Wind farm prioritisation based on potential impacts on wolf (Canis lupus) habitat in Croatia

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Wind farm prioritisation based on potential impacts on wolf *(Canis lupus)* habitat in Croatia

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DECLARATION OF OWN WORK

I declare that this thesis,

"Wind farm prioritisation based on potential impacts on wolf (*Canis lupus*) habitat in Croatia",

is entirely my own work and that where material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

Signature ……………………………………………………………………………………………

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Name of Supervisors Dr. Marcus Rowcliffe; Prof. Josip Kusak

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List of Acronyms

AUC = Area Under the Curve

EIA = Environmental Impact Assessment

AAPPIEN = Assessment of Acceptability of Plans, Programmes and Interventions for the Ecological Network

IUCN = International Union for Conservation of Nature

EU = European Union

GPS = Global Positioning System

BACI = Before After Control Impact

HSM = Habitat Suitability Model

SDM = Species Distribution Model

GLM = Generalized Linear Model

GAM = Generalized Additive Model

ROC = Receiver Operating Characteristic

IS = Irreplaceability Score

GIS = Geographic Information System

SGA = State Geodetic Administration

Abstract

Wolves (*Canis lupus*) in Croatia are estimated at nearly 200 individuals and form part of the Dinaric-Balkan population. As in most of Europe, they are currently expanding in size and distribution. However, the wolf still faces threats that could hamper its viability. In Croatia, these threats include the worsening of public attitudes and the construction of wind power plants in their distribution range. In order to meet the 2020 European targets for renewable energy production, the Republic of Croatia is planning to build 33 wind farms, with a total installed capacity of 1,555 MW. However, in order to meet such targets, only 747.25 MW are necessary.

In this study a suitability model for wolf breeding habitat was carried out using Maxent based on 6 environmental variables and 31 homesite locations collected between 1997 and 2015. The prediction of habitat suitability was then used to determine the potential impact of proposed wind farms on wolves. Lastly, a wind farm prioritisation process was carried out using the software Marxan. This allowed selecting the wind farms that contributed to the meeting of the energy targets at the minimum ecological impact on wolf breeding habitat.

The model showed good performance (AUC=0.805) and its prediction was consistent with the current knowledge and distribution of wolves in Croatia. The main predictors for suitability were distance to settlements, distance to farmland, distance to roads and distance to forest edge. Moreover, Marxan allowed the selection of highly cost-efficient wind farms. In fact, in the best scenario, selected wind farms were 44.5% of the total proposed wind farms and held only 23.3% of the total initial cost.

In conclusion, this study provides valuable information and useful tools for the conservation of wolves in Croatia. In particular, the habitat suitability map can be used for the implementation of the wolf management plan, for the prevention of human-wildlife conflicts and for future conservation planning. Moreover, the result of the prioritisation will be used to inform the strategic planning of wind farms in Croatia. Lastly, the framework adopted in this study can be expanded to multiple infrastructure and multiple large carnivores' species such as the Eurasian brown bear and the Eurasian lynx.

WORD COUNT: 14,931

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1 Introduction

1.1 Problem Statement

The grey wolf, *Canis lupus*, is the second most abundant species of large carnivore in Europe. With approximately 200 wolves (168-219, Štrbenac 2010), Croatia occupies the western part of the Dinaric-Balkan population (Kaczensky 2012). As such, it represents a particularly important area for European wolves, since it may allow the connection of the Dinaric-Balkan, the Alpine and the Italian Peninsula populations (Figure 1.1) (Fabbri, Caniglia *et al.* 2014). Currently, one of the main threats for Croatian wolves is represented by the potential construction of major infrastructure, notably wind farms, in their core habitat (Kaczensky 2012).

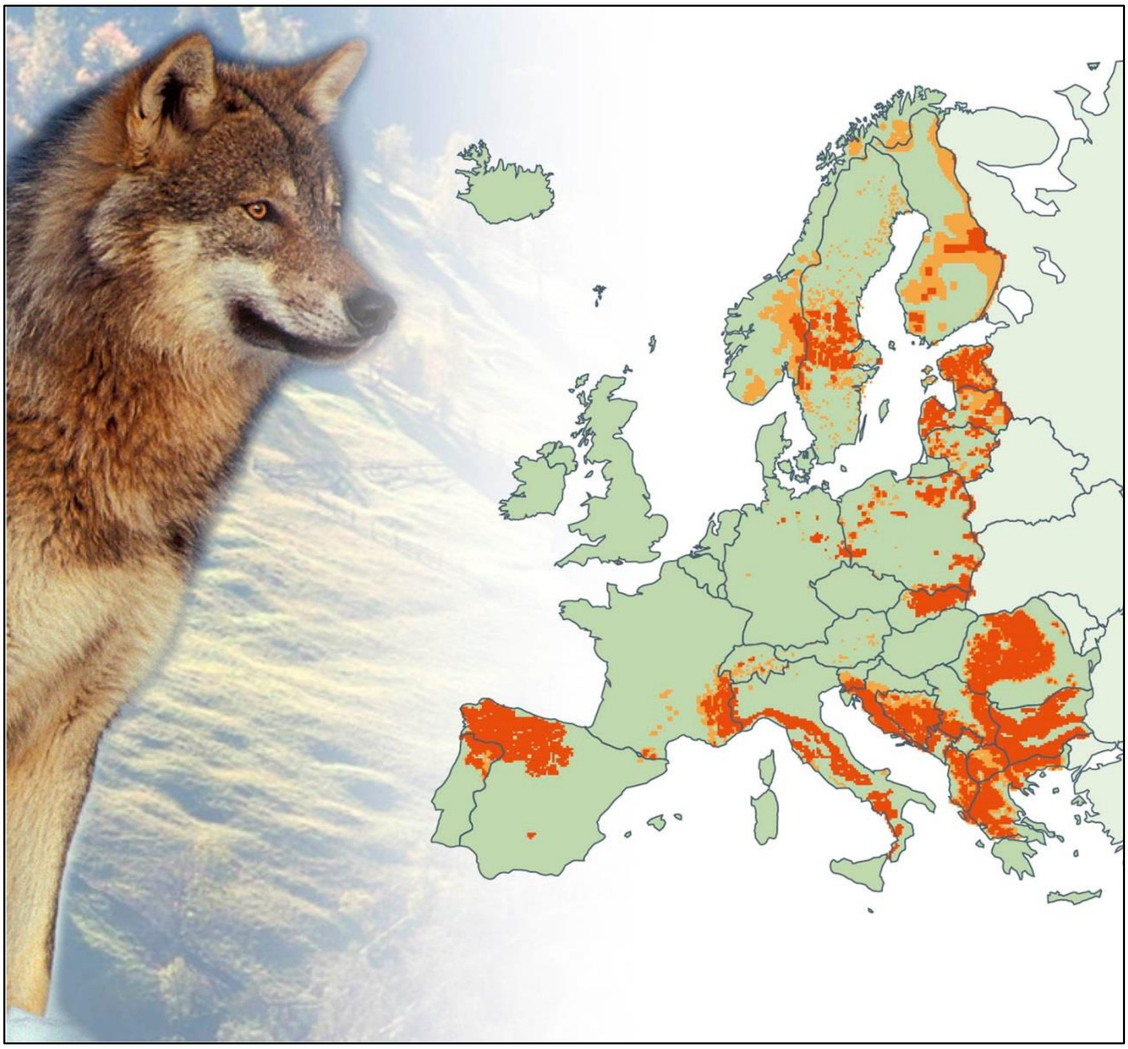

Figure 1.1 Wolf distribution in Europe (Linnell, Salvatori *et al.* 2008)

The wind power capacity installed in Croatia, as of July 2015, is 452.75 MW (MINGO 2015). However, in order to meet the target of the European Directive 2009/28/EC (EC, 2009), and according to the Energy Strategy for the Republic of Croatia, wind farms in Croatia have to reach a total installed capacity of 1,200 MW by 2020 (Croatian Parliament 2009a). To reach this target, a further installed capacity of 747.25 MW is needed. Notwithstanding, Croatia is planning to build 33 wind farms, with a total installed capacity of 1,555 MW (MINGO 2015). Therefore, planned wind farms would provide nearly twice as much installed capacity as needed to reach the 2020 target.

Although wind is a valuable source of renewable energy, the implementation of wind farms requires a large amount of land (Kiesecker, Evans *et al.* 2011). It is thus important that wind farms are strategically placed in areas where there is the minimum competition with other land use types, such as agriculture, natural habitats, protected areas and urban areas. Nonetheless, the vast majority of currently proposed wind farms are located in the wolf distribution range (Figure 1.2).

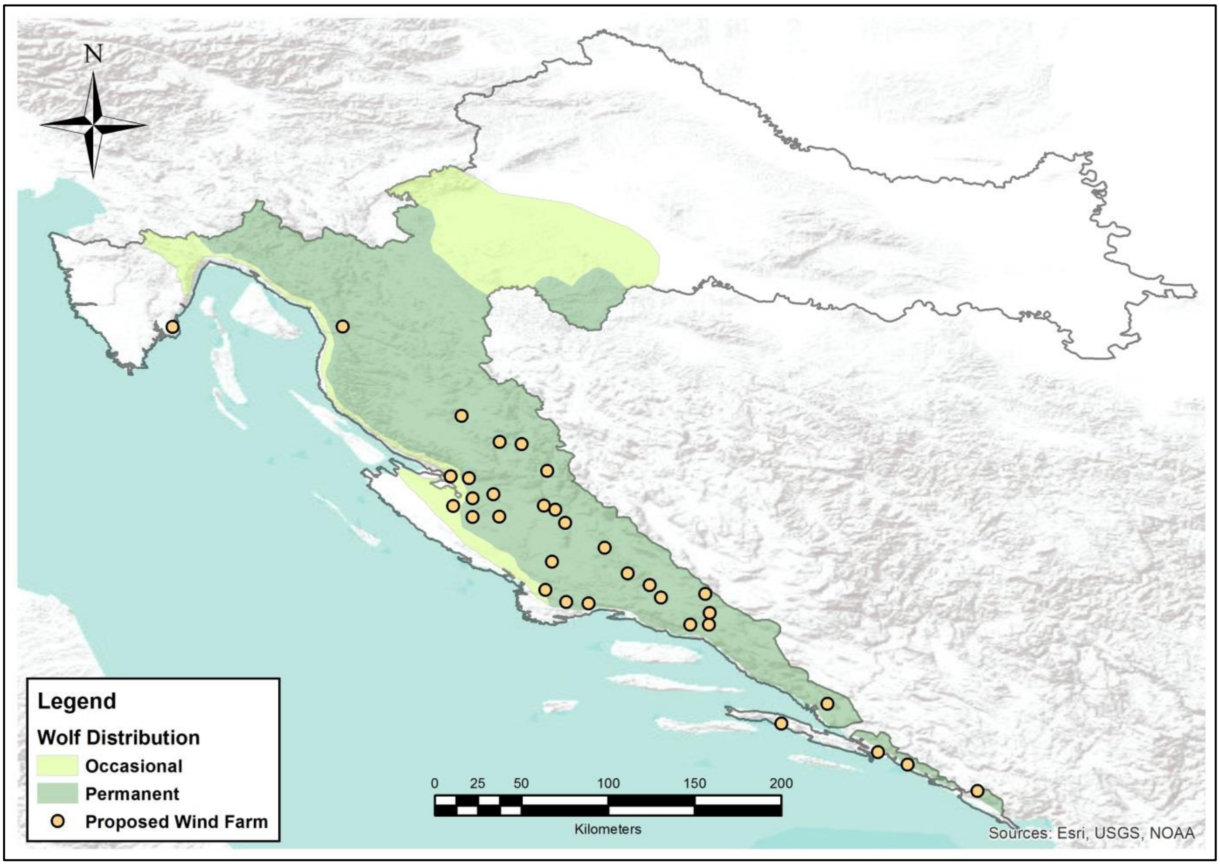

Figure 1.2 Distribution of wolves and proposed wind farms in Croatia (Štrbenac 2010, MINGO 2015)

Scientific evidence suggests that wind farms have a negative impact on wolves, particularly on their breeding sites (Àlvares, Rio-Maior *et al.* 2011, Helldin, Jung *et al.* 2012, Álvares, Rio-Maior *et al.* in press). According to Álvares, Rio-Maior *et al.* (in press), during wind farm operation, wolf dens tend to be located further than 4 km from the nearest turbine. This might be due to several reasons. Firstly, the construction of wind power plants causes substantial changes in the wolf habitat, including deforestation and fragmentation (Northrup and Wittemyer 2013). Secondly, a higher density of roads could lead to more collisions with vehicles, increased disturbance in previously inaccessible areas, and easier access for poachers (Helldin, Jung *et al.* 2012). Lastly, the noise produced by rotating turbines could interfere with wolf howling, which is particularly important during the breeding season (Harrington, Asa *et al.* 2003, Helldin, Jung *et al.* 2012). Moreover, during this season, wolves are more sedentary and thus may be more sensitive to all these sources of disturbance (Packard 2003).

Before being implemented, under the European and Croatian legislation, proposed wind farms have to undergo an Environmental Impact Assessment (EIA) and an Assessment of Acceptability of Plans, Programmes and Interventions for the Ecological Network (AAPPIEN) (Croatian Parliament 2009b, EC 2011). These assessments also need to take into consideration the impact of wind farms on wolf breeding habitat. However, the spatial distribution of wolf most suitable breeding areas in Croatia is not fully known and it is currently based only on expert opinions. Hence, at present, an exhaustive habitat suitability map that could be used for the assessment and the minimisation of potential impact on wolves does not exist.

1.2 Aims and Objectives

In a human-dominated region like Europe, the long term viability of large carnivore species strictly depends on land management decisions and on the coordinated planning of conflicting land use types (Linnell, Salvatori *et al.* 2008). Thus, the aim of this study is to provide scientific material that can influence wind farm implementation and support the long term viability of the wolf in Croatia.

The following objectives will contribute to the achievement of this aim:

1. Gathering of the information and data collection on the location of wolf breeding sites in Croatia;
2. Creation of a suitability map for wolf breeding habitat through habitat modelling;
3. Systematic prioritisation of proposed wind farms based on installed capacity and potential impact on wolves;
4. Creation of a map that allows wind farm developers to visualise the most affected breeding areas within each wind farm;
5. Proposal of a simple and evidence-based framework which can potentially include multiple infrastructure and other large carnivore species in Europe.

This thesis will start with a background section containing an overview of the wolf conservation status in Europe, a more detailed explanation of wind farm impacts on wolves, a review of previous literature, a general explanation of the methods adopted, and an ecological overview of Croatia. After the background, the thesis will continue with the description of the methodologies, the presentation of the results, and a final discussion.

2 Background

2.1 The Wolf as a Large Carnivore in Europe

The Grey Wolf (*Canis lupus*) is the second most abundant species of large carnivore in Europe (Chapron et al 2014). With a total estimated number of 12,000 individuals, the wolf is expanding across Europe (Chapron et al 2014). However, although some authors consider it a conservation success, this expansion is not only the results of active conservation actions (Chapron et al 2014, Boitani 2015). In fact, the social and economic transformations occurring since the end of WWII have led to an increasing rate of land abandonment in rural areas (Boitani 2015, Navarro and Pereira 2015). The decrease of human activities in such areas have led to the regeneration of secondary forests and left available habitat for the expansion of wolves (Navarro and Pereira 2015).

This expansion may also pose some threats related to the coexistence between people and wolves (Navarro and Pereira 2015). One of the main causes of human-wolf conflict is livestock depredation (Navarro and Pereira 2015). Despite the compensation schemes available in most countries, single farmers can be truly affected by the loss of livestock caused by wolves (Wilson 2004). Additionally, some people living near wolves are also concerned for their own and their family's safety (Røskaft, Händel *et al.* 2007). Thus, the coexistence with wolves can lead to negative human attitudes which can be further inflated by dramatic stories published in the media (Røskaft, Händel *et al.* 2007, Majić and Bath 2010). The human-wolf conflict is generally higher in recently recolonised areas, where traditional livestock-guarding knowledge was lost and people are not used to coexist with large carnivores (Navarro and Pereira 2015). For all these reasons, in several countries, wolves are often illegally killed by farmers and poachers (Huber, Kusak *et al.* 2002, Liberg, Chapron *et al.* 2012).

In Croatia, wolves form part of the Dinaric-Balkan population, which spreads across approximately 10 countries in south-east Europe and include *circa* 3,900 individuals (Kaczensky 2012). However, this estimate may not be completely accurate. In particular, since the population spans across many national borders, the number of individuals may be inflated. It has been shown that double-counting of bears along national borders between Norway, Russia, Finland and Sweden led to an inflation of population estimates of up to 119% compared to estimates that took into account "foreign residents" (Bischof, Brøseth *et* *al.* 2015). This might also be the case for the Dinaric-Balkan population where many packs are transboundary (Jeremić 2012). Furthermore, although the population is considered to be stable, a rigorous assessment of the trend is hindered by the use of a wide range of different techniques during monitoring (Kaczensky 2012).

In Croatia, wolves are estimated to be around 200 (168-219, Štrbenac 2010). However, Croatia is located in a strategic area for the long term viability of European wolves, since it allows the connection between the Dinaric-Balkan, the Alpine and the Italian peninsula populations (Fabbri, Caniglia *et al.* 2014). In the eastern Alps, successful reproduction events between wolves of Dinaric-Balkan and Italian peninsula origins have already been observed (Fabbri, Caniglia *et al.* 2014).

Although wolves in Croatia are likely to be increasing, they also face several threats (Kaczensky 2012). In particular, the main threat is the construction of wind farms in their distribution range (Skrbinšek and Bath 2010, Kaczensky 2012). Moreover, human attitudes are worsening as a result of increased livestock depredation in recolonised areas (Kaczensky 2012). In 2011, nearly 1,700 livestock were killed by wolves in Croatia, but compensation schemes are considered inadequate by farmers (Kaczensky 2012).

Despite and as a result of the overall expansion of wolves in Europe, conservation efforts are still needed. After having fought to save large carnivores from extinction for decades, European conservationists have to face the new challenge of peaceful coexistence (Boitani 2015).

2.2 Wind Farms and Wolves

2.2.1 Impact of Wind Farms on Wolves

Wind farms have been shown to have some direct and indirect negative implications on wildlife (Kuvlesky Jr, Brennan *et al.* 2007, Northrup and Wittemyer 2013). The most common impact is caused by direct collision of birds and bats with turbines (Drewitt and Langston 2006, Kunz, Arnett *et al.* 2007). However, wind farms also have negative impacts on non-volant wildlife, although the scientific literature currently lacks the information to rigorously assess and quantify them (Lovich and Ennen 2013). These impacts on terrestrial species mainly include habitat modifications and behavioural alterations (Kuvlesky Jr, Brennan *et al.* 2007). In particular, besides the installation of turbines, wind farms require the construction of roads, transformers, substations and transmission lines (Kuvlesky Jr, Brennan *et al.* 2007). All these infrastructures may cause habitat loss and fragmentation (Northrup and Wittemyer 2013). Moreover, maintenance facilities may also increase human access to previously undisturbed areas (Northrup and Wittemyer 2013). This, besides increasing human disturbance, might also increase the likelihood of collisions of wildlife with vehicles along roads (Kuvlesky Jr, Brennan *et al.* 2007). Another indirect impact of wind turbines may be caused by noise disturbance to those animals that use long distance vocalizations and alarm calls to communicate (Helldin, Jung *et al.* 2012).

Some studies have shown that wind farms could potentially affect wolves (Àlvares, Rio-Maior *et al.* 2011, Helldin, Jung *et al.* 2012, Álvares, Rio-Maior *et al.* in press). This impact seems to particularly concern breeding success and to cause the displacement of wolf reproduction sites (Àlvares, Rio-Maior *et al.* 2011, Álvares, Rio-Maior *et al.* in press). For example, Àlvares, Rio-Maior *et al.* (2011) show that during the construction and operation phases of one wind power plant, although wolves kept using areas occupied by the wind farm, they tended to abandon breeding 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, Rio-Maior *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 breeding sites located at least 4 km away from the nearest turbine (Álvares, Rio-Maior *et al.* in press). GPS-Telemetry data also showed shifts of home ranges partially away from wind power plants (Álvares, Rio-Maior *et al.* in press).

The actual reasons behind the impact of wind farms on wolves have only been proposed based on current knowledge on the effects of infrastructure on large mammals and are yet to be thoroughly investigated (Helldin, Jung *et al.* 2012). The first, most intuitive reason could be the change and loss of habitat, particularly for reproduction (Àlvares, Rio-Maior *et al.* 2011). In fact, the construction of wind turbines and other related facilities could cause significant changes in wolf breeding habitat, including deforestation and fragmentation (Northrup and Wittemyer 2013). Several studies have shown that, where forests are present, wolves tend to locate their den in relatively undisturbed and forested areas (Theuerkauf, Rouys *et al.* 2003, Person and Russell 2009).

Moreover, a higher density of roads and other infrastructures related to wind farms can lead to increased indirect threats and disturbance. For example, it has been shown that wolves avoid areas with relatively higher density of roads, houses and human disturbance, particularly during the breeding period (Theuerkauf, Rouys *et al.* 2003, Karlsson, Brøseth *et al.* 2007, Houle, Fortin *et al.* 2010). Àlvares, Rio-Maior *et al.* (2011) found that road traffic in wind farms increased 20 to 60 fold during construction and 4 to 13 fold during operation, compared to the pre-construction period. Moreover, Huber, Kusak *et al.* (2002) found that collisions with vehicles constituted nearly 20% of wolf mortality cases between 1986 and 2001 in Croatia. The presence of roads could also facilitate the access of poachers into wolf habitat and increase mortality due to retaliatory killing (Person and Russell 2008, Helldin, Jung *et al.* 2012). According to Huber, Kusak *et al.* (2002), 67.4% of wolf mortality cases in a 15-years period in Croatia were due to illegal killing.

The last reason that has been hypothesized is related to acoustic disturbance (Àlvares, Rio-Maior *et al.* 2011, Helldin, Jung *et al.* 2012). In particular, the noise produced by operating turbines could disguise or disturb wolf howling (Helldin, Jung *et al.* 2012). 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, Asa *et al.* 2003, Mech and Boitani 2003).

Although these impacts have been proposed, a rigorous assessment and quantification of their effects is hampered by the lack of before-after-control-impact (BACI) studies (Lovich and Ennen 2013). This type of approach requires the assessment of the situation before and after the construction of wind farms (Lovich and Ennen 2013). However, the time required to collect adequate data about wolf movements, demography and behaviour is longer than the time needed for wind farm implementation (Franklin 1989, Management 2005). It is thus very difficult to have information about the situation before wind farms construction.

2.2.2 Avoiding and Minimizing Impacts of Wind Farms on Wolves: an Example

During the implementation of two wind farms projects in Portugal (wind farm “Alto de Coutada” - 102 MW, and wind farm “Serra da Nave” – 100 MW), Soares, Duarte *et al.* (2011) adopted several measures to avoid or minimise the impacts on wolves. In particular, during the planning phase, alternative and less impacting positions were identified for the displacement of some turbines. In the construction phase, all construction activities were suspended during night time, when wolves are more active. Moreover, all activities carried out during the wolf breeding season were prohibited in some areas with particularly high habitat suitability. Lastly, during the operation phase, some mitigation measures have also been adopted like the implementation of barriers along new access roads.

2.3 Wolf Homesites

Wolf homesites, or breeding sites, or reproduction sites, are areas associated with pup rearing, and may be either dens or rendezvous sites (Harrington and Mech 1978). The former are the sites where wolf pups are raised during the first 8 weeks from birth (Mech 1970). Dens are generally located away from the peripheral zones of the territory and are mainly used by the breeding female and her pups (Packard 2003). There are several types of den which depend on the type of habitat. In particular, in forested habitats, dens may be formed by a bedding of leaves or dug under the roots of the trees, while in karstic areas it may be created from existing burrows between rocks (Packard 2003).

Each home range can have several dens, some of which can be re-used in different years by the same female (Capitani, Mattioli *et al.* 2006). Moreover, wolves may move the den site within a breeding season (Packard 2003). These shifts are usually short (i.e. *ca*. 250 metres), especially when the pups are young, although they can also be over several kilometres (Packard 2003).

After the denning period, between 8 and 20 weeks after birth, pups generally live in rendezvous sites (Packard 2003). These are areas above ground which include bedding, where pups huddle while resting, and play areas. Rendezvous sites are generally located in the same areas as the dens, although, during this period, wolf pups are able to move over longer distances and can be found far from such areas (Mech 1970).

2.4 Habitat Suitability Modelling

Habitat Suitability Models (HSMs), or Species Distribution Models (SDMs), allow ecologists and conservationists to predict the likelihood of occurrence of species based on their relationships with environmental variables (Hirzel and Le Lay 2008). HSMs identify the environmental requirements of a species based on the habitat characteristics in locations where the species is known to be present (Phillips, Anderson *et al.* 2006). Once the environmental requirements are found, they are projected into geographic space and can provide valuable information about species potential distribution (Phillips, Anderson *et al.* 2006).

Depending on the quality and the quantity of data needed, two main types of SDMs can be distinguished: presence-only and presence-absence SDMs. In particular, besides presence localities, presence-absence SDMs require the input of locations where the species in known to be absent (i.e. absences), in order to generate discriminative rules and statistics to create habitat suitability maps (Brotons, Thuiller *et al.* 2004). Examples of presence-absence SDMs are generalised linear models (GLM) and generalised additive models (GAM) (Brotons, Thuiller *et al.* 2004). On the other hand, in order to generate discriminative statistics, most presence-only models compare the presence localities with a set of random locations where the species might or might not be present (i.e. pseudo-absences) (Brotons, Thuiller *et al.* 2004). Examples of presence-only models are Mahalanobis distance, GARP and Maxent (Wisz, Hijmans *et al.* 2008).

2.4.1 Maxent

Maxent (Maximum Entropy Modelling) is one of the most used presence-only SDMs. In recent years, it has been adopted in more than 1,000 publications for a wide range of taxa and geographic areas (Merow, Smith *et al.* 2013). According to several studies, it is also one of the most accurate methods, having very high performances especially at small sample sizes (Elith, Graham *et al.* 2006, Hernandez, Graham *et al.* 2006, Wisz, Hijmans *et al.* 2008).

Maxent is a machine-learning method that models habitat suitability and species geographic distribution (Phillips, Anderson *et al.* 2006). In particular, it relates a set of species occurrence localities with habitat characteristics by creating simple functions of user-specified environmental variables, called “features” (Phillips and Dudík 2008). In order to do so, Maxent identifies the probability distribution of maximum entropy (Phillips, Anderson *et al.* 2006). This is the most spread out (i.e. most approximated, closest to uniform) probability distribution that describes an event based on available knowledge (Phillips, Anderson *et al.* 2006). Hence, Maxent finds the most approximated probability distribution based on the constraint that the expected value of each feature should match its empirical value (i.e. the average value at occurrence locations), within an error bound called the “regularization parameter” (Phillips and Dudík 2008).

The obtained probability distribution is then compared with the probability distribution of the pseudo-absences, where the probability of occurrence of the species is usually assumed to be 0.5 (Phillips, Anderson *et al.* 2006). This comparison allows the computation of discriminative values such as the Receiver Operating Characteristic curve (ROC curve) and the calculation of all related statistical analysis, including the determination of the Area Under the Curve (AUC) (Phillips, Anderson *et al.* 2006). Moreover, the projection of the probability distribution into geographic space enables the creation of a habitat suitability map (Phillips, Anderson *et al.* 2006). The model also produces an analysis of the contribution of environmental variables and response curves showing how the predicted probability of presence changes based on changes in each environmental variable (Phillips, Anderson *et al.* 2006).

2.4.2 Habitat Suitability Modelling for Wolf Conservation

Understanding wolf spatial ecology is a crucial step towards its effective conservation (Corsi, Duprè *et al.* 1999). For this purpose, habitat suitability models can be very useful tools (Elith 2000). For this reason they have been widely adopted, especially in recent years. The main methods used were logistic regression-based models (Mladenoff, Sickley *et al.* 1999, Glenz, Massolo *et al.* 2001), Mahalanobis distance (Corsi, Duprè *et al.* 1999, Cayuela 2004, Ahmadi, Kaboli *et al.* 2013) and Maxent (Bassi, Willis *et al.* 2015).

Previous study found that anthropic-related variables, such as distance to farmland, distance to roads and distance to settlements, and environmental variables, such as forest cover, elevation, wild prey availability and distance to water, were the most important predictors for wolf habitat suitability (Corsi, Duprè *et al.* 1999, Theuerkauf, Rouys *et al.* 2003, Jędrzejewski, Jędrzejewska *et al.* 2008, Ahmadi, Kaboli *et al.* 2013, Iliopoulos, Youlatos *et al.* 2014, Bassi, Willis *et al.* 2015). In general, according to these studies, wolves preferred to locate their homesites in forested areas, near water, and far away from sources of human disturbance such as villages, roads and farms. Moreover, in some studies, suitable areas were often found at higher elevations and on rugged or steeper terrains, probably as a consequence of lower human disturbance (Jędrzejewski, Niedzialkowska *et al.* 2005, Capitani, Mattioli *et al.* 2006).

Despite these general similarities among results, the relative contribution of predictors and the relationships between variables and habitat suitability show very high variability in the literature. These differences can be due to the method adopted, ecological differences between geographic areas, unavailability of some environmental data, unaccounted correlations between environmental variables and biases in data collection of wolf occurrences (Corsi, Duprè *et al.* 1999, Phillips, Dudík *et al.* 2009, Yackulic, Chandler *et al.* 2013). For example, it has been shown that presence locations are often biased towards easily accessible areas (i.e.

roads) and that in the big majority of publications this bias is often not mentioned or not taken into consideration (Phillips, Dudík *et al.* 2009, Yackulic, Chandler *et al.* 2013).

From a conservation perspective, wolf HSMs can be used to address several conservation issues, including conservation planning (Corsi, Duprè *et al.* 1999, Mladenoff, Sickley *et al.* 1999, Ahmadi, Kaboli *et al.* 2013), habitat restoration (Mladenoff, Sickley *et al.* 1999, Jędrzejewski, Jędrzejewska *et al.* 2008), wolf population management (Corsi, Duprè *et al.* 1999), and human-wildlife conflict prevention (Corsi, Duprè *et al.* 1999, Mladenoff, Sickley *et al.* 1999, Glenz, Massolo *et al.* 2001, Treves, Naughton-Treves *et al.* 2004, Marucco and McIntire 2010, Ahmadi, Kaboli *et al.* 2013, Bassi, Willis *et al.* 2015).

2.5 Spatial Planning and Wind Farm Prioritisation

Strategic spatial planning aims to find the optimal allocation of different land uses across different spatial scales in order to ensure a sustainable interaction among economic, environmental, social and political agendas (Albrechts, Healey *et al.* 2003).

At a landscape scale in Europe, spatial planning is particularly used for nature conservation, ecosystem services provision and infrastructure development (Albrechts, Healey *et al.* 2003). Recently, with the increasing concerns about greenhouse gas emissions and climate change, many renewable energy sources have been built or are planned to be built as alternatives to fossil fuels (EC 2009). However, although renewable sources offer "cleaner" energy, they can also have a significantly negative impact on the environment, especially at a local level (Kiesecker, Evans *et al.* 2011). Hence, in order to optimise their environmental benefits and minimise their socio-economic impact, it is important that they are located strategically within the landscape.

In recent years, particular attention has been given to wind farm spatial planning and prioritisation (Baban and Parry 2001, Punt, Groeneveld *et al.* 2009, Aydin, Kentel *et al.* 2010, Tegou, Polatidis *et al.* 2010, Drechsler, Ohl *et al.* 2011, Baltas and Dervos 2012, Göke and Lamp 2012). These studies aimed to identify the optimal allocation of wind turbines by taking into consideration physical, social and environmental constraints. For example, several studies analyse these constraints in order to produce suitability maps for future wind energy implementation (Baban and Parry 2001, Aydin, Kentel *et al.* 2010, Tegou, Polatidis *et al.* 2010, Baltas and Dervos 2012). Similarly, other studies identify the areas within a region where wind farms can meet specific energy production targets at the minimum monetary, social and ecological cost (Punt, Groeneveld *et al.* 2009, Drechsler, Ohl *et al.* 2011, Göke and Lamp 2012). The main constraints considered in these analyses were nature conservation areas, native habitats and wildlife (e.g. birds, bats, fishes), inhabited areas, wind potential, archaeological sites and tourist areas (Baban and Parry 2001, Punt, Groeneveld *et al.* 2009, Aydin, Kentel *et al.* 2010, Tegou, Polatidis *et al.* 2010, Drechsler, Ohl *et al.* 2011, Baltas and Dervos 2012, Göke and Lamp 2012). Among the studies mentioned above, only Drechsler, Ohl *et al.* (2011) and Punt, Groeneveld *et al.* (2009) used scientific evidence about species distribution in the consideration of wildlife outside protected areas.

The main methods that were adopted include multiple-criteria decision analysis (Tegou, Polatidis *et al.* 2010), fuzzy-logic-based methods (Aydin, Kentel *et al.* 2010), numerical optimisation (Punt, Groeneveld *et al.* 2009, Drechsler, Ohl *et al.* 2011), and the use of spatial planning software such as Marxan (Göke and Lamp 2012).

2.5.1 Marxan

Marxan is originally designed as a conservation planning software. In general, it allows identifying optimal configurations of complementary areas to be protected in order to meet specific conservation objectives at the minimum political, social or economic cost (Pressey, Cabeza *et al.* 2007, Ardron, Possingham *et al.* 2008). These areas, called “planning units”, are generally hexagonal cells that form a grid over a general planning area. Each planning unit contributes to the meeting of conservation objectives, called “targets” (e.g. protection of a certain number of species) at a certain monetary, social or ecological cost. Marxan allows the minimisation of this cost, while ensuring the achievement of the targets (Ardron, Possingham *et al.* 2008). Although it is mostly used in protected areas design, some studies have demonstrated that this software can address the same optimisation problem in other applications (Rondinini and Boitani 2007, Ban and Vincent 2009, Göke and Lamp 2012).

In order to solve this problem, Marxan uses simulated annealing. With this algorithm, Marxan repetitively changes current configurations by replacing planning units, thus forming similar, “nearby” configurations. Each change is accepted if the cost of the new configuration is lower than the previous one. However, at the beginning of the simulated annealing the algorithm randomly accepts some configurations with a higher cost. Replacing one planning unit might lead to a higher cost; however, a further replacement of another planning unit might lead to an overall better solution compared to the starting situation. The likelihood of accepting a higher cost configuration decreases along the annealing process with a rate that depends on a user-specified parameter called "temperature" (Ardron, Possingham *et al.* 2008).

Decreasing temperature along the annealing also reduces the likelihood of the algorithm to accept big changes (i.e. replacement of more planning units at each time). Therefore, big changes are more likely to be accepted at the beginning, in order to avoid the resulting configuration to stand in a "local" minimum cost. As such, replacing one unit may lead to a lower cost; however, if we change the starting configuration by making bigger changes, replacing that same planning unit may lead to an even lower cost (Ardron, Possingham *et al.* 2008).

Marxan applies the simulated annealing over many repeated runs. At the end of the computation, it produces 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, Possingham, and Klein 2008).

2.6 Study Site: an Ecological Overview of Croatia

Due to its location, its shape and its geographic features, Croatia includes four biogeographical regions: Mediterranean along the Adriatic coast, Alpine along the Dinaric Mountains, Pannonian in the east bordering with Hungary, and Continental in the remaining areas (Radovic 2006). For this reason, Croatia hosts an exceptional diversity of habitats and is one of the most biodiverse countries in Europe (Figure 2.1) (Radovic 2006).

The most common habitat is formed by forests, which occupy 44% of the national territory (Radovic 2006). Although forests are spread across the whole country, most of them are found along the Dinaric Mountains, especially in the north-western part. The main species of trees are beech (*Fagus sylvatica*), common oak (*Quercus robur*), silver fir (*Abies alba*), Norwegian spruce (*Picea abies*), durmast oak (*Quercus petraea*) and common hornbeam (*Carpinus betulus*) (Radovic 2006). Other important habitats are grasslands and meadows, which are mainly found in the Mediterranean ecoregion and in central mountainous areas (Radovic 2006). A smaller area is occupied by several other habitats, including wetlands, scrublands, coastal habitat and karstic underground habitats (Radovic 2006). The remaining area is mainly occupied by agriculture, which holds approximately 23% of the total land share (EC 2013). Most of agriculture is practiced in the Pannonian region, in the east, and in Dalmatia, in the south of the country (EC 2013).

In Croatia there is a great variety of biodiversity with a high quantity of endemic species, especially for vascular plants (Radovic 2006). Moreover, Croatia hosts some charismatic mammal species, including Balkan chamois (*Rupicapra rupicapra balcanica* – 400 individuals) Eurasian brown bears (*Ursus arctos arctos* – 1,000 individuals), grey wolves (*Canis lupus* – 200 individuals) and Eurasian lynx (*Lynx lynx* – 50 individuals) (Kaczensky 2012, Šprem, Fabijanić *et al.* 2012). All these species can mainly be found in mountainous areas along the Dinaric range. Figure 2.2 shows a map with all the toponyms found in this thesis.

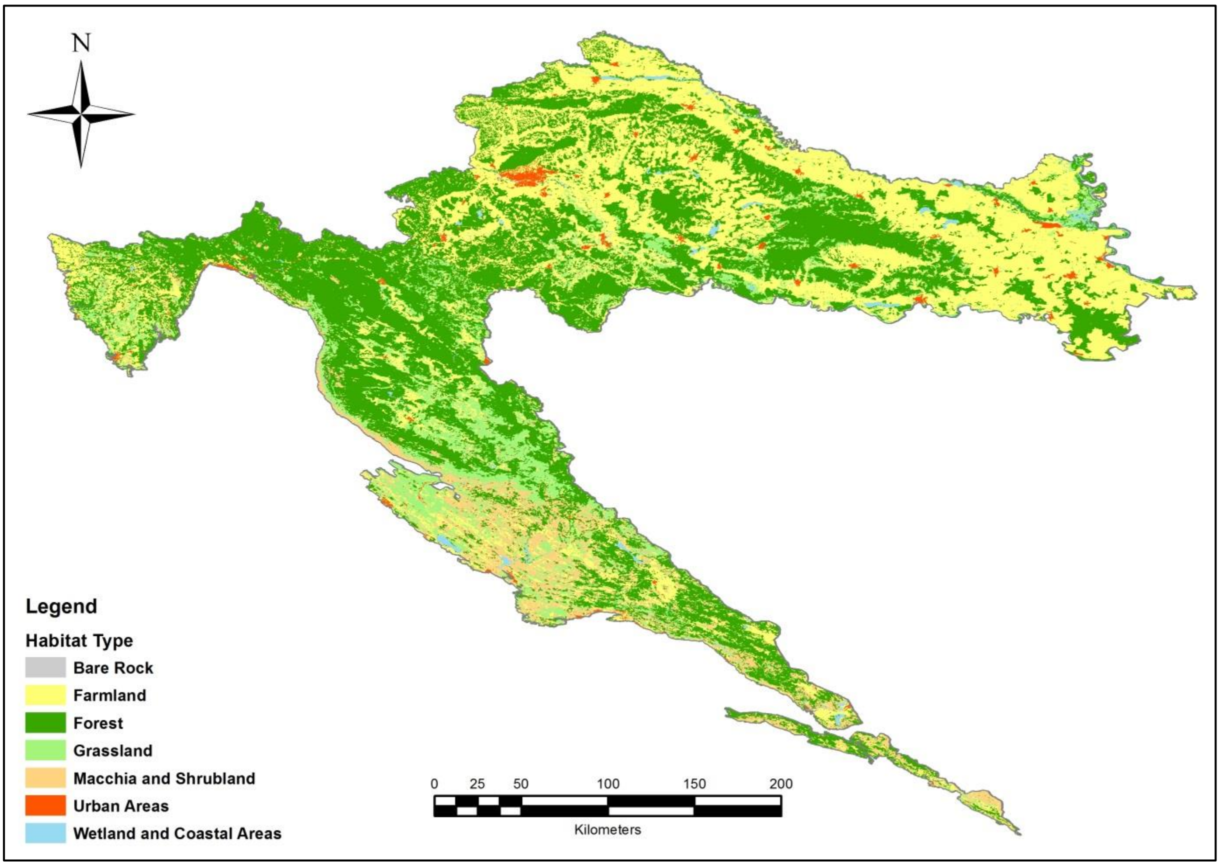

Figure 2.1 Distribution of the main habitat types in Croatia (Ministry of Culture 2005)

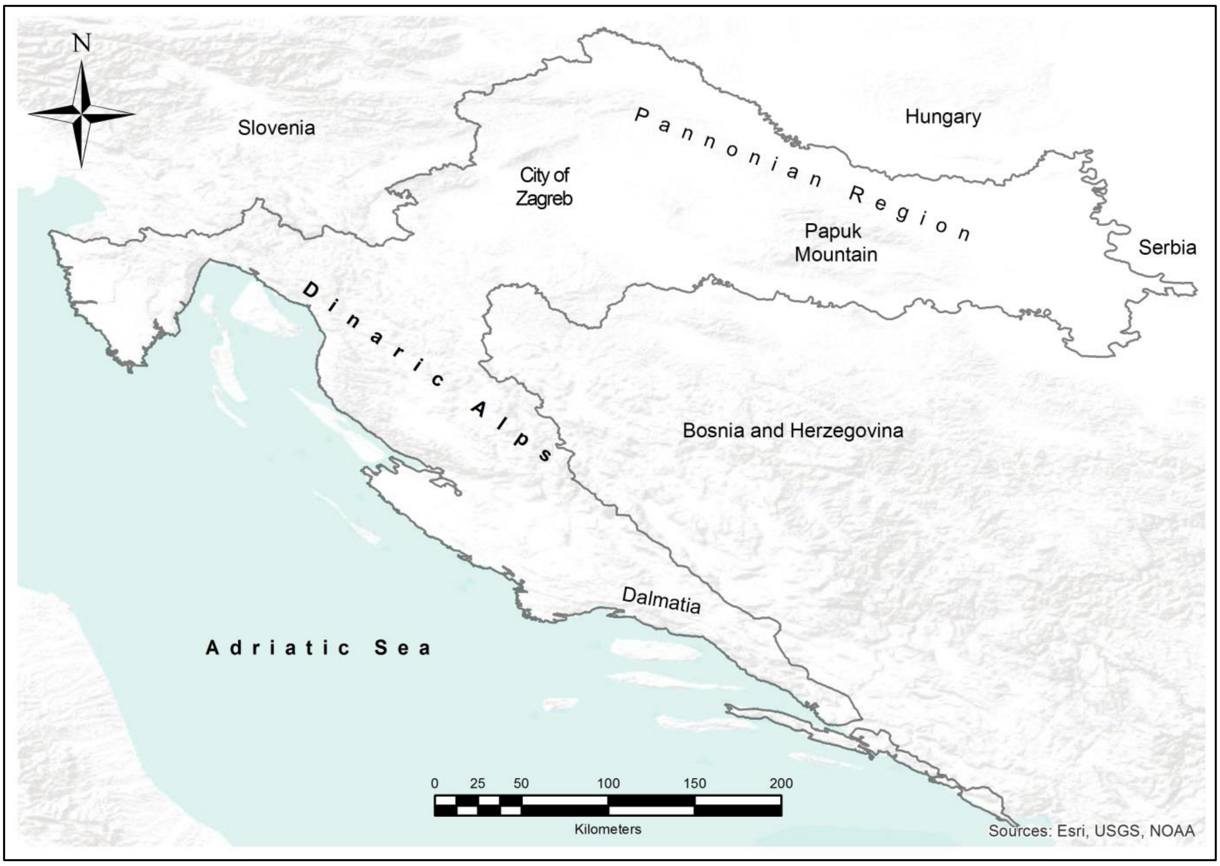

Figure 2.2 Location of the main toponyms mentioned in this thesis

3 Methods

3.1 Methodological Framework

This project aims to inform the strategic prioritisation of planned wind farms in Croatia based on their potential impact on wolf breeding habitat. A habitat suitability model was utilised to relate wolf homesites to a set of environmental variables and to produce a habitat suitability map for wolf breeding habitat. The output of the model was then used to determine the potential impact of planned wind farms on wolves. Finally, a strategic conservation planning software was used to prioritise these wind farms so as to minimise their impact while ensuring the achievement of the targets of the Croatian energy strategy. The methods utilised in this study were chosen to provide a simple and scientifically-based approach for the prompt prioritisation of planned wind farms in Croatia based on a relatively limited amount of available data and information.

3.2 Data Collection and Preparation

3.2.1 Homesites

The locations of homesites were collected in 4 main areas in the wolf distribution range from April to August between 1997 and 2015.

While dens were located through direct observations, with the help of GPS and VHF-telemetry data, rendezvous sites were located using the simulated howling survey method as recommended by 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, Asa *et al.* 2003, Packard 2003). A rendezvous site was considered as such when howling pups could be easily identified or when only adults were heard but the presence of pups was confirmed by other signs, such as direct observation, camera traps photos, dead pups or footprints. Once a rendezvous site was found in the field, in order to find its location, the direction of the howl was recorded and its distance estimated. In case some wolves had a collar, GPS location were also used to support the estimate of the rendezvous site location.

As wolves can use the same rendezvous site through different years (Capitani, Mattioli *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, Willis *et al.* (2015). This was a conservative measure to avoid overestimation by the model of the importance of the variables associated to those sites.

3.2.2 Environmental and Anthropic Variables

Six environmental variables were chosen as potential predictors for wolf breeding habitat based on other similar studies (Corsi, Duprè *et al.* 1999, Theuerkauf, Rouys *et al.* 2003, Capitani, Mattioli *et al.* 2006, Ahmadi, Kaboli *et al.* 2013): distance to settlements, distance to farmland, distance to roads, distance to forest edge, altitude, and slope.

In particular, distance to settlements is the distance to the closest village or aggregation of houses. Distance to farmland is the distance to the closest agricultural land, including arable land, permanent cropland, livestock farming and permanent pastures. Distance to roads is the distance to the closest road, including unpaved forest roads. Distance to forest edge is the distance to the closest forest edge from outside the forest. Thus, a value of "0" means that the site is located anywhere in the forest. All distances and altitude are expressed in metres, while slope is expressed in degrees.

The data from which these variables were created were obtained from different sources. In particular, altitude and slope were obtained from a Digital Elevation Model made available by the Croatian State Geodetic Administration (SGA). Distance to roads, updated to 2006, was obtained from a digital topographic map issued by the same institution. Finally, distance to settlements, distance to farmland and distant to forest edge were obtained from the 2006 Croatian National Habitat Classification (Ministry of Culture 2005). For all these variables a 250x250 m ASCII grid was created for the whole of Croatia using ArcMap 10.2.

Pearson's correlation coefficients (R) were calculated among all layers before running the model, in order to avoid collinearity and, thus, the distortion of variables' relative contribution in determining habitat suitability (Dormann, Elith *et al.* 2013). The threshold value to discriminate correlated variables was set to $R>0.7$ (Dormann, Elith *et al.* 2013, Kramer-Schadt, Niedballa *et al.* 2013, Syfert, Smith *et al.* 2013).

3.2.3 Wind Farms Data

For each wind farm the following data were obtained: name of the project holder, name of project, number of turbines, GPS coordinates for each turbine, and installed capacity (MW). All data were obtained from the Department of Renewable Resources and Energy Efficiency of the Croatian Ministry of Economy, Labour and Entrepreneurship and are publicly available (MINGO 2015).

3.3 Habitat Suitability Modelling

The habitat suitability model was performed using Maxent (Version 3.3.3) (Phillips, Anderson *et al.* 2006). There are three main reasons why Maxent was chosen in this study. Firstly, 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, Anderson *et al.* 2006). Secondly, for species that are still expanding in areas from where they were extirpated, like the wolf in Croatia (Kaczensky 2012, Chapron et al 2014), absence data might be located in unoccupied but suitable habitat (Elith, Phillips *et al.* 2011). Thus, an absence data might not be indicative of unsuitable habitat and might cause occupied suitable areas to be considered unsuitable (Elith, Phillips *et al.* 2011). Thirdly, among the most commonly used presence–only SDMs, Maxent was shown to have the highest performance, particularly at small sample sizes (Hernandez, Graham *et al.* 2006, Wisz, Hijmans *et al.* 2008).

After inputting the homesite locations and the environmental variables in Maxent, “subsampling” was selected as replicated run type, and the model was run for 15 replications. The “Random seed” setting was activated and the random test percentage was set to 25%, meaning that, for 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, Anderson *et al.* 2006). However, when the occurrence data are biased (e.g. close to roads for easier access), in order to avoid the bias to be represented in the whole model, the pseudo-absences can be selected from an area that shares the same bias as the presence points (Zaniewski, Lehmann *et al.* 2002, Dudík, Phillips *et al.* 2005, Phillips, Dudík *et al.* 2009). In this study, in order to consider potential biases in the occurrence locations, pseudo-absences were selected from the sampling distribution of wolf research carried out since 1997 as suggested by Fourcade, Engler *et al.* (2014). All the other settings were set as default, as they have been tested and optimised over a wide and diverse range of studies (Phillips and Dudík 2008).

Lastly, the relative contribution of environmental variables in the model was determined by three different statistical values: the percent contribution, the permutation importance, and the jackknife on the AUC. In particular, the percent contribution is a relative measure of the increase in regularized training gain (i.e. the deviance that maximizes the occurrence probability distribution compared to random) of a variable, compared to the increase in gain of other variables (Phillips 2005). 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). Finally, for each variable, the jackknife measures the AUC value excluding that variable, and including only that variable.

3.4 Wind Farm Prioritisation

The strategic prioritisation of planned wind farms was carried out using Marxan (Version 2.43). Although Marxan is generally used for protected areas design, in this study it was used with a different approach similar to the one adopted by Göke and Lamp (2012). This method for prioritising wind farms was chosen for several different reasons. Firstly, it fits the purpose of this study of meeting specific targets while minimising costs (Ball, Possingham *et al.* 2009). Secondly, it has been shown that it is relatively easy to handle and flexible to changing situations and regular data updates (Ardron, Possingham *et al.* 2008, Göke and Lamp 2012). Thirdly, unlike other optimisation methods using other types of algorithms, its output provides several near-optimal alternatives, as opposed to a single best solution (Ardron, Possingham *et al.* 2008). In spatial planning, a set of "good" solutions is often preferred to a single one, since it allows the negotiation among stakeholders and enables the consideration of other factors that could not be included in the first analysis (Possingham, Ball *et al.* 2000). Lastly, Marxan has shown to be suitable for the application to wind farm spatial planning and it has already been integrated in the planning process of offshore wind farms (Göke and Lamp 2012).

In this study, wind farms were considered as planning units, each of which contributes to the wind energy production targets at an ecological cost. This cost is represented by the ecological impact on wolf breeding habitat. Marxan was run in three different scenarios, each presenting different planning units. In the first and in the second scenarios, each planning unit was represented by each planned wind farm, with a surrounding buffer of 2 km and 4 km respectively. The two buffers were chosen according to the information currently available about the impact of wind farms on wolves (Àlvares, Rio-Maior *et al.* 2011, Álvares, Rio-Maior *et al.* in press). In the third scenario, a grid of hexagons of 1 km per side was created, and covered the whole area occupied by the planned wind farms with a 4 km buffer. Each hexagonal cell of the grid represented one planning unit. This last scenario was applied to create a habitat sensitivity map and to allow wind energy producers to visualise the areas which would have higher impact on wolf breeding habitat.

In all scenarios the cost of each planning unit was determined with the same criteria, using the output from the habitat suitability model. In particular, each planning unit encompasses several suitability cells from the habitat suitability map. The ecological cost was calculated by summing up the suitability values of the cells contained in each planning unit. Hence, the impact of wind farms on wolves was assumed to be proportional to the habitat suitability in each cell. The sum of the habitat suitability cells allows taking into consideration both the average cell value and the area of each planning unit. This approach provides a relative measure of ecological impact. For example, a wind farm built over a bigger area would have a higher impact than a smaller wind farm *ceteris paribus*. Similarly, an area with a higher average cell value would be relatively more affected than a less overall suitable area. 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.

On the other hand, each wind farm, with its installed capacity, 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 (Croatian Parliament 2009a).

The analysis was run for 100 repetitions, in each of which Marxan finds a near-optimal configuration of wind farms to meet the target while minimising the cost. After the analysis, the best solution over all repetitions is presented together with the so-called irreplaceability score. The irreplaceability score is the number of times in which a planning unit was selected in the optimal configuration over all repetitions (Ardron, Possingham *et al.* 2008). The penalty cost for not meeting the Marxan target was set sufficiently high for the target to be met in all repetitions.

Finally, through the setting of the parameter “Boundary Length Modifier”, Marxan allows taking into account the spatial compactness of the selected configuration. However, since this component is not relevant in these circumstances, the parameter was not used (i.e. it was set to 0).

4 Results

4.1 Habitat Suitability Modelling

A total of 31 homesites were found between 1997 and 2015 (Figure 4.1). Among these, 24 were rendezvous sites and 7 were actual dens.

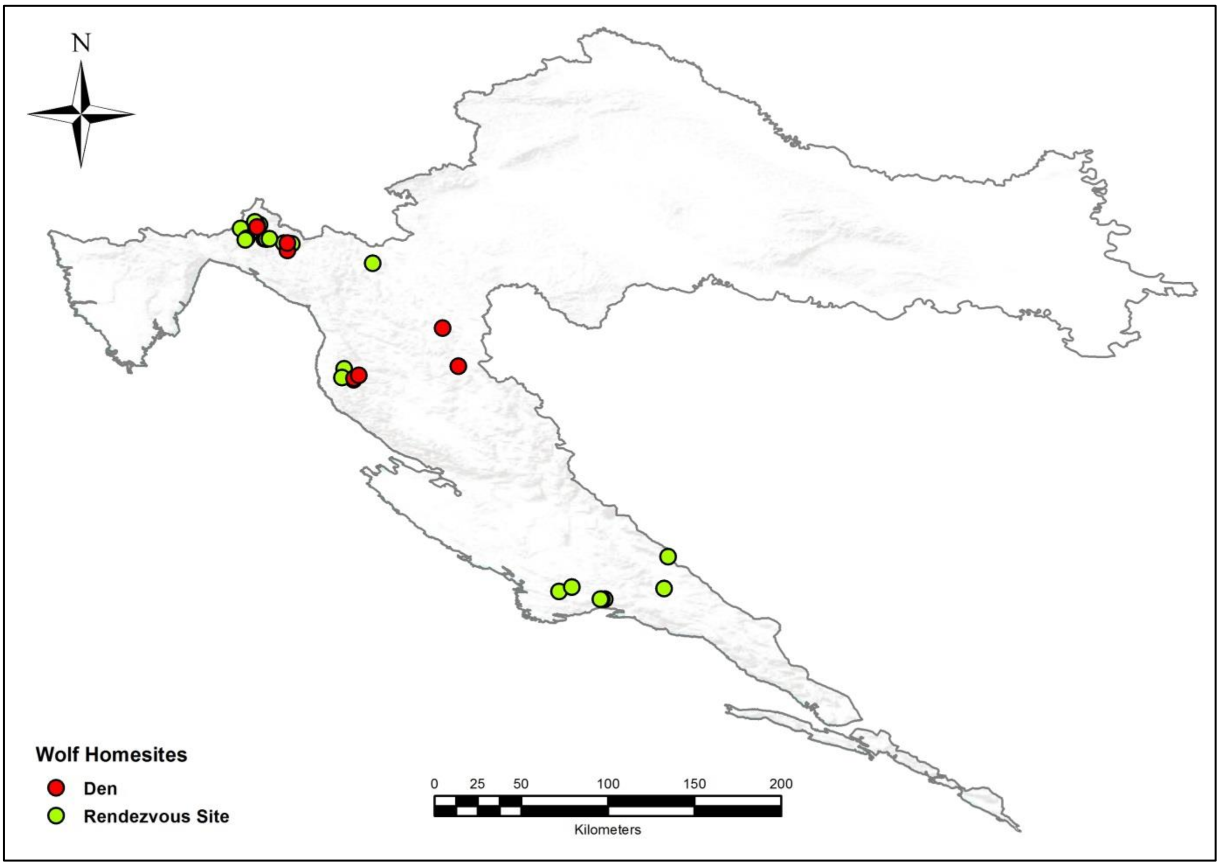

Figure 4.1 The 31 wolf homesite locations collected between 1997 and 2015

The correlation among environmental variables, as shown by the Pearson's correlation coefficients (Table 4.1), was weak in most cases (R<0.60) and slightly higher for distance to farmland with altitude (R=0.61), 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.

Table 4.1 Pearson's correlation coefficients (R) among environmental variables. The threshold to discriminate correlated variables was R>0.7

Variables	Altitude	Distance to Farmland	Distance to Forest Edge	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 Edge	-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

Overall, the model showed good performances, indicated by an AUC of 0.805 (SD=0.072). According to the percent contribution values, the most important predictors for wolf suitability were distance to settlements, distance to farmlands and distance to roads (Table 4.2), which were all positively correlated with habitat suitability (Figure 4.2). However, based on the permutation importance values, distance to forest edge seemed also to be very important, and negatively correlated with probability of occurrence.

Table 4.2 Main statistical values showing the relative contribution of environmental variables in Maxent

			Jackknife on AUC	
Variable	**Percent Contribution (%)**	**Permutation Importance (%)**	**Without Variable**	**With Only Variable**
Distance to Settlements	33.46	29.48	0.804	0.763
Distance to Farmland	23.13	14.43	0.801	0.760
Distance to Roads	21.41	11.86	0.751	0.591
Distance to Forest Edge	8.34	33.10	0.796	0.655
Altitude	11.38	8.42	0.802	0.674
Slope	2.27	2.71	0.816	0.590

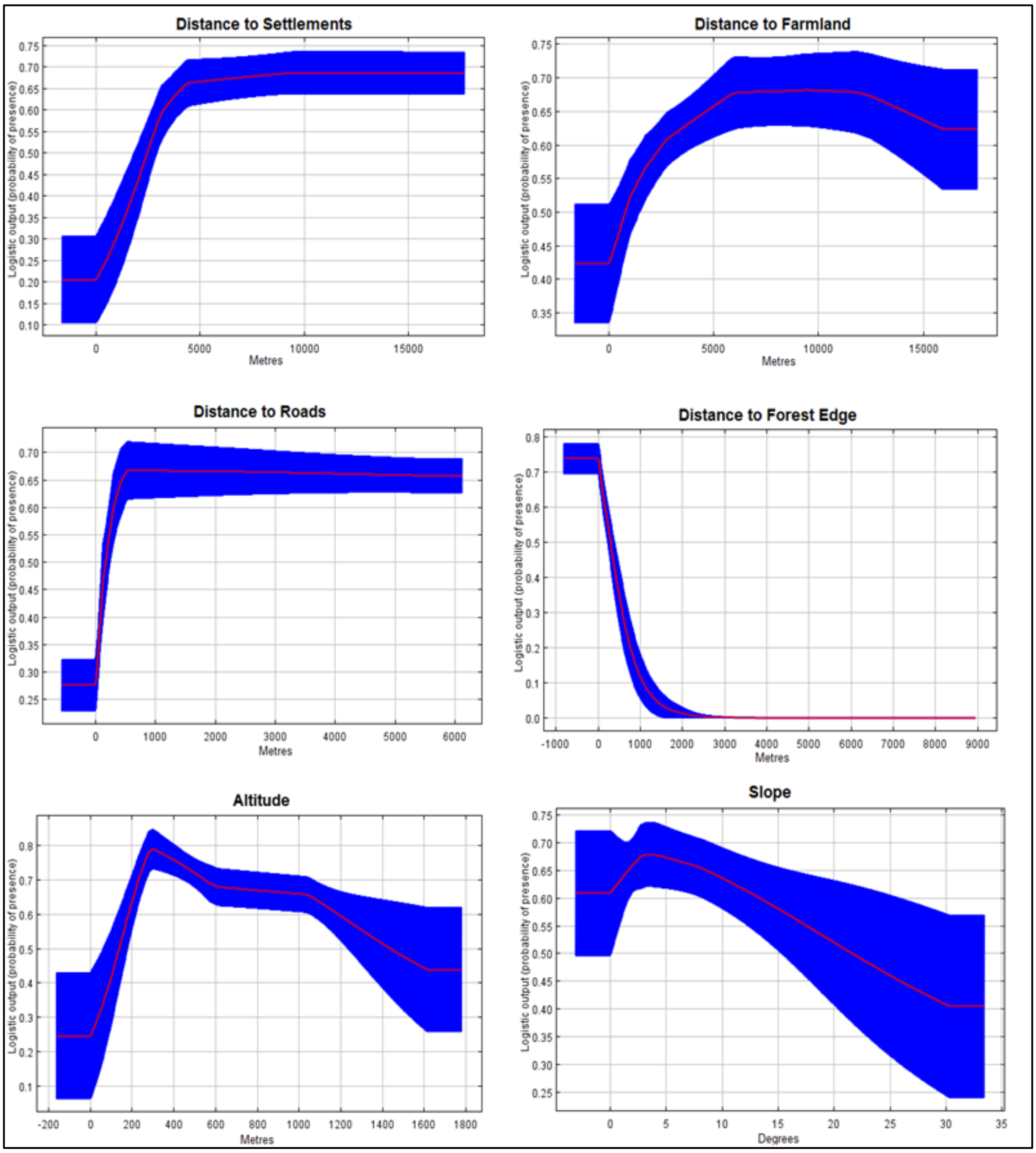

Figure 4.2 Response curves for the 6 model predictors. The curves show how the species probability of occurrence changes with each predictor, maintaining all other predictors at their average sample value. The red curves represent the mean trends, while the blue shades show the mean +/- the standard deviation. In each graph, the X axis shows the change in each environmental variable, while the Y axis shows the species' probability of presence.

The values of environmental variables at occurrence locations show a very high variability indicated by high standard deviation values (Table 4.3). Looking at the minimum values, it can be noticed that some homesites were located very near roads and farmland, while they tended to be located further from human settlements. Finally, apart in some extreme cases, homesites were, in average, very close or inside the forest.

Table 4.3 Minimum, maximum, mean and standard deviation values for the 6 environmental variables. 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	STD
Distance to Roads	0.00	2610.08	674.88	625.55
Distance to Farmland	0.00	15337.86	5604.21	3787.99
Altitude	285.47	1496.54	867.94	325.10
Slope	0.17	14.39	6.40	3.69
Distance to Settlements	901.39	10960.16	5106.61	2757.53
Distance to Forest Edge	0.00	2015.56	65.02	356.12

Based on the model output map (Figure 4.3), 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 high breeding habitat fragmentation caused by roads can also be noticed.

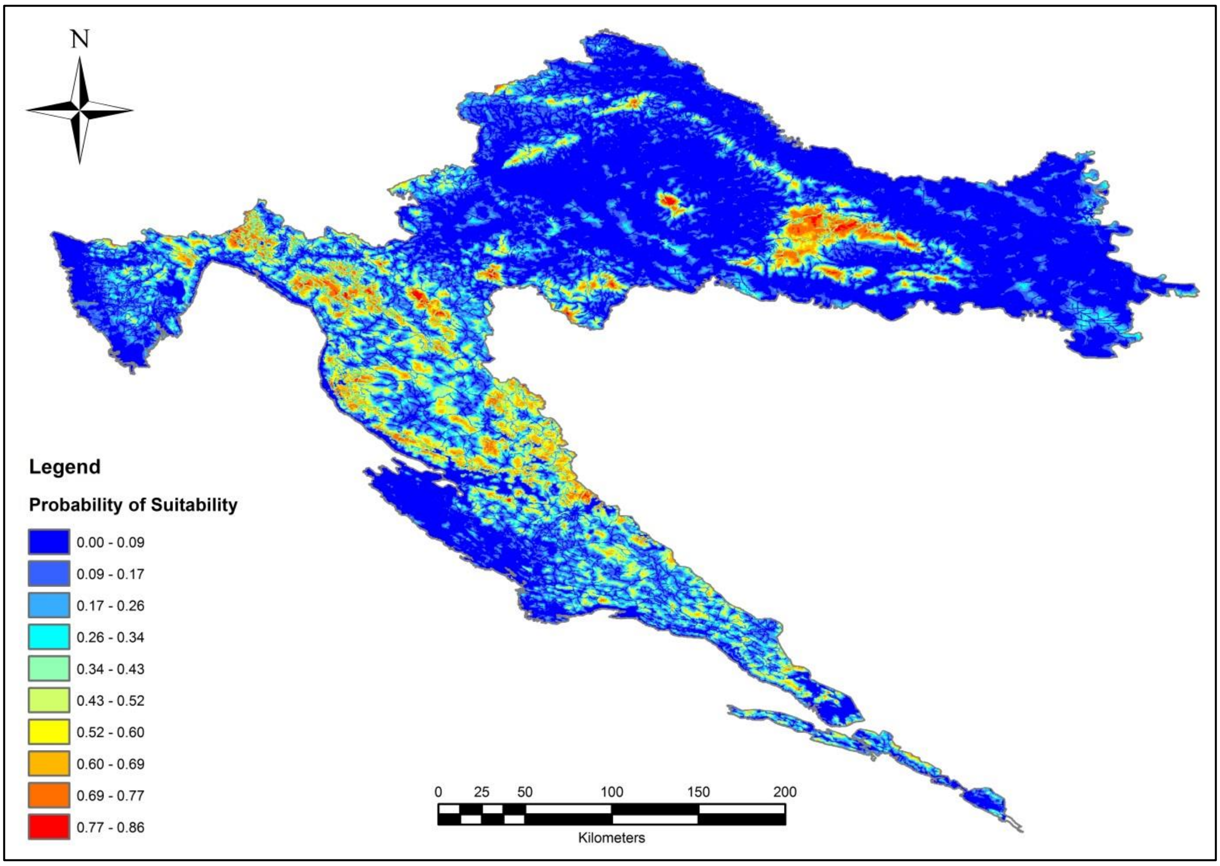

Figure 4.3 Habitat suitability map obtained with Maxent. Blue indicates low suitability, green indicates intermediate suitability and red indicates high suitability areas.

4.2 Wind Farm Prioritisation

Proposed wind farms are mainly located within the current wolf distribution and overlap with several high quality wolf reproduction areas (Figure 1.2, Figure 4.3, Appendix I). The Marxan analysis shows that, according to the 2 km and 4 km buffer scenarios (Figure 4.4, Table 4.4), the 2020 target of the Croatian energy strategy would be met respectively with only 15 and 12 wind farms. These correspond respectively to 44.5% and 36.4% of the 33 total proposed wind farms (Table 4.4).

In both scenarios, after the selection, the resulting installed capacity would be 748 MW (i.e. 48.1% of the total initial capacity). With respect to the potential impact on wolf breeding habitat, the optimisation would lead to a decrease of 76.69% in the 2 km buffer scenario, and of 80.49% in the 4 km buffer scenario. Thus, in the former, 44.5% of the proposed wind farms would hold only 23.31% of the total initial cost. Similarly, in the latter, 36.4% of the wind farms would hold only 19.5% of the total initial cost.

This indicates that Marxan allowed selecting highly cost-efficient wind farms. For example, the wind farm no.1 has the maximum irreplaceability score because it would produce a high amount of energy for a relatively small impact. On the other hand, the wind farm no.30, with an installed capacity even bigger than wind farm no.1, has an irreplaceability score of 0, since its cost is also very high. Finally, the wind farm no.24 has a high irreplaceability score, since, despite the low installed capacity, it also holds a very small cost. Moreover, the low cost associated to wind farms no.20, 22, 24 and 27 is due to the fact that these wind farms are planned around already operating ones. As such, their additional cost is limited.

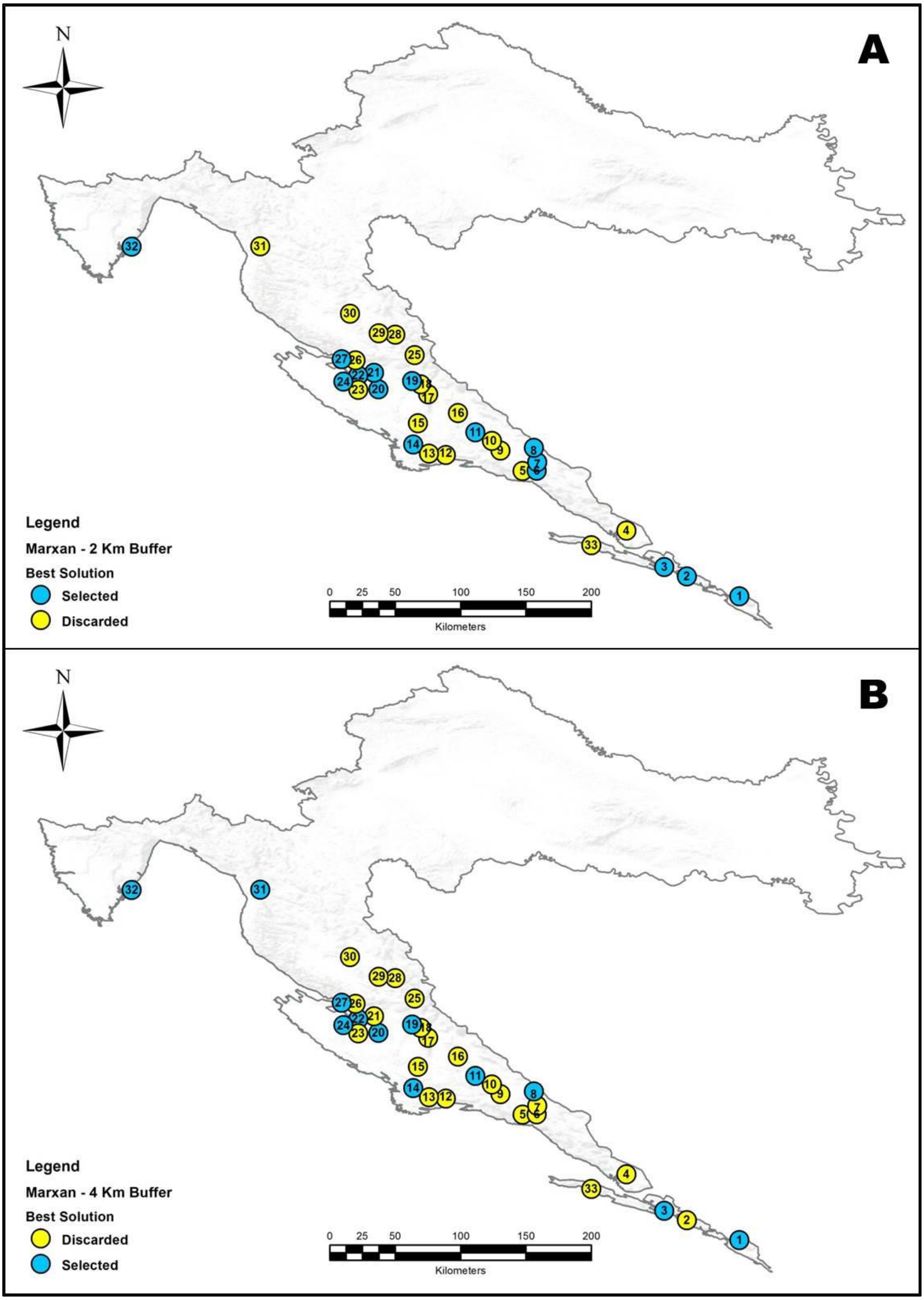

Figure 4.4 Best solution for the Marxan analysis over 100 repetitions in the 2 km (A) and 4 km (B) buffer scenarios. The number of each wind farms corresponds to the numbers in table 4.4

Table 4.4 Marxan values for all wind farms in the 2 km and 4 km buffer scenarios. IS=Irreplaceability score over 100 Marxan repetitions; MW=Installed capacity in MW; %=percent of the analogous initial value; % decrease=percent reduction compared to the analogous initial value. "MW in Best Solution" and "Cost in Best Solution" only show the MW and the cost of selected wind farms in the best solutions. The numbers in this table correspond to wind farms shown in figure 4.4. Further information about these wind farms can be found in Appendix I

		2 Km Buffer				4 Km Buffer			
Wind Farm No.	MW	Cost	IS	MW in Best Solution	Cost in Best Solution	Cost	IS	MW in Best Solution	Cost in Best Solution
1	117	48.40	100	117	48.40	92.23	100	117	92.23
2	57	149.01	32	57	149.01	224.28	32		
3	70	90.62	98	70	90.62	192.12	91	70	192.12
4	22	129.98	0			312.86	0		
5	10	45.78	10			173.67	0		
6	39	67.03	89	39	67.03	196.63	9		
7	48	89.37	80	48	89.37	264.87	9		
8	27	21.22	99	27	21.22	3.36	100	27	3.36
9	45	103.07	55			269.53	3		
10	33	250.52	0			470.15	0		
11	54	117.88	59	54	117.88	169.61	77	54	169.61
12	33	134.64	2			284.25	0		
13	45	118.26	20			168.89	40		
14	23	58.47	42	23	58.47	65.16	85	23	65.16
15	21	51.99	39			139.26	7		
16	64	385.12	0			759.12	0		
17	10	47.74	2			188.63	0		
18	42	126.77	15			243.79	8		
19	80	103.40	99	80	103.40	200.20	99	80	200.20
20	33	7.98	100	33	7.98	16.36	100	33	16.36
21	42	88.42	64	42	88.42	147.49	38		
22	48	7.33	100	48	7.33	8.89	100	48	8.89
23	23	133.52	0			81.62	40		
24	18	5.96	100	18	5.96	2.37	99	18	2.37
25	45	116.81	28			208.50	14		
26	10	21.58	40			80.70	11		
27	20	15.36	98	20	15.36	9.31	99	20	9.31
28	45	128.45	19			389.17	0		
29	20	133.15	0			237.81	0		
30	120	764.02	0			1777.15	0		
31	186	516.39	21			708.44	67	186	708.44
32	72	130.20	83	72	130.20	173.44	98	72	173.44
33	33	85.11	23			155.32	19		
TOTAL	**1555**	**4293.56**		**748.00**	**1000.66**	**8415.19**		**748.00**	**1641.49**
%	**100**	**100**		**48.10**	**23.31**	**100**		**48.10**	**19.51**
% Decrease	**0**	**0**		**51.9**	**76.69**	**0**		**51.9**	**80.49**

The Marxan analysis for the hexagonal grid shows the cost-efficiency of each hexagonal cell over the total area covered by the 33 proposed wind farms, considering a 4 km buffer around each turbine (Figure 4.5). The cells that produce the most with a relatively lower impact are more likely to be selected by Marxan and, thus, they have a high irreplaceability score. By comparing this figure with Figure 4.4 it can be seen that, in general, relatively high scoring cells are located mostly within the areas where wind farms were selected in the 4 km buffer scenario.

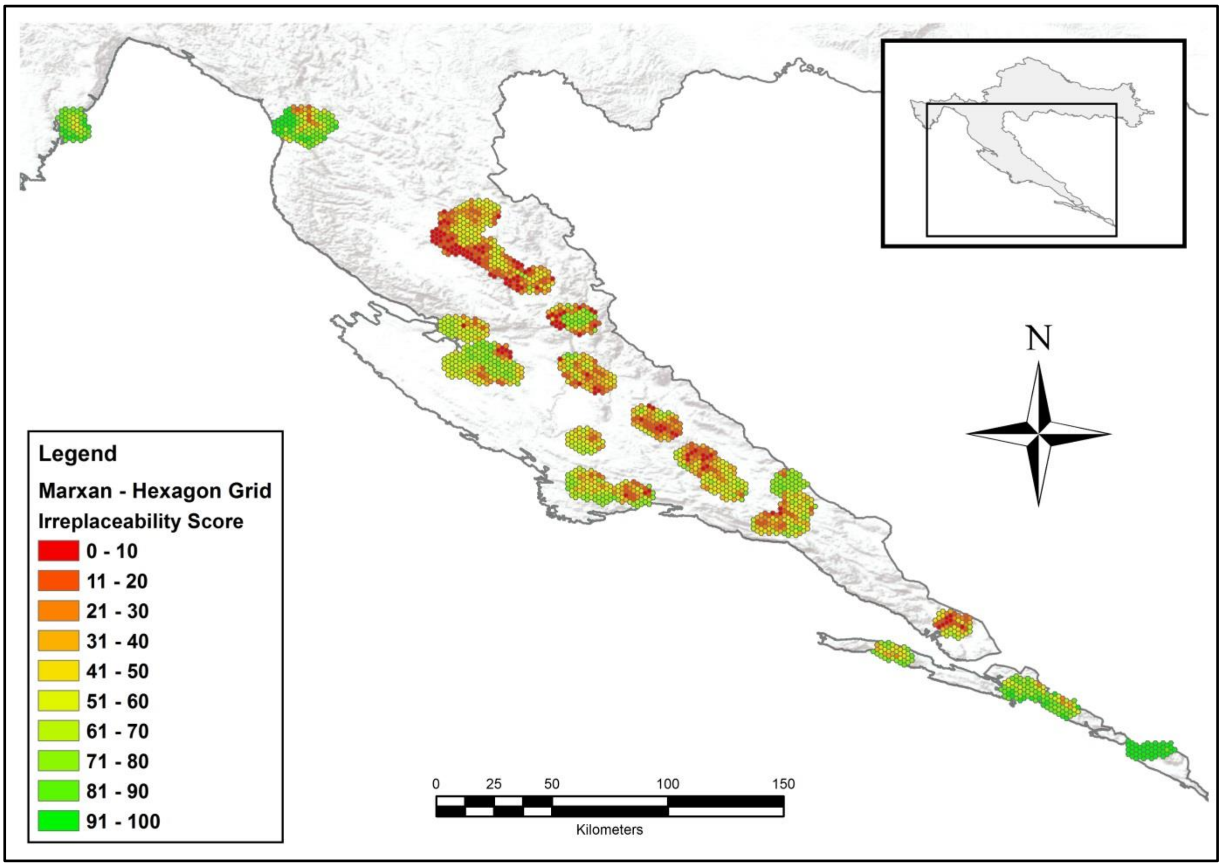

Figure 4.5 Marxan analysis of the hexagonal grid over the area covered by proposed wind farms with a 4 km buffer. The irreplaceability score is the number of times in which each cell was selected in the optimal configuration over 100 Marxan repetitions. The figure shows the extent to which wolf breeding habitat in each cell would be affected by wind farms construction**.**

5 Discussion

5.1 Habitat Suitability Model

This study presents the first habitat suitability model for wolf breeding habitat in Croatia. It is therefore important because it provides valuable information about wolf habitat selection and potential distribution.

The habitat suitability model obtained an AUC value of 0.805. According to Swets (1988, Hosmer Jr and Lemeshow 2004) and Elith (2000), such a value indicates good model performance. Moreover, this value of discriminative power is only slightly lower than the ones obtained in other similar studies. For example, Iliopoulos, Youlatos *et al.* (2014) obtained an AUC value of 0.818, while Bassi, Willis *et al.* (2015) and Ahmadi, Kaboli *et al.* (2013) reached an AUC of 0.876 and 0.894 respectively. However, their sample sizes (i.e. 35, 146 and 35 occurrences) were bigger than in this study, thus increasing the likelihood of obtaining a higher AUC value.

With respect to model predictors, the Pearson's correlation analysis showed that there was a moderate correlation between some of the variables. This correlation never had a coefficient higher than 0.64 and was therefore considered acceptable as in other studies (Dormann, Elith *et al.* 2013, Kramer-Schadt, Niedballa *et al.* 2013, Syfert, Smith *et al.* 2013). Nonetheless, the relative contributions of correlated variables should still 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 the two most important predictors for habitat suitability. However, they were also the most correlated variables. Thus, the values of the analysis of variable contributions for these two predictors may not be representative of their independent importance in determining habitat suitability. Nevertheless, settlements and farmlands are both related to human activities which might deter wolves from breeding in their proximity. Hence, their relative importance may be proportional to the type and extent of the disturbance they cause. In fact, it has been widely shown that wolves tend to avoid humans and to locate breeding sites far away from villages, farms and roads (Theuerkauf, Rouys *et al.* 2003, Kusak, Majić-Skrbinšek *et al.* 2005, Jędrzejewski, Jędrzejewska *et al.* 2008, Ahmadi, Kaboli *et al.* 2013, Bassi, Willis *et al.* 2015).

In this study, 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, Rouys *et al.* 2003, Kaartinen, Kojola *et al.* 2005, Ahmadi, Kaboli *et al.* 2013). Hence, it seems that roads are likely to have an effect on breeding habitat only for the first few hundred meters. Moreover, it has been shown that roads may facilitate wolf movements, especially during the denning season, when adult wolves have to provide food for other pack members (Zimmermann, Nelson *et al.* 2014).

Among the environmental predictors, the most influential was distance to forest edge, while altitude and slope only showed minor contributions. However, although similar results are common for human dominated areas (Theuerkauf, Rouys *et al.* 2003, Ahmadi, Kaboli *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, given the low dependency of wolves on particular habitats, in human dominated regions like Europe, anthropic variables are more likely to play a major role in determining habitat suitability (Mech and Boitani 2003, Ahmadi, Kaboli *et al.* 2013).

The habitat suitability map is consistent with the current knowledge about wolf habitat and wolf distribution in Croatia (Kaczensky 2012). Most of the predicted suitable areas correspond to the currently occupied areas, especially in the Dinaric Mountains and in the region in central Croatia protruding into the north-west of Bosnia and Herzegovina.

The main area predicted suitable outside the wolf current distribution is the region around the Papuk Mountain. This area may potentially accommodate a future expansion from northern Bosnia. However, this expansion is very unlikely in the near future, since the area is completely surrounded by farmland and is isolated by a fenced highway without crossing structure. This area is also rather far from currently occupied sites. All other areas which were predicted to be suitable mainly correspond to confined forest patches in mountainous areas and are too small and isolated to represent potentially meaningful expansion areas.

In unsuitable areas, especially in the currently occupied range, wolves might still be regularly present. This study only models dens and rendezvous sites, and does not consider the winter time, nor wolf movements in the breeding season. In fact, it was shown that, during the breeding season, adult wolves in North America may walk up to 48 km from the den to obtain food (Mech 1988). Despite this distance being smaller in Europe (Kusak, Majić-Skrbinšek *et al.* 2005), it is still likely that wolves spend a large part of their time in unsuitable breeding habitat. Moreover, although wolves avoid human disturbance for locating dens and rendezvous sites (Theuerkauf, Rouys *et al.* 2003, Kusak, Majić-Skrbinšek *et al.* 2005, Jędrzejewski, Jędrzejewska *et al.* 2008, Ahmadi, Kaboli *et al.* 2013, Bassi, Willis *et al.* 2015), they still visit and feed from highly humanized places, including villages, roads, farms and garbage dumps (Ciucci, Boitani *et al.* 1997, Kusak, Majić-Skrbinšek *et al.* 2005). Nonetheless, they always tend to minimize their direct contact with people, mainly by segregating their activity pattern during night time (Kusak, Majić-Skrbinšek *et al.* 2005).

In Croatia, this situation is particularly common in Dalmatia, where human-wolf conflict is more intense (Kusak, Majić-Skrbinšek *et al.* 2005). In this area, livestock depredation by wolves is the main cause of conflict (Kusak, Majić-Skrbinšek *et al.* 2005, Majić and Bath 2010). This often leads to retaliatory killing, which represents one of the main causes of wolf mortality in Croatia (Huber, Kusak *et al.* 2002, Kusak, Majić-Skrbinšek *et al.* 2005). This conflict, resulting from the coexistence of humans alongside wolves, might be one of the reasons why habitat suitability is predicted to be lower in Dalmatia than in other parts of the current wolf range. In fact, as it can be noticed in the habitat distribution map (Figure 2.1), forests in Dalmatia are more fragmented by a relatively large amount of farmland, compared to other areas in the wolf range.

In spite of the good performance, the model also presents some limitations mainly related to the difficulties in wolf data collection, notably in Karstic and highly rugged terrains. In particular, the main limitation was the large time interval over which the homesites were spread. In the model, the occurrence localities collected from 1997 to 2015 were related and projected to environmental variables fixed in 2006. Hence, the model was carried out assuming that general habitat conditions did not change substantially between 1997 and 2015.

Among the environmental predictors, apart from altitude and slope, which are obviously invariable across time, forest cover showed an increase of only 2.79% from 1997 to 2012 (FAO 2015). With respect to the predictors related to human disturbance, the changes were slightly higher. From 1996 to 2014, the total population decreased by 5.73%, with most of this decline occurring in rural areas, while arable land decreased by 8.11% between 1997 and 2012 (Croatian Bureau of Statistics 2011, FAO 2015). Although these changes were higher, they were still considered acceptable. This decision was consistent with that of Jędrzejewski, Jędrzejewska *et al.* (2008), who accepted a population increase of *circa* 5% over the time interval in which data were collected. Moreover, several other studies that share similar time discrepancies between occurrence localities and environmental variables have overlooked this type of limitation (Corsi, Duprè *et al.* 1999, Treves, Naughton-Treves *et al.* 2004, Iliopoulos, Youlatos *et al.* 2014, Bassi, Willis *et al.* 2015).

5.2 Wind Farm Prioritisation

This study presents important results to support the spatial planning of wind energy in Croatia and it will contribute to the assessment of environmental impacts of proposed wind farms. The prioritisation carried out in this study would potentially lead to a reduction of wind farm impacts on wolf breeding habitat of up to 80.5% with a decrease of only 52% in potential installed capacity. This reduction was similar in both buffer scenarios and was due to the selection of wind farms with a high capacity and a low cost. This low cost is not necessarily associated to unsuitable wolf habitat. For example it can be due to the presence of already existing wind farms. In fact, locating proposed wind farms near others already in operation would likely reduce their additional impact on the wolf, by avoiding disturbance in new “undisturbed” areas. The Marxan analysis also produced a sensitivity map across the whole planning area. This output will allow wind farm planners to identify the areas where wind turbines are more likely to have higher impacts and require modifications (e.g. displacement to other areas).

Although several studies have been published on the spatial planning of wind farms (Baban and Parry 2001, Punt, Groeneveld *et al.* 2009, Aydin, Kentel *et al.* 2010, Tegou, Polatidis *et al.* 2010, Drechsler, Ohl *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 these outputs and their effectiveness with the ones of other studies. However, Marxan is considered ideal in optimisation problem solving, also in different applications from strategic conservation planning (Ardron, Possingham *et al.* 2008, Göke and Lamp 2012). For example, Marxan was used in the context of wind farm spatial planning in at least one occasion. In particular, in an offshore wind energy implementation project in the Baltic Sea, it was integrated as a support tool in the spatial planning process (Göke and Lamp 2012). In this case study, Marxan has shown to be an adequate and successful method also in addressing wind farm prioritisation (Göke and Lamp 2012). For these reasons, and considering the type of problem addressed and the nature of the outputs required in this study, Marxan was preferred to the other conventional methods.

Despite the choice of the most suitable method, this study presented some limitations. In particular, the main weakness 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 (i.e. the 2 km or 4 km buffer), they would also share the ecological cost. Hence, if considered together, they would have the same installed capacity than 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, Possingham *et al.* 2008). Nonetheless, for the 2 and 4 km buffer scenarios the total overlapping area was only around 8% and 11% respectively, and was distributed equally across many wind farms. Hence, it is likely that no particular areas would benefit from wind farms being built together in clusters. Moreover, this limitation would have existed also in the other conventional methods used in previous similar studies.

This approach to Marxan can also be extended to other infrastructure and to the other two species of large carnivores in Croatia. 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 cost (Punt, Groeneveld *et al.* 2009, Drechsler, Ohl *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 occur equally for each single cost and that all cost are satisfactorily minimised.

5.3 Future Implications and Recommendations

This study provides valuable tools for the future conservation of wolves in Croatia and Europe. In particular, the habitat suitability model offers a better understanding of breeding wolf environmental requirements and provides a useful map showing the potential distribution of wolves in Croatia. This information can be used for the improvement of the management plan for the wolf in Croatia, for future conservation planning, for the prevention of human-wolf conflicts, for environmental impact assessments and for awareness raising campaigns (see section 2.4.2). Moreover, the results of the prioritisation show the optimal configuration of wind farms to meet the Croatian target at the lowest impact on wolf habitat, and will contribute to a large EIA for wind farms in Croatia. Hence, this study presents a scientific and evidence-based framework to support the sustainable implementation of proposed infrastructure, and contributes in ensuring the long-term viability of wolves and other charismatic and wide-ranging species in Croatia and Europe.

However, despite the usefulness and practicality of these outputs, 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 homesites in a more restricted time interval, in order to bypass the limitations highlighted in this study and produce a yet more accurate map of breeding habitat suitability.

Moreover, the qualitative and quantitative impact of wind farms on wolves and other non-volant animals should be clarified (Lovich and Ennen 2013). For this purpose, constant wolf monitoring should be carried out in and around areas where wind farms are proposed or built. Energy consumption in Croatia is projected to increase further by 2030 and wind energy has been identified as the main source of renewable energy (Ministry of Economy and UNDP 2008). Therefore, wolf monitoring should also be realized in areas where wind energy may potentially be implemented in the longer term. This would provide data over longer periods to carry out more accurate BACI analysis in the future. From this perspective, a more thorough and regular communication of intents and objections among scientists, politicians and wind power developers would be beneficial and is, thus, urgently required. In an environmental context, conservationists, politicians and wind farms developers should share at least part of their values and objectives. However, a regular communication and cooperation among these stakeholders in Croatia is currently lacking (Švarc 2006). It is therefore important that these parties find a common thread, while still acknowledging their differences in short-term stakes. Lastly, a more direct communication is essential to enable the adoption of an adaptive management approach for wolf monitoring and wind-energy-related decision making.

Furthermore, although prioritisation is a useful way to reduce wind farms' potential impacts on wolves during planning processes, other measures for the minimisation of these impacts should also be taken into consideration during the construction and operation phases. For example, in the construction phase of a wind power plant in Portugal, critical areas within the future wind farms were identified and all construction activities were prohibited during the denning period (Soares, Duarte *et al.* 2011). All activities in all areas were also forbidden from sunset to sunrise (i.e. the period when wolves are most active). Furthermore, since roads seem to represent one of the main factor impacting wolves around wind farms during the operation phase (Huber, Kusak *et al.* 2002, Àlvares, Rio-Maior *et al.* 2011, Helldin, Jung *et al.* 2012), in Portugal it has been proposed to close access roads in order to reduce traffic and direct human disturbance (Àlvares, Rio-Maior *et al.* 2011).

From a wider perspective, wind is a source of renewable energy that could curb our dependence on fossil fuels and significantly decrease greenhouse gasses emissions (Sims, Rogner *et al.* 2003). Thus, wind energy has several environmental advantages and represents an outstanding opportunity towards anthropogenic climate change mitigation (Edenhofer, Pichs-Madruga *et al.* 2011). On the other hand, the generation of energy through the use of wind turbines could have a negative environmental impact related to the large amount of land required for wind energy implementation (Kiesecker, Evans *et al.* 2011). In anthropic-dominated regions like Europe, where the available surface of land is limited, the landscape is the result of competition among agriculture, urbanisation, conservation, energy production and other land use types. This competition is the main factor that determines the state of our environment and economies (Rounsevell, Reginster *et al.* 2006). It is, therefore, crucial that land management decisions take into consideration the environmental, social and economic opportunities and implications of each land use activity.

In conclusion, this study presents a systematic and repeatable framework for infrastructure prioritisation based on its ecological impact on wide-ranging carnivore species. In particular, it offered scientific evidence of the spatial distribution of wolf breeding habitat and adopted it in the strategic prioritisation of planned wind farms in Croatia. As such, it provides fundamental information for wolf conservation and represents a small step towards a more equal and sustainable land management in Europe; environmentally, socially and economically.

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7 Appendices

7.1 Appendix I

Further information about the proposed wind farms In Croatia.

Wind Farm Number	Capacity (MW)	N. of Turbines	Project Holder	Project Name
1	117	37	Cannon Libertas Co.	VE Konavodska brda
2	57	20	VE MRAVINJAC d.o.o. za proizvodnju enerjie	VE Mravinjac
3	70	27	Vjetroelektrana Rudine d.o.o.	VE Rudine
4	22	10	Hyperborea d.o.o.	VE Rujnica
5	10	5	Vjetroelektrana Orjak d.o.o.	VE Kom-Orjak-Greda
6	39	12	Vjetroelektrana Katuni d.o.o.	VE Katuni
7	48	16	Vjetroelektrana lukovac d.o.o.	VE Lukovac
8	27	9	Dalekovod Professio	VE Voštane
9	45	30	Vjetroelektrana Jelinak d.o.o.	VE Čemernica
10	33	11	Zelovo d.o.o.	VE ST3-1/2
11	54	18	Aiolos Projekt	VE Ogorje
12	33	22	Vjetroelektrana Opor	VE Opor
13	45	30	Acciona Enerjia	VE Boraja II
14	23	10	Vjetroelektrana Glunča	VE Glunča
15	21	8	IVICOM Consulting GmbH. - PODRUŽNICA ZAGREB	VE Mideno brdo
16	64	36	Jura Energija	VE Svilaja
17	10	5	Vjetroelektrana Ljubač	VE Ljubač - faza 1
18	42	31	C.E.M.P.	VE Krš Padene-Proširenje
19	80	38	C.E.M.P.	VE Krš Padene (KPA) 1. faza
20	33	11	Ventus Flatus	VE ZD3P
21	42	11	Vjetroelektrana Orljak	VE Orljak
22	48	15	Kunovac	VE ZD2P
23	23	10	Venti	VE Krug - Bikina Glava
24	18	7	EKO Zadar DVA	VE ZD4P
25	45	15	Poštak	Proširenje ZD6 (dio) snage oko 45 MW

Wind Farm Number	Capacity (MW)	N. of Turbines	Project Holder	Project Name
26	10	10	C.E.N.S.U.R. - Zrmanja	Kompleks male vjetroelektrana Jasenice
27	20	6	IN POSTERUM d.o.o.	VE ZD5
28	45	15	Vjetroelektrana Bruvno	VE Bruvno
29	20	6	Dalekovod Professio	VE Mazin 2
30	120	61	LIKA-FENIKS	Kompleks vjetroelektrana Udbina 120MW
31	186	63	Energija Projekt	VE Senj
32	72	49	EURUS d.o.o. Za projektiranje i nadzor	VE Goli
33	33	13	WPD ENERSYS d.o.o.	VE Bila Ploča