alpha diversity analysis

In order to assess the plant biodiversity of blanket bogs affected by wind farms and to compare non-impacted and impacted relevés, five α diversity estimators were calculated. These were species richness (S), Shannon's (H') and Simpson's (D) indices, and two different measures of evenness, namely Shannon's equitability (E_H) *sensu* Pielou (1975) and the Evenness (E_{var}) *sensu* Smith & Wilson (1996). For each relevé the measures were calculated using TURBOVEG (Hennekens & Schaminée 2001) and JUICE (Tichý 2002). We performed a one-way ANOVA test (significance $p<0.05$) on the resulting matrix, considering the diversity estimators as dependent variables, and

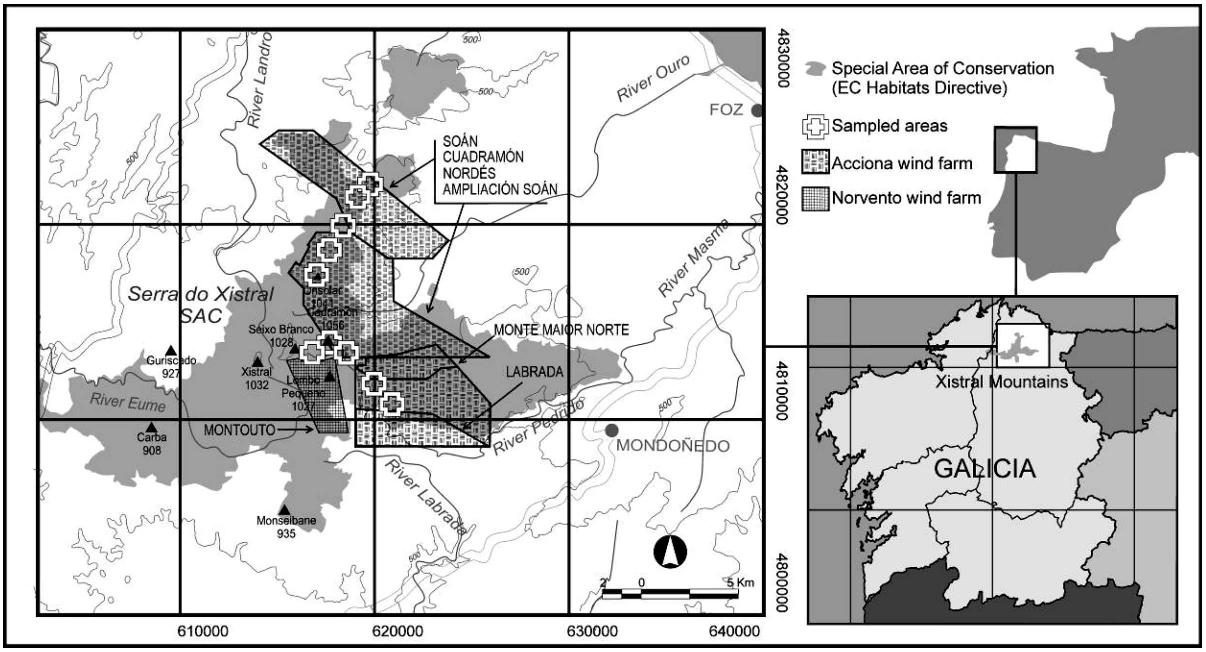

Figure 1. Map of the Serra do Xistral SAC showing the sampled areas and the associated wind farms. The wind farms are labelled with the names of their developers.

presence of impact and sampled areas as factors. Statistical analyses were carried out using SPSS 15.0 for Windows.

Beta diversity analysis

In order to detect any differences in diversity between habitats or communities in impacted and non-impacted areas, tests for significance of six measures of β diversity were computed. The β diversity measures used were: Whittaker (Whittaker 1960), Jaccard dissimilarity, Sorensen dissimilarity, Harrison beta-2 dissimilarity (Harrison *et al.* 1992), Williams beta-3 dissimilarity (Williams 1996) and Simpson's dissimilarity. Values were calculated using JUICE (Tichý 2002). We calculated the β diversity values within each group (non-impacted and impacted) by comparing randomly selected pairs of relevés. From all of the possible pairings (1485 impacted and 990 non-impacted), 500 pairs were randomly selected within each group and their β diversities were calculated. By performing this randomisation we excluded any variability not caused by the wind farm installation, such as the sampled area factor. We then performed a one-way ANOVA using SPSS 15.0 for Windows to test for significant differences between the β diversities of the impacted and non-impacted areas. We repeated this process five times.

Qualitative analysis

For a better understanding of the qualitative differences in plant communities between impacted and non-impacted sites, and to identify characteristic groups of species, a cluster analysis for the species recorded in at least five relevés was performed, again using SPSS 15.0 for Windows (Ward Method with a square root transformation of the Euclidean distance).

The relevés were then classified into syntaxonomical groups according to their floristic composition and structure. We assigned each relevé to a vegetation unit according to the values of the indices of similarity between the sampled relevé and the constancy columns of 151 associations from 17 syntaxonomical classes. These constancy columns were obtained from 2,824 bibliographic relevés using the phi coefficient as a fidelity measure (Chytrý *et al.* 2002) with no transformation of the species cover data. As there were large differences between the numbers of relevés for each association, we used two different standardisation parameters for the size of the target group: group to analyse is (i) the average size (0.64% of the total), or (ii) 5% of the total, which gives higher weight to common species. We employed the Frequency-Positive Fidelity Index (FPFI) as a similarity index due to its robustness with respect to the heterogeneity of the dataset (Tichý 2005). The reference matrix (for bibliographic and sampled relevés) was obtained using the JUICE program (Tichý 2002).

RESULTS

Average α diversity values were always higher for unaffected relevés, indicating that impacted areas are less diverse than non-impacted areas (Table 1). Nevertheless, we cannot reject the null hypothesis regarding species richness, as there were no significant differences ($P<0.05$) between impacted and non-impacted sites (Table 2). Rather than being related to impacts, the observed differences in species richness were related to the spatial variation found amongst the ten sampled areas.

The Shannon (H') and Simpson (D) indices showed that the disturbance caused by wind farms significantly reduced plant diversity ($p<0.05$; Table 2). As with the species richness, the Shannon index revealed that the location of sampled areas also influenced the variance between the two groups.

The values of evenness were slightly higher for non-impacted than for impacted areas, suggesting that the species abundances were more homogeneously distributed in non-impacted relevés. Non-impacted relevés were more equitable in terms of E_H than the impacted ones, regardless of their locations within the sampled areas. However, in terms of E_{var}, wind farms did not influence the evenness of the blanket bog plant communities since the observed differences amongst relevés appeared to be due to their locations (Table 2).

Table 1. Values of α diversity estimators from impacted and non-impacted areas. SD = standard deviation.

		mean	SD
Species richness (S)	Non-impacted	9.77	3.16
	Impacted	8.34	2.89
	Total	8.99	3.08
Simpson index (D)	Non-impacted	0.75	0.12
	Impacted	0.61	0.20
	Total	0.67	0.18
Shannon index (H')	Non-impacted	1.72	0.36
	Impacted	1.39	0.49
	Total	1.54	0.46
Evenness (E_H)	Non-impacted	0.77	0.10
	Impacted	0.66	0.15
	Total	0.70	0.14
Evenness (E_{var})	Non-impacted	0.46	0.07
	Impacted	0.44	0.07
	Total	0.45	0.07

Table 2. Results of ANOVA using α diversity indices as dependent variables, and impact and sampled areas as factors.

Factor	**Species richness (S)**		**Simpson index (D)**		**Shannon index (H´)**		**Evenness Pielou (E_H)**		**Evenness (E_{var})**	
	F	*Sig.*	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*
Impact	0.021	0.884	0.257	0.003	1.111	0.011	0.244	0.001	0.005	0.340
Areas	6.677	0.000	0.431	0.086	4.328	0.004	0.191	0.357	0.099	0.037
Intercept	1230.259	0.000	42.589	0.000	219.448	0.000	46.947	0.000	18.933	0.000

The estimators of β diversity produced the highest values in impacted areas (Figure 2). There were significant differences ($p<0.05$) between impacted and non-impacted areas in the five repetitions that were performed, and for all of the estimators. The results showed similar significant differences in all cases (Table 3). This increase in β diversity implies greater habitat heterogeneity in the impacted areas.

The cluster analysis (Figure 3) showed one species grouping comprising characteristic species of the blanket bog communities (*Agrostis curtisii* Kergušlen, *Calluna vulgaris* (L.) Hull, *Carex durieui* Steudel ex Kunze*, Molinea caerulea* (L.) Moench and *Erica mackaiana* Bab.). This group was clearly separated from introduced species and other common species at the first level.

Referring to the analysis of similarity between relevés and constancy columns of known vegetation units, the sampled relevés were assigned to twelve plant associations belonging to six different syntaxonomical classes (Table 4). However, only eight associations can be regarded as correctly assigned. It is likely that the errors in assignation were caused by bias in the reference matrix because some of the communities were not included in the constancy columns due to lack of bibliographic data. Allocations to uncited associations were interpreted as corresponding to vicarious communities for the Xistral or the biogeographic area.

Most of the areas sampled were characteristic of the *Carici durieui-Eriophoretum angustifolii* association of blanket bog habitats and its degradation phase, the *Molinea-Carici durieui* community. These plant associations have not been formally described, but they are likely to be endemic to the Xistral Mountains. Blanket bogs usually present very homogenous vegetation, but according to our β diversity results the impacted areas presented elevated community heterogeneity. Likewise, there were two communities of anthropic grasslands (*Cynosuro cristati-Trifolietum repentis* and *Caro verticillati-Cynosuretum cristati*) in impacted sites that were not found in non-impacted areas. In addition, there was a considerable reduction in the extent of the *Carici durieui-Eriophoretum angustifolii* community and an increase in the *Gentiano pneumonanthes-Ericetum mackaianae* community in the impacted compared to the non-impacted areas (Figure 4).

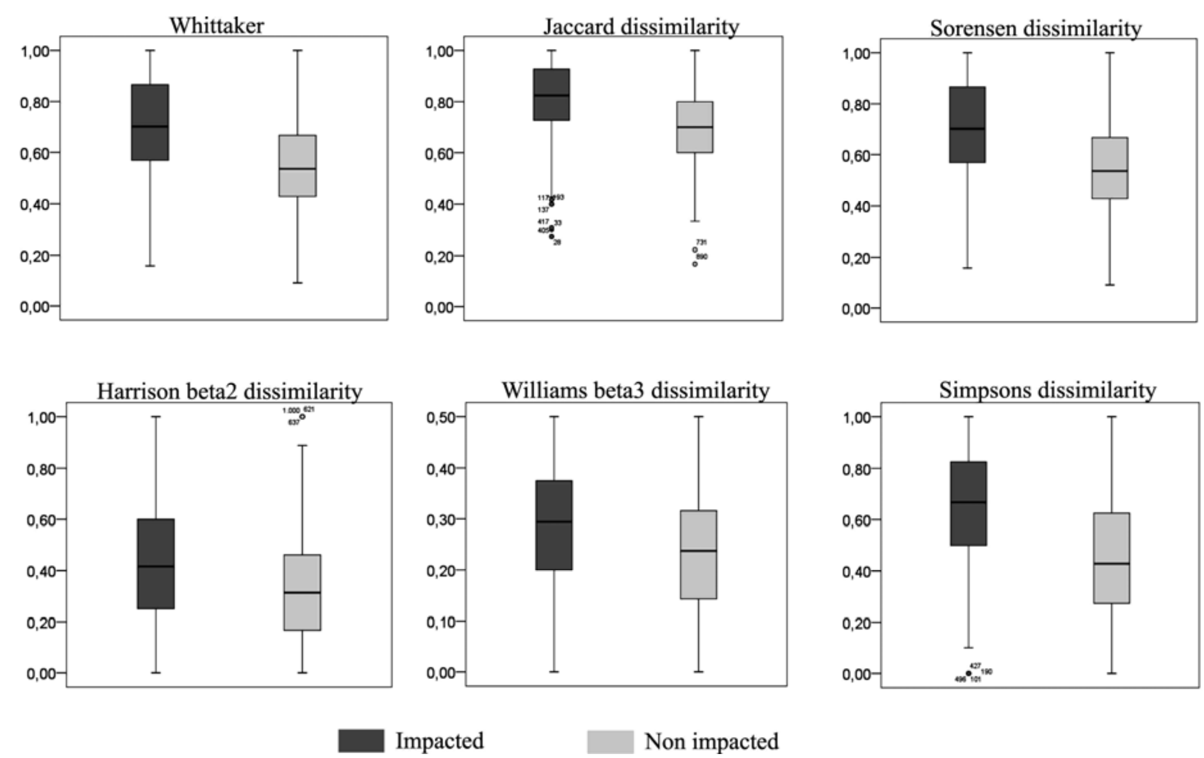

Figure 2. Selected β diversity box plots for impacted and non-impacted areas.

Table 3. ANOVA results for one of the five tests performed to compare β diversity between randomly selected pairs of relevés.

		sum of squares	**degrees of freedom**	**mean square**	**F**	**significance**
Whittaker	between groups	5.383	1	5.383	145.022	0.000
	within groups	37.041	998	0.037		
	total	42.424	999			
Jaccard dissimilarity	between groups	3.130	1	3.130	142.264	0.000
	within groups	21.959	998	0.022		
	total	25.090	999			
Sorensen dissimilarity	between groups	5.383	1	5.383	145.022	0.000
	within groups	37.041	998	0.037		
	total	42.424	999			
Harrison beta2 dissimilarity	between groups	2.787	1	2.787	58.526	0.000
	within groups	47.528	998	0.048		
	total	50.315	999			
Williams beta3 dissimilarity	between groups	0.768	1	0.768	61.569	0.000
	within groups	12.451	998	0.012		
	total	13.219	999			
Simpsons dissimilarity	between groups	8.047	1	8.047	135.732	0.000
	within groups	59.169	998	0.059		
	total	67.216	999			

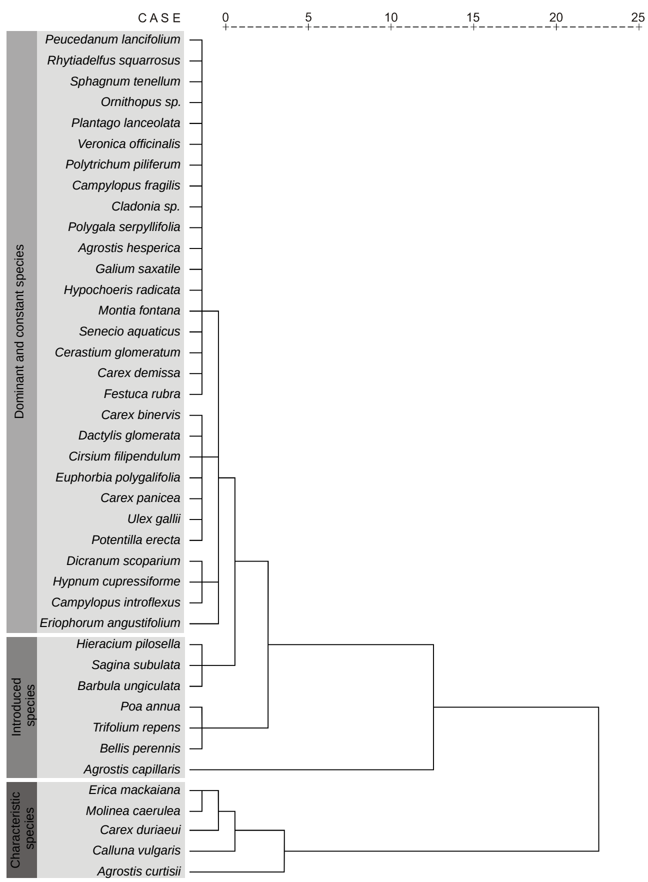

Figure 3. Cluster analysis showing the relationships between the 41 most frequent species in the sampled relevés. Nomenclature follows Castroviejo *et al.* (1986–2007) and Tutin *et al.* (1964–1980).

Table 4. Syntaxonomical classes and associations assigned to the sampled relevés, together with the corresponding cited associations. Allocations to uncited associations were interpreted as vicarious communities for the Xistral.

CLASS	ASSIGNED PLANT ASSOCIATIONS	CORRESPONDING CITED ASSOCIATIONS
Scheuchzerio-Caricetea nigrae	*Carici durieui-Eriophoretum angustifolii*	*Carici durieui-Eriophoretum*
	Molinea-Carici durieui community	*Molinea-Carici durieui* community
	Drosero intermediae-Rhynchosporetum albae	*Drosero intermediae-Rhynchosporetum*
Molinio-Arrhenatheretea	*Senecioni aquatici-Juncetum acutiflori*	*Senecioni aquatici-Juncetum acutiflori*
	Cynosuro cristati-Trifolietum repentis	*Cynosuro cristati-Trifolietum repentis*
	Caro verticillati-Cynosuretum cristati	*Caro verticillati-Cynosuretum cristati*
Nardetea strictae	*Nardo strictae-Caricetum binervis*	*Serratulo seoanei-Nardetum strictae*
	Selino pyrenaei-Nardetum strictae	
Calluno-Ulicetea	*Violo-Callunetum*	*Gentiano pneumonanthes-Ericetum mackaianae*
	Carici binervis-Ericetum ciliaris	
	Cirsio filipenduli-Ericetum ciliaris	
	Genisto anglicae-Ericetum tetralicis	

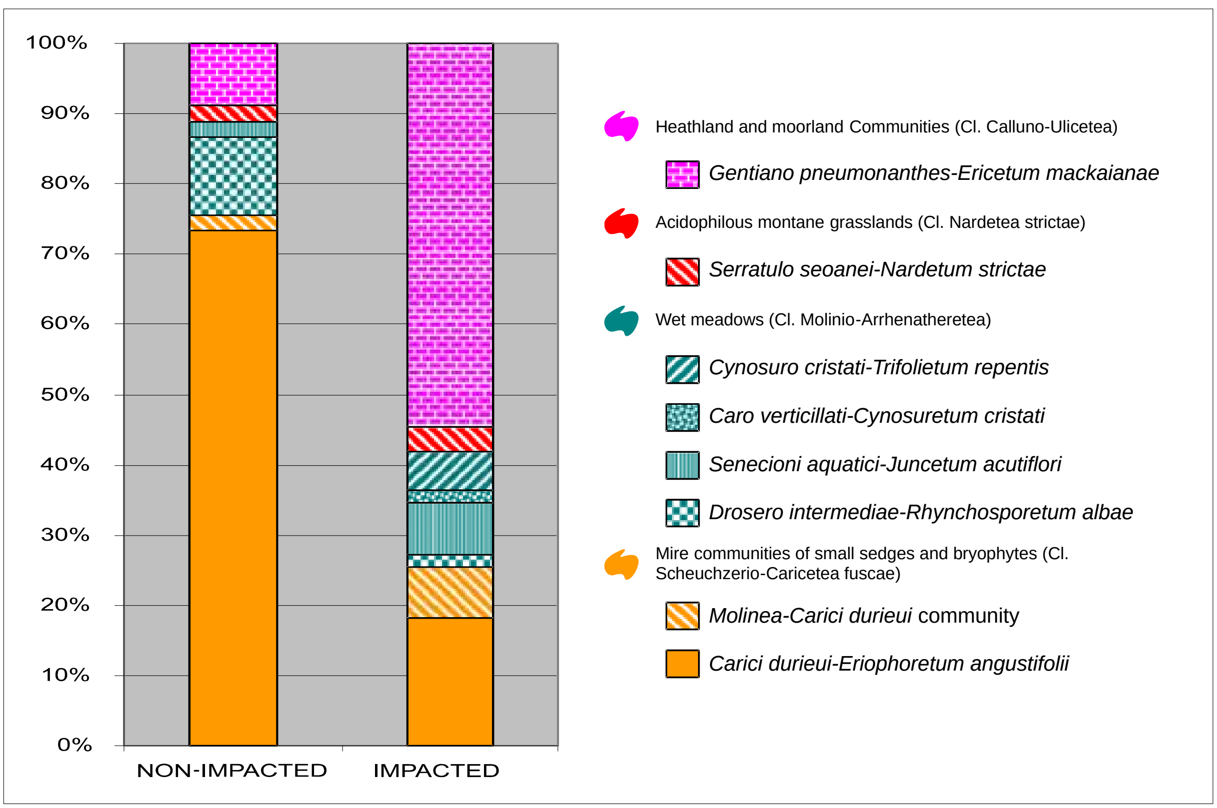

Figure 4. Histogram showing the percentage of plant communities found in impacted and non-impacted areas. Standardisation of the group of reference to 5%.

Standardisation with the two different target group sizes produced different sample allocations. Both methods indicated an increase of wet heath and meadow communities and a reduction of bog sedge communities but, interestingly, standardisation to 5% provided better results. The average quality of the assignations with this standardisation was 13.97% as compared to 9.76% with standardisation to the average group size. This was because the standardisation to 5% gave more weight to common species and so facilitated the detection of meadow communities.

DISCUSSION

Our results showed that the areas affected by wind farms present lower plant biodiversity even just nine years after the start of construction. Three of the five estimators of *α* diversity revealed significant differences. However, the variation in species composition has been shown to be affected by sampled area in addition to the impacts of wind turbine installation. Given that there were no available pre-impact data and our non-impacted sites were not entirely independent of the impact factor, a Before-After-Control-Impact (BACI) design would not have been useful.

The absence of significant differences in species richness suggested, as observed by Ma (2005), that species richness is determined by different and independent ecological processes from those driving diversity measures such as the Shannon or Simpson indices. The pattern found in the study area can be explained by both the spatial heterogeneity of disturbance and the 'patchiness' of resources.

The discrepancy between the results produced by the two Evenness indices may be explained by the fact that E_{var} is independent of species richness, since it is based on the variance of species abundance. Consequently, E_{var} shows the same sensitivity for rare and abundant species. Conversely, E_H affords greater weight to abundant than to rare species, as it measures the observed diversity as a proportion of the expected maximum diversity. It might be argued that E_{var} is not the most suitable estimator of evenness for cases such as this, where spatial variability is high.

With regard to loss of biodiversity, impacts can be especially serious for threatened species such as *Barbilophozia binsteadii* (Kaal.) Loeske*, Sphagnum magellanicum* Brid. and *Splachnum ampullaceum* Hedw., which are regarded as endangered species, or *Cephalozia connivens* (Dicks.) Lindb., *Sphagnum pylaesii* Brid.*, Leucobryum glaucum* (Hedw.) Ångstr. in Fries*, Woodwardia radicans* (L.) J. Sm., *Narcissus asturiensis* (Jord.) Pugsley, *Narcissus cyclamineus* DC. and *Narcissus pseudonarcissus* subsp. *nobilis* (Haw.) A. Fern., which can be considered as vulnerable species on the basis of the Galician Threatened Species Catalogue (Consellería de Medio Ambiente y Desarrollo Sostenible 2007), the 2006 Red List, the updated Check List of Bryophytes of the Iberian Peninsula (Sérgio *et al.* 2006) and the Spanish Red List of Vascular Plants (Bañares *et al.* 2003). Endemic species such as *Euphorbia polygalifolia* subsp. *hirta* (Lange) M. Laínz, *Carex durieui* Steud. ex Kunze, *Agrostis hesperica* Romero García, Blanca & Morales Torres and *Thymelaea coridifolia* subsp*. dendrobryum* (Rothm.) M. Laínz, as well as species included in the EU Habitats Directive annexes (EU 1992), like *Cladonia rangiferina* (L.) Web. in Wigg.*, Cladonia arbuscula* (Wallr.) Fot., *Leucobryum glaucum, Sphagnum* spp. (except *Sphagnum pylaesii*) and *Arnica montana* subsp. *atlantica* A. Bolòs can also be affected by the habitat destruction caused by wind farms. Moreover, several species are very sensitive to hydrological changes. Changes in groundwater regime and chemical composition have adverse repercussions for *Sphagnum* species including *S. capillifolium* (Ehrh.) Hedw., *S. compactum* Lam. & DC., *S. cuspidatum* Ehrh. ex Hoffm, *S. auriculatum* Schimp., *S. papillosum* Lindb., *S. subnitens* Russow & Warnst, *S. subsecundum* Nees, *S. tenellum* (Brid.) Perss. Ex Brid. and several sensitive vascular plants (*Drosera intermedia* Hayne in Dreves*, Drosera rotundifolia* L., *Pinguicula lusitanica* L., *Pinguicula vulgaris* L., *A. montana* subsp. *atlantica, Cirsium filipendulum* Lange *etc.*).

Loss of biodiversity as a result of human activities has been thoroughly documented (Cooper *et al.* 2005, Mälson *et al.* 2007, van der Wal *et al.* 2008 *etc*.). It is usually described at two levels (Bhat & Magurran 2007): (i) the loss of *α* diversity (diversity within habitats and samples) due to local extinctions and (ii) lower *β* diversity (diversity among habitats and samples) resulting from the homogenisation of floras across sites within a region. Although our results indicate an increase of local *β* diversity, the qualitative analysis of these results at regional scale suggests that what is taking place is a decline in distribution of the rarest habitats in favour of common habitats. In other words, there is a loss of *β* diversity at regional scale.

Cluster analysis clearly separated plant species appearing in affected and unaffected areas (Figure 3). Curiously, *Eriophorum angustifolium* Honck. was not included in the set of species linked to pristine blanket bog communities. This could be explained by its wide ecological range.

The plant communities that cover the summits and slopes of the Xistral are experiencing significant habitat loss. Despite the fact that these communities are the main components of a priority natural ecosystem (code 7130) established for conservation by the European Community Council, this vegetation is being drastically transformed in areas affected by wind farm construction. The impacts are reflected by a reduction of the *Carici durieui-Eriophoretum angustifolii* endemic community (i.e. the most representative plant association of the Xistral Mountains blanket bogs) and its substitution by wet heaths or humid grasslands, in addition to the appearance of new communities (wet meadows).

Most of the negative effects of wind farms on vegetation arise from the opening of roads and the ‘restoration’ activities that allow the colonisation of bogs by pioneer and invasive alien species from disturbed habitats. This is demonstrated by the cluster analysis (Figure 3) for the area we surveyed, the introduced species being combined with the most frequent ones before linking to the characteristic blanket bog species. Collateral effects linked to the opening of roads are the increase in grazing of the blanket bog by livestock (horses and cows) and traffic pollution, causing a progressive deterioration of the environment. Moreover, several peat landslides have been triggered by wind farm construction. Although none reached the magnitude of the slide observed by Lindsay & Bragg (2004) at Derrybrien (County Galway, Ireland), it is obvious that they contribute to modifying the structure and function of the blanket bogs. Comprehensive interdisciplinary studies will be needed to accurately evaluate their impact in the short and long terms.

CONCLUSIONS

1. The areas affected by wind farm construction showed lower plant α diversity than un-impacted patches.
2. Altered blanket bog plant communities in the Xistral Mountains are being replaced by grasslands and heaths.
3. In view of the background of habitat and plant diversity losses, threatened and rare species should be monitored.
4. Restoration activities must be compatible with the autochthonous vegetation in order to avoid the loss of native communities, the spread of invasive species and putative hybridisation.

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