Framework for strategic wind farm site prioritisation based on modelled wolf reproduction habitat in Croatia

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ABSTRACT

In order to meet carbon reduction targets, many nations are greatly expanding their wind power capacity. However, wind farm infrastructure potentially harms wildlife, and we must therefore find ways to balance clean energy demands with the need to protect wildlife. Wide-ranging carnivores live at low density and are particularly susceptible to disturbance from infrastructure development, so are a particular concern in this respect. We focused on Croatia, which holds an important population of wolves, and is currently planning to construct many new windfarms. Specifically, we sought to identify an optimal subset of planned wind farms that would meet energy targets while minimising potential impact on wolves. A suitability model for wolf breeding habitat was carried out using Maxent, based on 6 environmental variables and 31 reproduction site locations collected between 1997 and 2015. Wind farms were prioritised using Marxan to find the optimal trade-off between energy capacity and overlap with critical wolf reproduction habitat. The habitat suitability model predictions were consistent with current knowledge: probability of wolf breeding site presence increased with distance to settlements, distance to farmland and distance to roads, and decreased with distance to forest. Spatial optimisation showed that it would be possible to meet current energy targets with only 31% of currently proposed wind farms, selected in way that reduces the potential ecological cost (overall predicted wolf breeding site presence within wind farm sites) by 91%. This is a highly efficient outcome, demonstrating the value of this approach for prioritising infrastructure development based on its potential impact on wide-ranging wildlife species.

KEYWORDS

Wolf; *Canis lupus*; wind farms; habitat suitability modelling; spatial planning; Croatia.

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1. INTRODUCTION

Wind energy has many environmental advantages and represents an opportunity to mitigate anthropogenic climate change (Sims et al. 2003, Edenhofer et al. 2011). However, it also has several environmental drawbacks, mainly related to the large amount of land required for its implementation (Kiesecker et al. 2011) and to the impacts it may have on several wildlife species. These species include: birds and bats, marine mammals, and large terrestrial species such as reindeer (*Rangifer tarandus*), red deer (*Cervus elaphus)*, wolverine (*Gulo gulo*), Eurasian brown bear (*Ursus arctos*) and wolf (*Canis lupus*) (Drewitt and Langston 2006, Madsen et al. 2006, Kunz et al. 2007, Helldin et al. 2012, Colman, et al. 2013, Voigt et al. 2015). In particular, wind plants can have a negative impact on wolf breeding success (Àlvares et al. 2011, Helldin et al. 2012, Álvares et al. in press). For example, Àlvares et al. (2011) show that during the construction and operation phases of one wind power plant, wolves tended to abandon reproduction sites and have a decreased reproduction rate in areas closer than 2 km from the nearest turbine. Moreover, in two case studies in Portugal, wolf breeding parameters were monitored in a 15-year-long period before, during and after the construction of wind farms (Álvares et al. in press). In this study, the authors showed that, during the construction phase, wolves kept breeding in the wind farms area with decreased reproduction rate, while, during the operation phase, wolves started selecting reproduction sites located at least 4 km away from the nearest turbine (Álvares et al. in press). GPS-Telemetry data also showed shifts of home ranges partially away from wind power plants (Álvares et al. in press).

The reasons behind the impact of wind farms on wolves are mainly related to habitat changes. Several studies have shown that wolves tend to locate their dens in forested areas and avoid relatively high density of roads, human-made structures and human disturbance, particularly during homesite selection (Sazatornil et al. 2016, Theuerkauf et al. 2003, Karlsson et al. 2007, Person and Russell 2009, Houle et al. 2010, Iliopoulos et al. 2014). Besides the installation of turbines, wind farms require the construction of roads, transformers, substations and transmission lines, which cause habitat loss and fragmentation (Kuvlesky Jr et al. 2007, Àlvares et al. 2011, Northrup and Wittemyer 2013). Access roads can increase the chance of wolf collisions with vehicles and facilitate the access of poachers into wolf habitat (Person and Russell 2008, Àlvares et al. 2011, Helldin et al. 2012). Between 1986 and 2001, roadkills and illegal killings constituted nearly 90% of reported mortality cases in Croatia (Huber et al. 2002). Moreover, despite the lack of evidence, Helldin et al. (2012) speculated that the noise produced by wind turbines may disturb vocal communication in terrestrial animals, including wolf howling. It has been shown that howling in wolves has several important functions that tend to peak during the breeding season, including territorial defence and coordination of movements among separated packmates (Harrington et al. 2003, Mech and Boitani 2003).

In Croatia, wind energy has been identified as the main source of renewable energy to be implemented by 2030 (Sedlar et al. 2011). The current wind power installed capacity, as of March 2016, is 452.75 MW (Anonymous 2015). However, in order to meet the target of the Directive 2009/28/EC of the European Parliament, and according to the Energy Strategy for the Republic of Croatia (Official Gazette 130/09), wind farms have to reach a total installed capacity of 1,200 MW by 2020. To reach this target, a further installed capacity of 747.25 MW is needed. Notwithstanding, 39 wind farms, with a total installed capacity of 1,918.8 MW, are planned to be built (Anonymous 2015). Therefore, they would provide more than twice as much installed capacity as needed to reach the target set for 2020. Moreover, the vast majority of wind farms are located in the wolf distribution range (Fig 1).

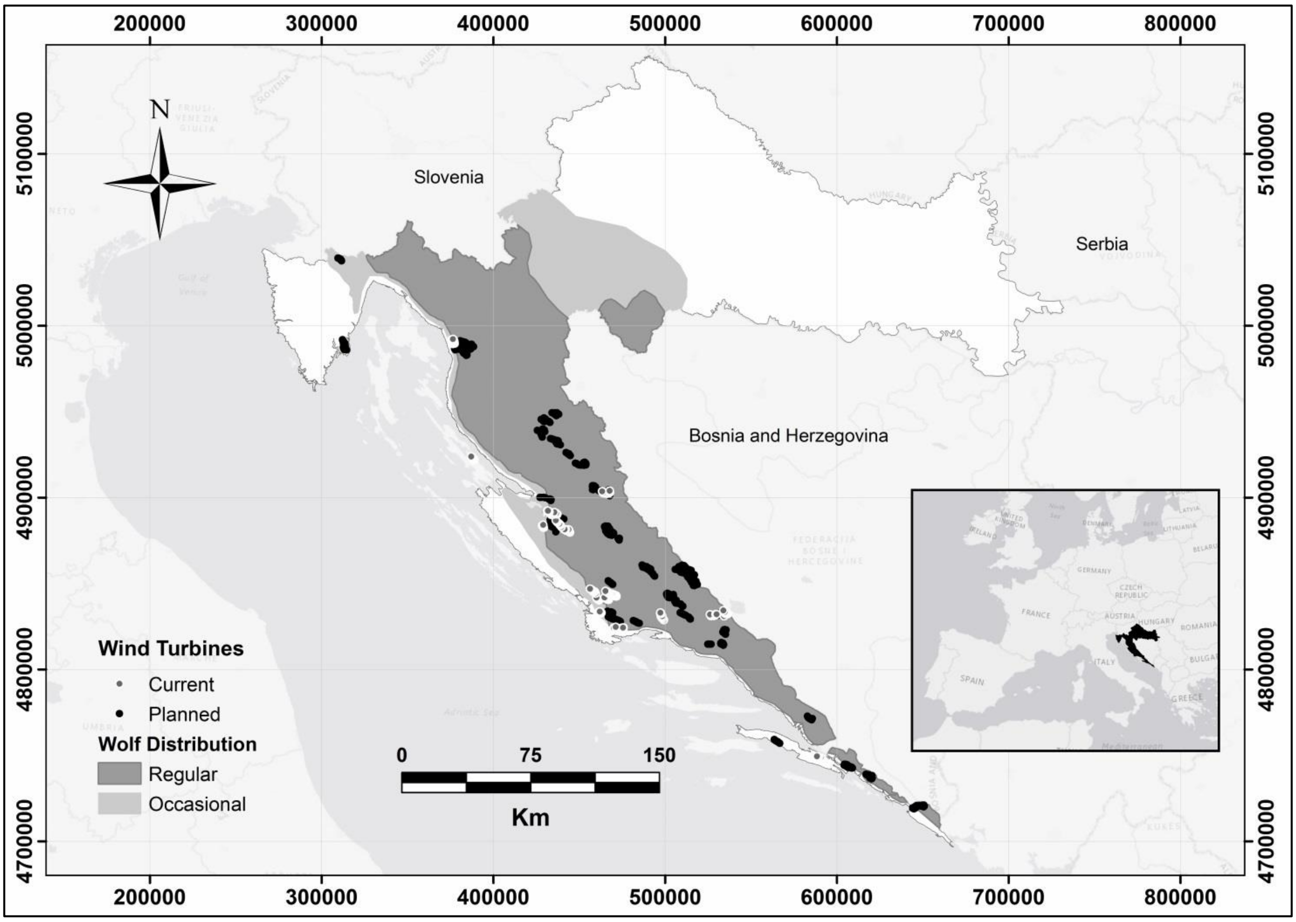

Fig.1 Distribution of wind farms and wolves in Croatia. Coordinates are in metres (HTRS96/Croatia TM).

The grey wolf (*Canis lupus*) in Croatia is part of the Dinaric-Balkan population, which spreads across 10 countries in south-east Europe and include *circa* 3,900 individuals (Kaczensky et al. 2013). With approximately 200 wolves (168-219) (Kusak and Huber 2010), Croatia occupies the western part of the population (Kaczensky et al. 2013). As such, it represents a particularly important area for European wolves, since it allows the connection with the Alpine and the Italian Peninsula populations (Fabbri et al. 2014, Ražen et al. 2015). Although the wolf population in Croatia has been relatively stable in the last 10 years, since 2011 it is undergoing a gradual decline in abundance (Jeremić et al. 2014, Kaczensky et al. 2013). The main causes of this contraction are negative public attitudes and persecution (Majić and Bath 2010), and habitat loss and fragmentation, due to the construction of major infrastructure like highways and wind energy plants (Kusak et al 2009a, Kaczensky et al. 2013).

Because of the potentially negative impacts of wind farms on biodiversity, many studies have given particular attention to developing and implementing tools for wind farm spatial planning and prioritisation (Vasilakis et al. 2016, Bright et al. 2008, Bastos et al. 2015, Baban and Parry 2001, Punt et al. 2009, Aydin et al. 2010, Tegou et al. 2010, Drechsler et al. 2011, Baltas and Dervos 2012, Göke and Lamp 2012). Adopted approaches include the use of species sensitivity maps (Vasilakis et al. 2016, Bright et al. 2008), integrative dynamic modelling of habitat and impacts (Bastos et al. 2015), multiple-criteria decision analysis (Tegou et al. 2010), fuzzy-logic-based methods (Aydin et al. 2010), numerical optimisation (Punt et al. 2009, Drechsler et al. 2011), and the use of spatial planning software such as Marxan (Göke and Lamp 2012). The main environmental parameters considered were nature reserves and conservation areas, but many studies overlooked the actual distribution of species and habitats, especially outside such areas. For these reasons, research on the localisation of infrastructure like wind farms and on their effects on ungulates and large carnivores is strongly needed (Gortazar 2012, Helldin et al. 2012). This study presents the first habitat suitability model for wolf breeding habitat in Croatia. We use the output of the model to inform the strategic prioritisation of proposed wind farms, in order to minimise potential impacts on wolves while meeting energy targets. This framework can be adopted for other infrastructure and can be extended to multiple wildlife species.

2. METHODS

2.1 Data Collection and Preparation

The locations of wolf reproduction sites from 11 packs were collected in four main areas (Gorski kotar, Dalmatia, Plitvice and Velebit) from April to September between 1997 and 2015. Reproduction sites (also known as homesites or breeding sites) are areas associated with pup rearing, and may be either dens and/or rendezvous sites (Harrington and Mech 1978). Dens are the sites where wolf pups are raised during the first 8 weeks from birth, while rendezvous sites are areas above ground where pups are raised between 8 and 20 weeks of age, and include play areas and bedding (Mech 1970, Packard 2003). While dens were located through direct observations, with the help of GPS and VHF-telemetry data, rendezvous sites were identified using the simulated howling survey method, following the recommendations of Harrington and Mech (1982). All howling surveys were carried out between July and September. During this time, the packs are still relatively sedentary, the response rate is high, and young wolf howls are more likely to be distinguishable from adults' (Harrington and Mech 1982, Harrington et al. 2003, Packard 2003). A rendezvous site was considered as such when the presence of pups was confirmed either by howling or by other signs, such as direct observation, camera trap photos, dead pups or footprints. Once the approximate area of a rendezvous site was found, its location was estimated by experienced researchers through repeated close approaches to responding pups, up to *circa* 200 metres. Some wolves in the population were tracked with GPS collars during the study period (Kusak et al. 2005, Kusak 2010). GPS locations from these wolves were also used to locate rendezvous sites.

As wolves can use the same rendezvous site in different years (Capitani et al. 2006), locations that were closer than 500 metres were assumed to be part of the same site and were excluded from our sample as suggested by Bassi et al. (2015). Moreover, only one point per year was selected for each pack. This was a conservative measure to minimise the potential effect of pseudo-replication and avoid overestimating the importance of the variables associated with those sites.

2.2 Model predictors and wind farms data

Six environmental variables were chosen as potential predictors for wolf breeding habitat based on other similar studies (Corsi et al. 1999, Theuerkauf et al. 2003, Capitani et al. 2006, Ahmadi et al. 2013). Variables were: distance to settlements, distance to farmland (i.e. arable land, permanent cropland, livestock farming and permanent pastures), distance to roads (including unpaved forest roads), distance to forest (cells within forest assigned 0), altitude, and slope. For all these variables a 250x250 m ASCII grid was created for the whole of Croatia using ArcMap 10.2. All distances were calculated from the centroid of the cells.

Correlation coefficients (R) were calculated among all layers using the Band Collection Statistics tool in ArcMap 10.2, in order to avoid collinearity and, thus, the distortion of variables' relative contribution in determining habitat suitability (Dormann et al. 2013). The threshold value to discriminate correlated variables was set to $R>0.7$ (Dormann et al. 2013, Kramer-Schadt et al. 2013, Syfert et al. 2013).

The data from which these variables were created were obtained from different sources. In particular, altitude was obtained from a Digital Elevation Model (DEM) made available by the Croatian State Geodetic Administration (SGA). Slope was derived from the same DEM using the "Slope" tool in ArcMap 10.2. Distance to roads, updated to 2006, was obtained from a digital topographic map issued by the same institution. Distance to settlements, distance to farmland and distance to forest were obtained from the 2006 Croatian National Habitat Classification (Official Gazette 7/06).

Finally, the locations of wind turbines within each wind farm were obtained from the Department of Renewable Resources and Energy Efficiency of the Croatian Ministry of Economy, Labour and Entrepreneurship (Anonymous 2015).

2.3 Habitat Suitability Modelling

The habitat suitability model was performed using the presence-only Species Distribution Model (SDM) Maxent (Version 3.3.3) (Phillips et al. 2006). Maxent models habitat suitability by identifying the maximum entropy distribution of a species' presence localities based on user-specified environmental variables (Phillips et al. 2006).The program provides a habitat suitability map together with variables' response curves and model evaluation data including the area under the Receiver Operating Characteristic curve (AUC) and the variables' permutation importance. The AUC quantifies the predictive performance of the model, with an AUC of 0.5 indicating a random distribution of presence points, and an AUC tending towards 1 indicating increasing discrimination of presence points compared to random locations (Phillips et al. 2006). The permutation importance is a relative measure of how much the AUC changes when the values of a variable at occurrence and background locations are randomly permuted (Phillips 2005).

Before starting the simulations, occurrence locations and environmental variables were loaded into the model. In Maxent, occurrence locations are treated as cells, corresponding to the cells of the predictors in which they fall. In this analysis, the cell size was 250x250 metres. The model was run for 15 replications. In each replication, 25% of presence localities were randomly set aside and used as test points to compute the main Maxent outputs. In order to determine the AUC, Maxent compares the presence localities with a set of pseudo-absence points randomly selected from a user-specified area (Phillips et al. 2006). However, when the occurrence data are potentially biased (e.g. close to roads with easier research access), in order to avoid such bias to be represented in the whole model, the pseudo-absences can be selected from an area that shares the same potential bias as the presence points (Zaniewski et al. 2002, Dudík et al. 2005, Phillips et al. 2009). Hence, in this study, pseudo-absences were selected from the sampling distribution of wolf research carried out since 1997 as suggested by Fourcade et al. (2014).

After running the model, the effect of pseudo-replication potentially resulting from considering more than one homesite per pack was examined by running a set of 20 test-models in Maxent inputting only one homesite per wolf pack (i.e. 11 points) randomly selected each time. These models were run using the same parameters as the main output of this study. Selecting one point per pack allows pseudo-replication to be removed from the test-models, which were then compared to the main output map, using the spatial correlation coefficient calculated with the Band Collection Statistics tool in ArcMap 10.2. The aim of this approach was to test that the output of the test-models would not differ substantially from the main output. Additionally, in order to control for the effect of potential spatial autocorrelation among reproduction sites, the Moran's Index on model residuals (1 – probability of suitability in occurrence locations) was calculated over 30 distance bands (from 2 to 60 km) between reproduction sites, using the Incremental Spatial Autocorrelation tool in ArcMap 10.2. This approach determines whether the values of residuals are located randomly across space or in some sort of spatial clustering, and it has already been used to test autocorrelation in Maxent outputs (Mateo-Tomás and Olea 2010, De Marco et al. 2008, Dormann et al. 2007).

2.4 Wind Farm Site Prioritisation

The strategic prioritisation of planned wind farm sites was carried out using Marxan (Version 2.43), a program originally designed for protected area spatial planning (Pressey et al. 2007, Ardron et al. 2008), but suitable for a wide range of applications (Rondinini and Boitani 2007, Ban and Vincent 2009, Göke and Lamp 2012). The program identifies optimal configurations of complementary areas (called "Planning Units") in order to meet specific objectives at the minimum political, social or economic cost (Pressey et al. 2007, Ardron et al. 2008). In order to do so, Marxan applies the simulated annealing optimisation algorithm over many repeated runs, producing two main types of output: the best solution among all runs and the irreplaceability score. The irreplaceability score is the number of times in which each planning unit was selected among all runs (Ardron et al. 2008).

In this study, Marxan was used in an unusual way, similar to the approach adopted by Göke and Lamp (2012). Wind farms were considered as Marxan planning units, each of which contributes to the wind energy production targets at an ecological cost on wolf breeding habitat. According to some observations made on wolf packs in Portugal, wolves avoid breeding within 4 km of operational wind farms (Alvares et al. in press). Thus, based on currently available information and adopting a precautionary approach, a buffer of 4 km was added around each existing and planned wind turbine. The cost of each planning unit was determined using the output of the Maxent model, which provides a spatial measure of ecological suitability. The ecological cost of each planning unit was calculated by summing the predicted suitability values of its grid cells. Hence, the impact of wind farms on wolves was assumed to be proportional to the total habitat suitability across cells within the boundaries of the buffer strip. The sum of the cells takes into consideration both the area and the average cell value of each planning unit. For example, a wind farm built over a bigger area would have a higher impact than a smaller wind farm *ceteris paribus*. Similarly, a planning unit with a high average cell suitability value would have a higher impact than a similarly sized but on average less suitable unit. Lastly, in the cost determination, the presence of operating wind farms was also considered. As such, in areas where operating and proposed wind farms overlapped, the cost of adding a new wind farm was considered nil. This decision was made based on the assumption that if a planned wind farm is built around other wind farms already in operation, then its additional ecological cost on wolves would be lower than the cost of building that same wind farm in a previously undisturbed area.

On the other hand, each proposed new wind farm contributes to the energy production targets set in the Croatian energy strategy. The installed capacity target for all planning units in Marxan was set to 747.25 MW and was determined by removing the already installed capacity (452.75 MW) from the 2020 installed capacity target of 1,200 MW (Energy Strategy for the Republic of Croatia - Official Gazette 130/09). The Marxan analysis was run for 100 repetitions, and the conservation feature penalty factor, a parameter representing Marxan's emphasis on meeting a target, was set to 100 (i.e. sufficiently high for the target to be met in all repetitions).

3.RESULTS

3.1 Habitat Suitability Modelling

A total of 31 reproduction sites were found between 1997 and 2015 (Fig 2). Among these, 24 were rendezvous sites and 7 were dens. Sites were obtained from 11 wolf packs. The values of environmental variables at occurrence locations show a very high variability indicated by high standard deviation values (Table 1). Looking at the minimum values, it can be seen that some reproduction sites were located very near roads and farmland, while all sites tended to be located further from human settlements. Finally, as shown by median values, reproduction sites were mainly found inside or very close to the forest, with only two sites outside (respectively 2015 and 250 metres away). The correlation among environmental variables, as shown by the spatial correlation coefficients (Appendix 1), was weak in most cases (R<0.60) and slightly higher for distance to farmland with altitude (R=0.62), and distance to farmland with distance to settlements (R=0.64). However, since all values were below 0.7, all variables were accepted in the model.

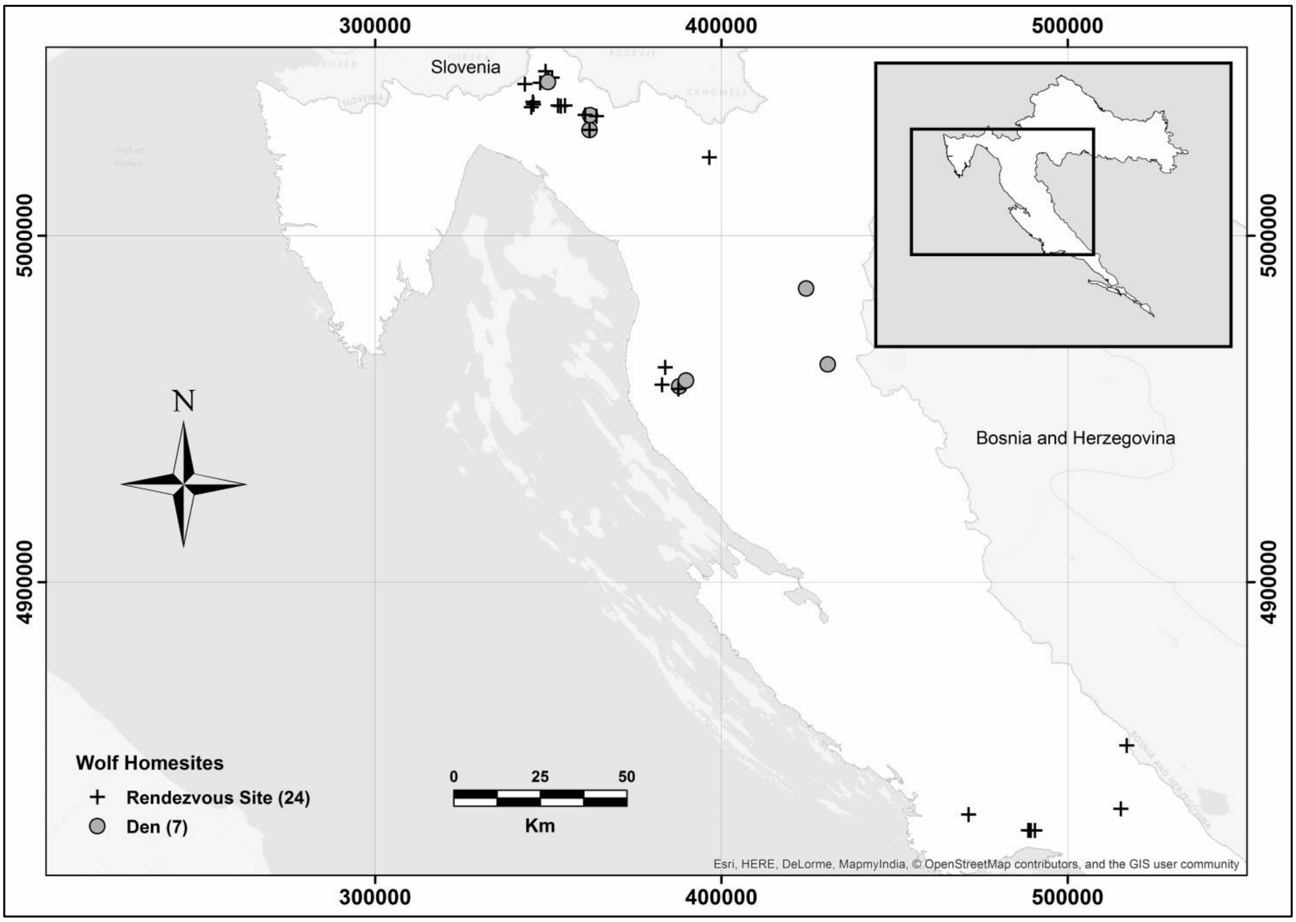

Fig. 2 The 31 wolf reproduction site locations collected between 1997 and 2015. Coordinates are in metres (HTRS96/Croatia TM).

Table 1 Main values for the 6 environmental variables. Min=Minimum value; Max=Maximum value; STD=Standard deviation. For "distance to" variables, nil values indicate that a homesite is located in the same cell (measuring 250x250 m) of an environmental feature and, thus, do not necessarily pinpoint a distance of 0 metres.

Variable	Min	Max	Mean	Median	STD	Permutation Importance (%)
Distance to Settlements	901.39	10960.16	5106.61	4472.14	2757.53	29.48
Distance to Farmland	0.00	15337.86	5604.21	5505.68	3787.99	14.43
Distance to Roads	0.00	2610.08	674.88	353.55	625.55	11.86
Distance to Forest	0.00	2015.56	65.02	0.00	356.12	33.10
Altitude	285.47	1496.54	867.94	960.53	325.10	8.42
Slope	0.17	14.39	6.40	5.97	3.69	2.71

Overall, the model showed good performances, indicated by an AUC of 0.805 (SD=0.072). According to the permutation importance values, the most important predictors for wolf reproduction site suitability were distance to forest, which was negatively correlated with probability of presence, and distance to settlements, distance to farmland and distance to roads, which were all positively correlated with habitat suitability (Table 1, Fig 3).

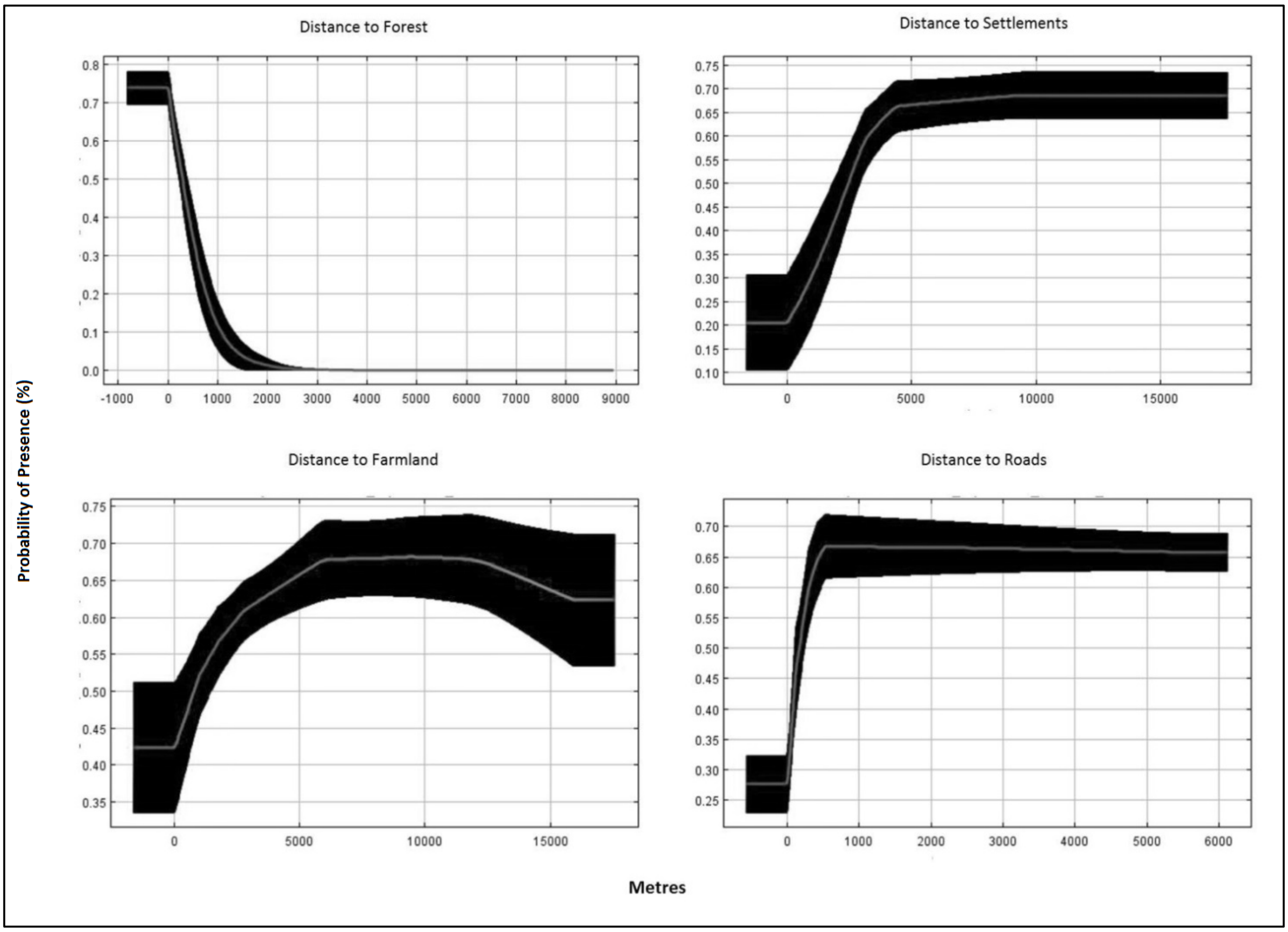

Fig. 3 Response curves for the 4 main model predictors. The curves show how the reproduction site probability of presence changes with each predictor, maintaining all other predictors at their average sample value. The white curves represent the mean trends, while the black shades show the standard deviation. In each graph, the X axis shows the change in each environmental variable, while the Y axis shows the reproduction site probability of presence.

Based on the predicted habitat suitability map (Fig 4), most suitable areas are found along the Dinaric Mountains and in smaller, isolated and currently unoccupied areas in the northern and north-eastern parts of Croatia. In the map, a reduction of suitable breeding habitat along roads and settlements can also be noticed.

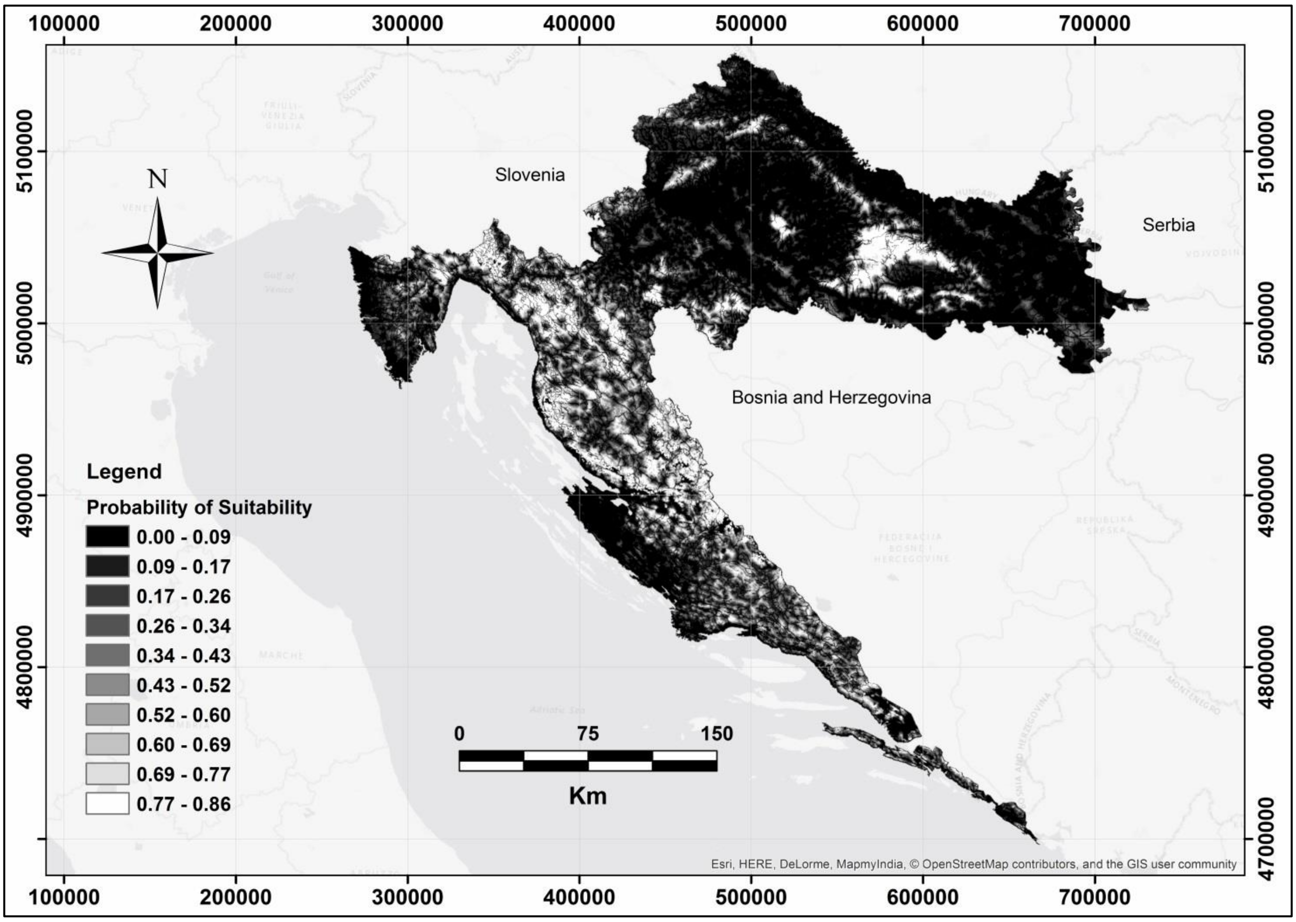

Fig. 4 Habitat suitability map obtained with Maxent. Darker shades indicate low suitability, lighter shades indicate high suitability. Coordinates are in metres (HTRS96/Croatia TM)

When the output map of the main model was compared to the 20 test-models run with only one point per pack, the average value of the spatial autocorrelation coefficient was 0.79 (SD=0.02), while the 20 test-models among themselves had an average value of 0.94 (SD=0.04) (Appendix 2). However, the 20 test-models showed, on average, a much lower performance (AUC=0.68) and a much higher standard deviation (SD=0.13). The results of the Incremental Spatial Autocorrelation on model residuals did not show autocorrelation (Moran's I included between ± 0.1; z-score <1.35) (Appendix 3). For these reasons, the main model was considered adequate.

3.2 Wind Farm Prioritisation

Proposed wind farms are mainly located within the current wolf distribution range and overlap with several high quality wolf reproduction areas. The Marxan analysis shows that the 2020 target of the Croatian energy strategy could be met with only 12 wind farms (Fig 5; Table 2). These correspond to 30.77% of the 39 total proposed wind farms. After wind plant selection, the resulting installed capacity would be 748 MW (i.e. 38.98% of the total proposed capacity). With respect to the potential impact on wolf breeding habitat, the optimisation would lead to a decrease of 90.97% in ecological cost. Thus, 38.98% of proposed installed capacity would hold only 9.03% of the total ecological cost. This indicates that Marxan allowed selecting highly cost-efficient wind farms.

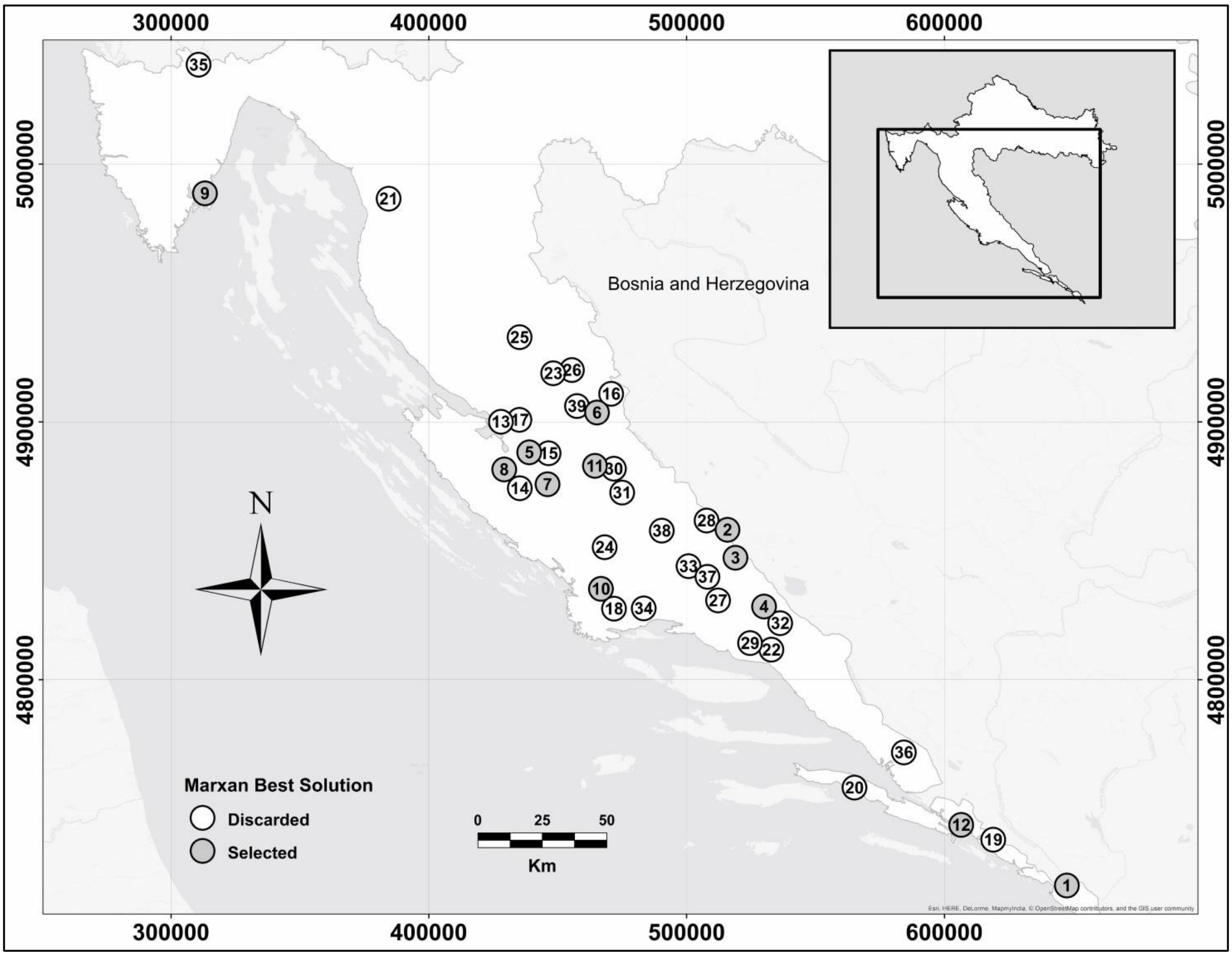

Fig. 5 Best solution for the Marxan analysis over 100 repetitions. The number of each wind farm corresponds to the numbers in Table 2. Coordinates are in metres (HTRS96/Croatia TM).

Additionally to the best selection, Table 2 also reports the irreplaceability score for each wind farm across 100 runs. This output provides less categorical information which could be particularly useful during negotiations and planning processes. Moreover, it may be more suitable for the integration of this study with others focusing on different types of impacts.

Table 2 Marxan values for all wind farms. Cost=Maxent suitability scores summed across windfarm cells; MW=Installed capacity in MW; IS=Marxan Irreplaceability Score; Wind farms in bold correspond to selected wind farms in Marxan Best Solution. Percentages show the proportions compared to all wind farms. The ID numbers in this table correspond to wind farms shown in figure 5.

ID	Wind Farm Name	Cost	Cost%	MW	MW%	IS
1	**VE Konavodska brda**	**92.13**	**0.94**	**117**	**6.10**	**100**
2	**VE Ravno Vrdovo**	**14.78**	**0.15**	**120**	**6.25**	**100**
3	**VE Rust**	**135.28**	**1.38**	**120**	**6.25**	**100**
4	**VE Voštane**	**3.79**	**0.04**	**27**	**1.41**	**100**
5	**VE ZD2P**	**0.00**	**0.00**	**48**	**2.50**	**100**
6	**VE ZD6**	**0.00**	**0.00**	**20**	**1.04**	**100**
7	**VE ZD3P**	**12.74**	**0.13**	**33**	**1.72**	**98**
8	**VE ZD4P**	**1.91**	**0.02**	**18**	**0.94**	**94**
9	**VE Goli**	**172.02**	**1.76**	**72**	**3.75**	**84**
10	**VE Glunča**	**61.61**	**0.63**	**23**	**1.20**	**76**
11	**VE Krš Padene (KPA) 1. faza**	**203.72**	**2.08**	**80**	**4.17**	**72**
12	**VE Rudine**	**185.84**	**1.90**	**70**	**3.65**	**71**
Total for selected wind farms		**883.82**	**9.03 (-90.97)**	**748**	**38.98 (-61.02)**	**-**
13	VE ZD5	8.83	0.09	20	1.04	65
14	VE Krug - Bikina Glava	80.76	0.82	23	1.20	32
15	VE Orljak	138.97	1.42	42	2.19	29
16	Proširenje ZD6 (dio) snage oko 45 MW	152.76	1.56	45	2.35	26
17	Kompleks male vjetroelektrana Jasenice	78.13	0.80	10	0.52	20
18	VE Boraja II	172.55	1.76	45	2.35	14
19	VE Mravinjac	223.96	2.29	57	2.97	7
20	VE Bila Ploča	163.45	1.67	33	1.72	5
21	VE Senj	707.42	7.23	186	9.69	3
22	VE Katuni	228.27	2.33	39	2.03	2
23	VE Mazin 2	194.95	1.99	20	1.04	1
24	VE Mideno brdo	133.62	1.36	21	1.09	1
25	Kompleks vjetroelektrana Udbina 120MW	1824.40	18.64	120	6.25	0
26	VE Bruvno	388.47	3.97	45	2.35	0
27	VE Čemernica	282.92	2.89	45	2.35	0
28	VE Debelo brdo	624.44	6.38	35	1.82	0
29	VE Kom-Orjak-Greda	157.78	1.61	10	0.52	0
30	VE Krš Padene-Proširenje	317.00	3.24	42	2.19	0
31	VE Ljubač - faza 1	123.81	1.26	10	0.52	0
32	VE Lukovac	266.47	2.72	48	2.50	0
33	VE Ogorje	410.76	4.20	54	2.81	0
34	VE Opor	313.10	3.20	33	1.72	0
35	VE Plašine	286.82	2.93	23.8	1.24	0
36	VE Rujnica	302.71	3.09	22	1.15	0
37	VE ST3-1/2	231.19	2.36	33	1.72	0
38	VE Svilaja	769.29	7.86	64	3.34	0
39	VE Vučipolje	322.86	3.30	45	2.35	0
Total for all wind farms		9789.51	100	1918.8	100	-

4.DISCUSSION

4.1 Framework and Methodological Choices

The presented framework used an SDM and an optimisation program to predict potential impacts of wind farms on wolves and identify the optimal set of wind farms which would contribute to meeting energy targets at the minimum possible cost. This study aims to provide a framework to inform the current wind energy development in Croatia, using all available information and adopting relatively simple and commonly-used programs, such as Maxent and Marxan.

Maxent was chosen for several reasons. Being a presence-only SDM, it does not require absence data, which can be unreliable and difficult to obtain for elusive and wide-ranging species like wolves (Mech and Boitani 2003, Phillips et al. 2006). For species that do not occupy all suitable areas, like the wolf in Croatia (Kaczensky et al. 2013, Chapron 2014), absence data might be located in unoccupied but suitable habitat (Elith et al. 2011). Thus, an absence data might not be indicative of unsuitable habitat and might cause unoccupied suitable areas to be considered unsuitable (Elith et al. 2011). Moreover, among the most commonly used presence–only SDMs, Maxent was shown to have high performances, particularly at small sample sizes (Hernandez et al. 2006, Wisz et al. 2008). Regardless of this decision, the choice of SDM is highly dependent on the type and amount of available data (Hernandez et al. 2006). Thus, other methods may be more appropriate in other studies and in different circumstances.

With regards to wind farm prioritisation, Marxan was chosen as, besides fitting the purpose of this study of meeting specific targets while minimising costs (Ball et al. 2009), it is relatively easy to handle and flexible to changing situations and regular data updates (Ardron et al. 2008, Göke and Lamp 2012). Unlike other optimisation methods using other types of algorithm, Marxan output provides several near-optimal alternatives, as opposed to a single best solution (Ardron et al. 2008). In spatial planning, a set of "good" solutions is often preferred to a single one, since it allows negotiation among stakeholders and enables the consideration of other factors that could not be included in the first analysis (Possingham et al. 2000). For these reasons Marxan was considered the most appropriate program.

This prioritisation approach may be extended to other infrastructure and to other wide ranging and non-volant species, such as ungulates and large carnivores. However, some complications could arise when considering multiple and incommensurate costs in optimisation processes (Göke and Lamp 2012). In particular, in order to be minimised, the different types of costs have to be merged in a single overall value (Punt et al. 2009, Drechsler et al. 2011, Göke and Lamp 2012). As such, each single cost has to be given a subjective weight that reflects its importance in the calculation of the total cost. For large carnivores, it may be difficult to determine these weights, since detailed information about the extent of wind farms' impacts on each species are not available. Moreover, once the total cost is minimised, it should be verified that the minimisation occurs equally for each single cost and that all costs are satisfactorily minimised. For these reasons, particular caution should be used when considering multiple species simultaneously.

4.2 Habitat Suitability Model

This study provides the first habitat suitability model for wolf reproduction sites in Croatia. The model showed good performance, obtaining an AUC value of 0.805 (Swets 1988, Elith 2000, Hosmer Jr and Lemeshow 2004), comparable to that of other similar studies (Ahmadi et al. 2013, Iliopoulos et al. 2014, Bassi et al. 2015). The comparison of this model with the 20 test-models run with only one point per pack show a strong correlation (R=0.79). The use of more than one reproduction site per pack in the main model allowed a substantial increase in sample size (11 to 31), and resulted in a much higher performance compared to the test-models. Moreover, the Incremental Spatial Autocorrelation analysis on the residuals did not show spatial clustering against any of the distance bands. For these reasons, any potential pseudo-replication which may have been present among reproduction sites was not considered to substantially and negatively affect the main output.

With regards to predictors, some variables in the habitat suitability model were moderately correlated, and their relative contributions to the model should therefore be interpreted with caution, as it is impossible to determine which is the most important in predicting suitability (Baldwin 2009). For example in this study, distance to settlements and distance to farmland were important predictors for habitat suitability. However, since they were the most correlated variables (R=0.64), their contributions may not be representative of their independent importance in determining habitat suitability. Nevertheless, settlements and farmlands are both related to human activities which deter wolves from breeding in their proximity (Sazatornil et al. 2016, Theuerkauf et al. 2003, Kusak et al. 2005, Jędrzejewski et al. 2008, Ahmadi et al. 2013, Bassi et al. 2015). Hence, their relative importance may be proportional to the type and extent of the disturbance they cause.

The distance to roads was positively correlated with wolf habitat suitability and was another important variable. However, looking at the response curve it can be noticed that, with increasing distance, the suitability increases rapidly, reaching a plateau after few hundred meters. This result is consistent with other studies (Theuerkauf et al. 2003, Kaartinen et al. 2005, Ahmadi et al. 2013). Hence, it seems that roads are likely to have an effect on breeding habitat only for the first few hundred meters.

Among the environmental predictors, the most influential was distance to forest, as shown in other works (Theuerkauf et al. 2003, Ahmadi et al. 2013). Some environmental variables that could potentially have higher contributions, such as prey availability and water sources, were not considered in this study, since adequate data were not available. In any case, in human dominated regions like Europe, anthropic variables are more likely to play a major role in determining habitat suitability (Sazatornil et al. 2016, Mech and Boitani 2003, Ahmadi et al. 2013).

The habitat suitability map is consistent with the current knowledge about wolf habitat and wolf distribution in Croatia (Kaczensky et al. 2013). The main area predicted suitable outside the wolf range in eastern Croatia presents favourable environmental conditions for wolf reproduction. However, the absence of the wolf in this area may be explained by the fact that it is completely surrounded by farmland, it is isolated by a fenced highway without crossing structures, and it is rather far from currently occupied sites.

In unsuitable areas, especially in the currently occupied range, wolves might still be regularly present. This study only models reproduction habitat, and does not consider the winter time, or wolf movements in the breeding season. Therefore, although wolves tend to avoid human disturbance for locating dens and rendezvous sites (Sazatornil et al. 2016, Theuerkauf et al. 2003, Kusak et al. 2005, Jędrzejewski et al. 2008, Ahmadi et al. 2013, Bassi et al. 2015), it is still likely that they spend a large part of their time in unsuitable breeding habitat, particularly for feeding (Ciucci et al. 1997, Kusak et al. 2005).

In the model, the occurrence localities were collected from 1997 to 2015. This relatively large interval is due to the difficulties in wolf data collection, notably in karstic and highly rugged terrains. Hence, the model assumed that general habitat conditions did not change substantially between 1997 and 2015. The biggest changes are likely due to two highways which were built in Croatia over that period. However, these roads have many wildlife crossing structures, and are successful in maintaining habitat connectivity for large carnivores (Kusak et al. 2009a; Kusak et al. 2009b). With regards to other variables, forest cover showed an increase of only 2.53% from 1997 to 2015 (Anonymous 2016); the total human population decreased by 5.73% from 1996 to 2014, with most of this decline occurring in rural areas; and arable land decreased by 8.11% between 1997 and 2012 (Anonymous 2016). The decision to consider these changes negligible was consistent with that of other studies (Jędrzejewski et al. 2008). Moreover, several other studies seem to have overlooked this type of limitation (Corsi et al. 1999, Treves et al. 2004, Iliopoulos et al. 2014, Bassi et al. 2015).

4.3 Wind Farm Prioritisation

The prioritisation process carried out in this study would potentially lead to a reduction of wind farm impacts on wolf breeding habitat of up to 90.97% with a decrease of only 61.02% in potential installed capacity. Cost minimisation may not be necessarily achieved by avoiding unsuitable wolf habitat independently of the spatial distribution of the farms (e.g. aggregation, scattering). For example, locating proposed wind farms near others already in operation would likely reduce their additional impact on the wolf, by avoiding disturbance in new areas. Nonetheless, this may not hold totally true in case wolf howling was susceptible to acoustic disturbance from rotating turbines, as it has been proposed (Helldin et al. 2012). Furthermore, this conclusion may not be valid for volant species like birds and bats, where it has been suggested that turbines should not be located close together, especially near key areas and along flight paths (LAG VSW 2014, Drewitt and Langston 2006). Further studies on the impacts of wind farms on wildlife should take into consideration their spatial configuration (Drewitt and Langston 2006).

Although several works have been published on the spatial planning of wind farms (Baban and Parry 2001, Punt et al. 2009, Aydin et al. 2010, Tegou et al. 2010, Drechsler et al. 2011, Baltas and Dervos 2012, Göke and Lamp 2012), the obtained results are highly specific to the area, the type of environment, the nature of the costs, the planning units considered, and the method adopted. It is therefore difficult to compare this output and its effectiveness with other studies. One limitation of this study was related to the determination of the ecological cost in the areas where two or more proposed wind farms overlapped. The Marxan analysis was carried out by assuming that each wind farm would be built independently from other farms. However, if two or more proposed wind farms share the area over which they may have a potential effect, they would also share the ecological cost. Hence, if considered together, they would have the same installed capacity as if both were considered singularly, but they would have a lower cumulative cost. Unfortunately, this shortfall could not be prevented, since Marxan cannot handle overlapping planning units (Ardron et al. 2008). Nonetheless, the total overlapping area was only around 10%, and it was distributed equally across many wind farms. It is, thus, likely that no particular areas would benefit from wind farms being built together in clusters. Moreover, this limitation would have existed also in most, if not all, methods used in previous similar studies.

4.4 Future Implications and Recommendations

The habitat suitability model carried out in this study offers a better understanding of wolf breeding habitat in Croatia, The prioritisation process showed the optimal configuration of wind farms to meet the Croatian target at the lowest impact on wolf habitat, and will contribute to a larger environmental impact assessment for wind farms in Croatia. However, despite the usefulness of this research, more work is required to improve the accuracy of scientific findings and increase the effectiveness of science on policy and decision making. Notably, more effort should be put into the identification of more wolf reproduction sites in a more restricted time interval, in order to produce a more accurate model for breeding habitat. The qualitative and quantitative impact of wind farms and other infrastructure on wolves and other non-volant animals should also be clarified through BACI (Before-After-Control-Impact) studies (Gortazar 2012, Lovich and Ennen 2013). In the meantime, a precautionary approach should be adopted by minimising potentially negative impacts during both construction and operation phases even after strategic planning processes (Helldin et al. 2012). Potential mitigation measures include closing access roads, or avoid engineering work during wolves' denning periods or activity hours (Àlvares et al. 2011). Finally, more efficient communication and collaboration among scientists, politicians and wind power developers would be beneficial. This is essential to enable the adoption of an adaptive management approach for wolf monitoring and wind-energy-related decision making.

In conclusion, this study provides valuable tools for the future conservation of wolves in Croatia, and presents a scientific and evidence-based approach for the prioritisation of proposed infrastructure based on their potential impact on wide-ranging wildlife species. Although this study adopted this framework for the specific case of wolves in Croatia, this approach can be applied to many other similar scenarios.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: The authors declare that they have no conflict of interest.

Statement on the welfare of animals: All procedures performed in studies involving animals were in accordance with the ethical standards of the institution or practice at which the studies were conducted. This article does not contain any studies with human participants performed by any of the authors.

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Appendices

Framework for strategic wind farm site prioritisation based on modelled wolf reproduction habitat in Croatia

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Table A1.1 Correlation coefficients among environmental variables calculated in ArcGIS 10.2. The threshold to discriminate correlated variables was R>0.7.

Variables	Altitude	Distance to Farmland	Distance to Forest	Distance to Roads	Distance to Settlements	Slope
Altitude	1.00	0.62	-0.29	0.24	0.56	0.58
Distance to Farmland	0.62	1.00	-0.25	0.25	0.64	0.39
Distance to Forest	-0.29	-0.25	1.00	-0.08	-0.21	-0.26
Distance to Roads	0.24	0.25	-0.08	1.00	0.39	0.15
Distance to Settlements	0.56	0.64	-0.21	0.39	1.00	0.33
Slope	0.58	0.39	-0.26	0.15	0.33	1.00

Table A2.1 Comparison between the spatial correlation coefficients and the AUC values of the main model against the 20 test-models.

Output Maps	Main	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 12	Test 13	Test 14	Test 15	Test 16	Test 17	Test 18	Test 19	Test 20	AUC	SD (of AUC)
Main		0.79	0.77	0.75	0.81	0.78	0.80	0.81	0.81	0.76	0.78	0.82	0.79	0.80	0.78	0.78	0.82	0.75	0.77	0.80	0.76	0.805	0.072
Test 1	0.79		0.84	0.86	0.97	0.98	0.91	0.97	0.93	0.85	0.85	0.95	0.93	0.95	0.89	0.98	0.91	0.97	0.95	0.97	0.95	0.629	0.136
Test 2	0.77	0.84		0.96	0.94	0.89	0.97	0.86	0.96	0.97	0.96	0.92	0.94	0.93	0.98	0.89	0.94	0.80	0.91	0.90	0.84	0.671	0.127
Test 3	0.75	0.86	0.96		0.93	0.91	0.92	0.83	0.91	0.97	0.89	0.90	0.95	0.94	0.96	0.89	0.92	0.78	0.87	0.90	0.82	0.763	0.101
Test 4	0.81	0.97	0.94	0.93		0.98	0.97	0.97	0.98	0.94	0.95	0.99	0.99	0.96	0.97	0.98	0.96	0.93	0.96	0.97	0.96	0.692	0.117
Test 5	0.78	0.98	0.89	0.91	0.98		0.94	0.96	0.96	0.90	0.90	0.95	0.98	0.94	0.94	0.99	0.93	0.95	0.95	0.97	0.97	0.699	0.128
Test 6	0.80	0.91	0.97	0.92	0.97	0.94		0.94	0.99	0.95	0.98	0.96	0.96	0.93	0.99	0.95	0.97	0.89	0.96	0.95	0.92	0.695	0.138
Test 7	0.81	0.97	0.86	0.83	0.97	0.96	0.94		0.96	0.87	0.92	0.97	0.93	0.92	0.91	0.97	0.95	0.97	0.97	0.98	0.97	0.646	0.144
Test 8	0.81	0.93	0.96	0.91	0.98	0.96	0.99	0.96		0.93	0.97	0.96	0.97	0.94	0.98	0.95	0.96	0.92	0.96	0.96	0.94	0.644	0.143
Test 9	0.76	0.85	0.97	0.97	0.94	0.90	0.95	0.87	0.93		0.96	0.94	0.95	0.92	0.97	0.90	0.96	0.80	0.91	0.92	0.86	0.724	0.101
Test 10	0.78	0.85	0.96	0.89	0.95	0.90	0.98	0.92	0.97	0.96		0.96	0.94	0.88	0.97	0.90	0.96	0.85	0.94	0.92	0.90	0.747	0.106
Test 11	0.82	0.95	0.92	0.90	0.99	0.95	0.96	0.97	0.96	0.94	0.96		0.96	0.93	0.95	0.95	0.98	0.92	0.95	0.97	0.95	0.676	0.139
Test 12	0.79	0.93	0.94	0.95	0.99	0.98	0.96	0.93	0.97	0.95	0.94	0.96		0.93	0.98	0.97	0.95	0.89	0.93	0.94	0.95	0.715	0.130
Test 13	0.80	0.95	0.93	0.94	0.96	0.94	0.93	0.92	0.94	0.92	0.88	0.93	0.93		0.93	0.93	0.93	0.89	0.91	0.95	0.87	0.665	0.125
Test 14	0.78	0.89	0.98	0.96	0.97	0.94	0.99	0.91	0.98	0.97	0.97	0.95	0.98	0.93		0.94	0.97	0.86	0.94	0.94	0.90	0.720	0.106
Test 15	0.78	0.98	0.89	0.89	0.98	0.99	0.95	0.97	0.95	0.90	0.90	0.95	0.97	0.93	0.94		0.94	0.96	0.97	0.98	0.97	0.686	0.127
Test 16	0.82	0.91	0.94	0.92	0.96	0.93	0.97	0.95	0.96	0.96	0.96	0.98	0.95	0.93	0.97	0.94		0.87	0.94	0.96	0.90	0.694	0.103
Test 17	0.75	0.97	0.80	0.78	0.93	0.95	0.89	0.97	0.92	0.80	0.85	0.92	0.89	0.89	0.86	0.96	0.87		0.96	0.96	0.96	0.582	0.160
Test 18	0.77	0.95	0.91	0.87	0.96	0.95	0.96	0.97	0.96	0.91	0.94	0.95	0.93	0.91	0.94	0.97	0.94	0.96		0.98	0.95	0.660	0.129
Test 19	0.80	0.97	0.90	0.90	0.97	0.97	0.95	0.98	0.96	0.92	0.92	0.97	0.94	0.95	0.94	0.98	0.96	0.96	0.98		0.94	0.648	0.145
Test 20	0.76	0.95	0.84	0.82	0.96	0.97	0.92	0.97	0.94	0.86	0.90	0.95	0.95	0.87	0.90	0.97	0.90	0.96	0.95	0.94		0.742	0.119
Average **SD**	0.79 0.02																				**Test-models average = 0.94** **Test-models SD = 0.04**	0.69	0.12

Table A3.1 Results of the Incremental Spatial Autocorrelation calculated in ArcGIS 10.2. Z-score values bigger than 1.65 and smaller than -1.65 indicate significant spatial clustering with a 90% confidence level. The distance is the distance between reproduction sites.

Distance (Km)	Moran's I	Expected I	Variance	Z score	P value
0	-	-	-	-	-
2	0.07	-0.06	0.03	0.74	0.46
4	0.06	-0.05	0.02	0.72	0.47
6	0.03	-0.04	0.02	0.54	0.59
8	0.10	-0.04	0.01	1.35	0.18
10	0.06	-0.04	0.01	1.06	0.29
12	0.07	-0.04	0.01	1.23	0.22
14	0.07	-0.04	0.01	1.21	0.22
16	0.07	-0.04	0.01	1.31	0.19
18	-0.02	-0.04	0.01	0.24	0.81
20	-0.04	-0.04	0.01	-0.03	0.97
22	-0.05	-0.04	0.01	-0.11	0.91
24	-0.06	-0.03	0.01	-0.18	0.85
26	-0.05	-0.03	0.01	-0.16	0.87
28	-0.08	-0.03	0.01	-0.46	0.64
30	-0.08	-0.03	0.01	-0.46	0.64
32	-0.08	-0.03	0.01	-0.46	0.64
34	-0.08	-0.03	0.01	-0.46	0.64
36	-0.09	-0.03	0.01	-0.55	0.58
38	-0.04	-0.03	0.01	-0.10	0.92
40	-0.04	-0.03	0.01	-0.10	0.92
42	-0.05	-0.03	0.01	-0.16	0.88
44	-0.05	-0.03	0.01	-0.24	0.81
46	0.01	-0.03	0.01	0.59	0.55
48	0.02	-0.03	0.01	0.66	0.51
50	0.01	-0.03	0.01	0.54	0.59
52	0.01	-0.03	0.01	0.57	0.57
54	0.00	-0.03	0.00	0.45	0.65
56	0.00	-0.03	0.00	0.45	0.65
58	0.00	-0.03	0.00	0.41	0.68
60	0.00	-0.03	0.00	0.41	0.68

Figure A3.1. Correlogram of the incremental spatial autocorrelation (based on the table A3).