Spatial distribution of wind turbines is crucial for the survival of red kite populations

Michael Schaub *

Swiss Ornithological Institute, CH-6204 Sempach, Switzerland

ABSTRACT

Energy production with wind turbines is increasing, because this form of energy production is CO_2 neutral and renewable, and because wind power is subsidised in many countries. However, wind turbines are not without impact on biodiversity, rather, they can affect bird and bat populations through collision-induced mortality. It is relatively well studied how wind turbine architecture or the surrounding habitat affect the collision risk of birds and bats. It is much less well understood how losses due to collisions affect bird and bat populations. Moreover, it is currently unknown how the spatial configuration of wind turbines in the landscape affects populations. I addressed these two questions using an individual-based simulation model inspired by the Swiss red kite Milvus milvus population. This species is a frequent collision victim at turbines and one of Europe's sole endemic species. I predicted the fate of populations in relation to the number and spatial configuration of wind turbines. I found that population growth rates declined progressively with an increasing number of wind turbines. These negative effects can be weakened if wind turbines are aggregated in power plants. Quantitatively the results strongly depended on the parametric form of the relationship between collision risk and the distance between wind turbines and kite nest location. Unfortunately, empirical knowledge about this relationship is scarce. As the effect of wind turbines depends on their total number and their spatial configuration within the area inhabited by a raptor population, I emphasise the importance of making environmental impact assessments not on a case-by-case basis but rather for an entire region with all its wind power plants, which collectively exert an impact on a raptor population. This must include the impact of extant as well as planned wind turbines in the same region in order to be biologically meaningful.

1. Introduction

The production of energy with wind turbines has the advantage that wind is a renewable energy resource and that no greenhouse gases are emitted. The construction of wind turbines has therefore received a lot of support from the public and from local and federal governments through subsidies. As a result, the number of wind farms is increasing worldwide (Pullen and Sawyer, 2011). However, while exploitation of wind energy does not chemically pollute nature, it still can have negative impacts on biodiversity. These negative effects include mortality of airborne animals, especially birds and bats, due to the collision with wind turbines, habitat loss at the power plant site and the displacement of individuals through dispersal, when the altered habitat is avoided (Drewitt and Langston, 2006). A careful planning of the number and locations of new wind turbines is necessary when wind energy exploitation wants to live up to its "green" reputation.

The effects of wind turbines on wildlife, and possible mitigation measures, have been studied increasingly over the past years.

These studies involve the monitoring of mortality in birds and bats, the relationship between the type of wind turbine and collision risk, and the evaluation of locations of wind farms to minimise their environmental impact (e.g., Barrios and Rodriguez, 2004; Eichhorn and Drechsler, 2010; Kiesecker et al., 2011; Kuvlesky et al., 2007; Smallwood, 2007). They have revealed that the absolute numbers of turbine-killed birds and bats was often quite low, but varied greatly among sites (reviewed in Drewitt and Langston (2006) and Stewart et al. (2007)) and that turbine collision risk of birds depended on rotor blade characteristics as well as on turbine illumination (reviewed in Drewitt and Langston (2006)). Recommendations about the spatial locations of wind turbines are hitherto based mostly on the overlap between the occurrence of target species (e.g., sensitive raptors) and wind speed maps. It was concluded that turbines should be planned at places with strong and reliable wind and where the target species does not occur (Bright et al., 2008; Eichhorn and Drechsler, 2010) or in areas which are already disturbed by humans (Kiesecker et al., 2011).

There is no doubt that birds and bats are killed by collisions with wind turbines; however, it is much less known whether these losses of individuals are relevant at the population level and how

strong cumulative effects of a collection of wind turbines spread out over an entire area are (Drewitt and Langston, 2006; Kuvlesky et al., 2007; Masden et al., 2010; Stewart et al., 2007). Garvin et al. (2011) showed that raptor abundance was reduced by 47% in Wisconsin (USA) after the construction of wind turbines in the study area. This reduction was likely due to the abandonment of raptors from the wind farm project area. In a before-after impact study, Dahl et al. (2012) demonstrated that breeding success in territories of white-tailed eagles (*Haliaeetus albicilla*) adjacent to wind turbines declined compared to before their construction resulting in a decline of the population growth. Carrete et al. (2010) showed that even few turbine-killed Egyptian vultures (*Neophron percnopterus*) negatively affected the population growth of that species in Spain. Their study highlighted the fact known from life-history theory that long-lived species are very sensitive to an increase in mortality, even if the increase is small (Saether and Bakke, 2000). A main reason for why knowledge about the impact of wind turbines on populations is so limited is that there are logistical challenges: individuals from a complete population and not just individuals living in the close vicinity of turbines need to be monitored before and after the installation of a wind power plant. The lack of knowledge about the impact of wind turbines on population growth rates of potentially affected species is unfortunate, since the ultimate measure of the impact of any action must be the growth rate of a population (Carrete et al., 2010; Kuvlesky et al., 2007; Masden et al., 2010). Drewitt and Langston (2006) pointed out that "further research is required in particular to develop spatial and demographic models which can help predict effects of individual wind farms and groups of developments which have cumulative effects across extensive areas". Although their review is already a few years old, this conclusion still holds true.

When new wind turbines are planned, an environmental impact assessment study is typically required by environmental authorities. In Switzerland, such a study must evaluate the location of the planned turbines, e.g. whether they are in the vicinity of a population of rare birds and whether there is a concentration of migrating birds at the location. However, population-level consequences, i.e. whether the population growth of a rare species is negatively affected due to the installation of wind turbines, are not evaluated. Furthermore, the evaluation is typically restricted to one plant, and thus cumulative effects of multiple plants remain unknown. The spatial distribution of wind turbines can potentially have a strong impact on the population dynamics of the target species. Intuitively it is clear that a lower number of randomly distributed territorial birds will be affected by a certain number of wind turbines when they are aggregated in a few wind farms, than when they are scattered over the entire area. However, the strength of the effect of the aggregation of turbines on population growth is unknown.

The potential effects of the number and the spatial configuration of wind turbines on population dynamics can be assessed by simulations. Although simulations cannot answer the question of how much a particular population is affected by wind turbines, they are nevertheless very powerful in that potential effects of varying numbers and configurations of wind turbines can be neatly evaluated. Simulations also allow the identification of parameters which have a large impact on the outcome and thus to target future research. I developed an individual-based simulation model that mimicks the red kite (*Milvus milvus*), a large soaring bird of prey that frequently falls victim to wind turbines (Dürr, 2009). The red kite is endemic to Europe and its populations are declining in many areas (Knott et al., 2009); hence the interest to understand how wind turbines affect red kite populations. This is urgent as energy production by wind power plants is increasing and many more wind turbines are likely to be built in the near future (Pullen and Sawyer, 2011). In my study, I was particularly interested in

understanding how much a red kite population is affected by different numbers of wind turbines in a given area, as well as by their spatial configuration. To study configuration effects, I assumed that a constant number of wind turbines is aggregated in a variable number of wind farms so that the energy produced is constant. I assessed the impact of wind turbines on the red kite population by kite population growth rate, by demographic parameters (survival, dispersal), and by the number of turbine-killed individuals. Finally, I performed sensitivity analyses to understand how much my results depend on certain untested assumptions.

2. Methods

2.1. Individual based simulation model

I developed a discrete-time, individual-based simulation model to study the effects of a varying number of wind turbines and their spatial distribution on the dynamics of a hypothetical red kite population. Briefly, the model is constructed as follows: a number of red kite females is randomly distributed in a given area. Each kite is characterised by the coordinates of its nest in the area. Within this area, there is a core area in which a number of wind turbines is randomly distributed. The fringe area is included to model dispersal from the core area. Each year the kites produce fledglings which disperse. Each kite is subject to baseline mortality and to an additional mortality due to the collision of wind turbines. Turbine-induced mortality depends on the distance between a kite nest and a turbine. The population is allowed to develop for a number of years, after which some kite population metrics in the core area are recorded. The monitored population in the core area is geographically and demographically open. I parameterised the simulation model with values of demographic state and rate variables estimated from an increasing red kite population in Switzerland (Aebischer and Schaub, unpubl. data). In the following I describe the model in detail.

2.1.1. Initial conditions

Within a core area of 50×50 km (2500 km^2) the locations of a number of wind turbines were chosen randomly subject to a constraint that the minimal distance between two turbines was at least 5 km. The locations of a number of kite nests were generated similarly, subject to the constraint of a minimal inter-nest distance of 2 km. This distance represents a typical nearest-neighbour distance in Switzerland. The total area over which kites were distributed was larger by a buffer of 25 km around the core area containing wind turbines; thus kite nest locations were generated in an area of 100×100 km ($10,000$ km^2; see Fig. 1). This buffer zone was created in order to be able to include emigration from and immigration into the core area by dispersing individuals. The generation of wind turbine and kite nest locations was independent of each other. I monitored the simulated kite population just before the start of the breeding season (pre-breeding census) and distinguished between three age classes: 1 year old, 2 years old, and older than 2 years old. The initial number of kites in each of the three age classes was 102, 70 and 250, respectively. The ratio of these numbers corresponds to the stable age distribution (calculated as the right eigenvector of the matrix projection model, see below) of a red kite population in Switzerland and assumes a density of 2.5 breeding pairs per 100 km^2. This density is relatively low for red kites (Aebischer, 2009).

2.1.2. Population dynamics over time

Based on the initial configuration of nests and turbines, the kite population then develops according to a Markov process, i.e., its state at time $t + 1$ depends on its state at time t via transition rates
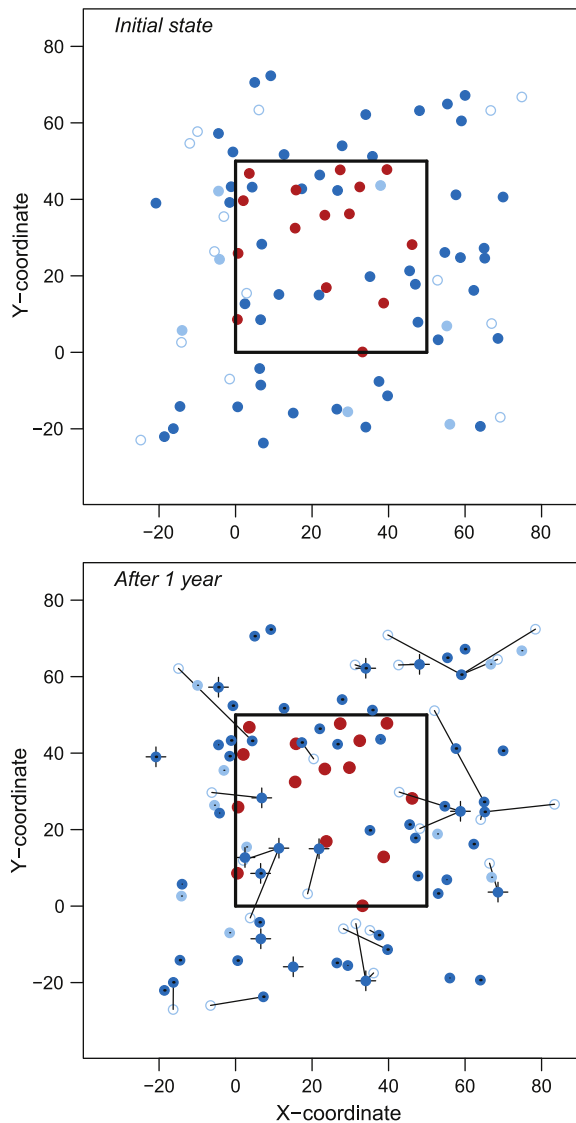
Fig. 1. Example of a simulation. The upper panel shows the distribution of wind turbines and of kites at the beginning and the lower panel the distribution after 1 year. The square in the centre is the core area where wind turbines occur. The symbols in both panels are: wind turbine (red dots), 1-year old kites (open dots), 2-year old kites (closed light blue dots), adult kite (closed blue dot), black cross (dead individual). The site of origin and settlement are connected with a line in dispersing individuals. Note that the number of kites and of wind turbines displayed in the graphs is lower than the numbers used in the simulations to increase visibility. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which are represented by reproduction, survival and dispersal parameters. The location and number of wind turbines remains unchanged. First, all females older than 2 years were assumed to reproduce each year, which means that kites start to reproduce at age 3. The number of fledged females is drawn from a Poisson distribution with parameter $\pi = 1.7/2$, where 1.7 is the average reproductive success (males and females) of red kites (Aebischer and Schaub, unpubl. data), thus I assumed an even sex ratio at fledging. Second, each individual kite i may or may not survive a year. Survival is composed of natural survival and of an additional mortality component due to the collision with turbines. Natural survival is modelled as a Bernoulli trial with success probability s_i, thus $S_i \sim \text{Bern}(s_i)$, with $S_i = 1$ indicating survival and $S_i = 0$ indicating death. Parameter s_i is age-dependent and was 0.45, 0.74 and 0.84 for juveniles (age 0–1), subadults (age 1–2) and adults

(older than 2 years), respectively (Aebischer and Schaub, unpubl. data). Depending on the distances D_{ij} between the nest of kite i and turbine j the additional risk r_{ij} of dying due to the collision at turbine j is $r_{ij} = f(D_{ij})$. I call this function the risk–distance function and used the same function for all age classes. For kite i and each turbine j another Bernoulli trial was performed with success probability $1 - r_{ij}$, thus $P_{ij} \sim \text{Bern}(1 - r_{ij})$. Kite i has survived one year, if $S_i \prod_j P_{ij} = 1$, where the product is over all turbines in the study area. This formulation ensured that wind turbine-induced mortality is additive to natural mortality and that the effects of all wind turbines are cumulated. Fledged individuals that survived may disperse, but not individuals of older age classes, because red kites are strongly philopatric to their breeding sites (Newton et al., 1989). I draw dispersal distances from a half-normal distribution with a mean of 10 km, while dispersal angle was drawn from a uniform distribution on the range (0, 360). These dispersal distances correspond to an average dispersal distance of red kites (Newton et al., 1989). Kites were allowed to settle anywhere, but not closer than 2 km to already occupied kite nests. If the determined nest position of an establishing disperser did not meet this condition, new positions were determined until the condition was met. If no valid position could be found after 25 trials, the average dispersal distance was increased by 10 km. Twenty-five new locations were then generated and if a location satisfied the condition, it was retained. If none of them fulfilled the condition, dispersal distance was again increased by 10 km, and 25 new locations were drawn, and so on, until a valid new position was found. In this way, I simulated density-dependence in the core area operating via territory saturation. The chosen nearest-neighbour distance of 2 km resulted in a maximal density of 25 nests/100 km², which is relatively high, but not unusual for red kites (Aebischer, 2009).

These steps (reproduction, survival, dispersal) were repeated over 10 years. The information about the state of all individual kites that were ever alive (in which age class they are, whether they are alive or dead, whether they died due to turbine collision) and their position was monitored. Based on this individual-specific information, I calculated the number of kites 2 years or older (corresponding to breeding pairs) in the 50×50 km core area for each time step. The average growth rate of the population was estimated with a linear regression of the logarithm of population size against time. I tallied up the number of individuals that dispersed from and to the core area as well as the apparent survival probability, which is the probability to survive and to remain in the core area. Finally, I counted the total number of individuals that died due to turbine collision.

The steps described under Sections 2.1.1 and 2.1.2 (initial conditions and population dynamics under turbine impact) were repeated 1000 times; hence, I simulated 1000 replicate population trajectories for each experimental treatment, and I report the means and confidence intervals of the monitored parameters.

2.2. Experimental treatments: wind turbine number and spatial configuration

The basic simulation model just outlined was used to study the effect of a varying number of wind turbines and their spatial configuration on red kite population dynamics. I considered different risk–distances functions, because there is hardly any empirical knowledge about the risk–distance function.

2.2.1. Number of turbines

First, I studied the impacts of the number of wind turbines on red kite population dynamics. I assumed a total of 0, 1, 25 or 50 turbines in the core area. These turbines were not aggregated in wind farms, so each turbine was at least 5 km away from the closest one. The highest number of wind turbines in the core area

corresponds to a density of 2 turbines/100 km^2. This corresponds to the targeted average density of wind turbines in Switzerland in the year 2050 (www.suisse-eole.ch/de.html), but is relatively low compared to extant densities in other countries (e.g. in Brandenburg, Germany, the current density is 9 turbines/100 km^2 (Dürr, 2009)) and also to the effective densities that are scheduled for parts of Switzerland, such as the Jura mountains.

2.2.2. Aggregation of turbines in wind farms

Second, I studied the impact of the aggregation of 50 turbines into 1, 5, 10, or 25 wind farms. Since the total number of turbines was fixed at 50, the number of turbines per wind farm varied accordingly from 50, 10, 5, to 2. I also considered the extreme scenario of no aggregation, which is the same as the last scenario of the previous case. When wind turbines were aggregated in wind parks, I assumed that each turbine contributed to the collision risk of the kites, thus that there was no avoidance effect. Or to put in

other words, kites were always impacted by all wind turbines, regardless of whether they were aggregated in wind farm or not.

2.2.3. Risk–distance function

The risk–distance function plays a crucial role for the mortality risk of a kite and thus likely is very important for population dynamics. In order to study the sensitivity of kite population growth to the assumed risk–distance function, I used five different varieties of a basic function. All of them were negative exponential functions, but with different intercepts and slopes. The variation of the intercepts mainly changes the collision risk when the distance between the kite nest and the turbine is very low, while the variation of the slope mainly changes the collision risk at larger distances. Thus, loosely speaking, the variation of the intercept mimicks turbine characteristics, such as tower height or rotor speed which are known to affect collision risk. By contrast, the variation of the slope is more a feature of the kite behaviour; the flatter the slope the larger is the kite's home range and consequently the more time it spends in the vicinity of a turbine. The collision risks in relation to the distances between the position of a kite and a wind turbine under the five considered risk–distance functions are shown in Fig. 2.

2.3. Sensitivity analysis

In order to understand how the chosen nearest-neighbour distance, dispersal parameters and level of natural mortality affected the results, I conducted a sensitivity analysis by varying these parameters (Supporting information Appendix A). Since the collision risk can vary among wind turbines (Ferrer et al., 2012; Martinez-Abrain et al., 2012) I also considered a scenario where the intercept of the risk–distance function varies randomly. This helps to validate the main findings when spatial heterogeneity of collision risk occurs.

I used R 2.14.0 (R Development Core Team, 2004) for all simulations. All code is provided in the supplementary material (Supporting information Appendix B).

3. Results

3.1. Impact of the number of turbines

The simulated red kite population increased annually by 5.2% (95% CI: 0.2–8.2%) in the core area in the absence of wind turbines. The population growth rate decreased with increasing number of wind turbines (Fig. 3). The flatter the slope and the larger the intercept of the risk–distance function the stronger was the decrease of the population growth rate with increasing number of wind turbines. In the most extreme case, the kite population declined by 1.2% (95% CI: −5.0 to +2.3) annually. Without wind turbines, the net export from the kite population was 2.1 individuals (95% CI: −7.0 to +11.0) in the last study year (Fig. 3). This shows that the kite population operated as a source population, it was increasing and could export individuals to other populations. The net export of individuals declined with increasing number of turbines which was the result of increased immigration and decreased emigration (Supporting information in Appendix C, Table C1), and with stronger risk–distance functions. The net export became negative when a large number of wind turbines was present, suggesting that the kite population has turned from a source to a sink. The average annual number of kites killed due to all wind turbines present in the area increased with the number of wind turbines (Fig. 3). It was again strongly dependent on the assumed risk–distance function. The age-specific apparent survival probabilities declined with
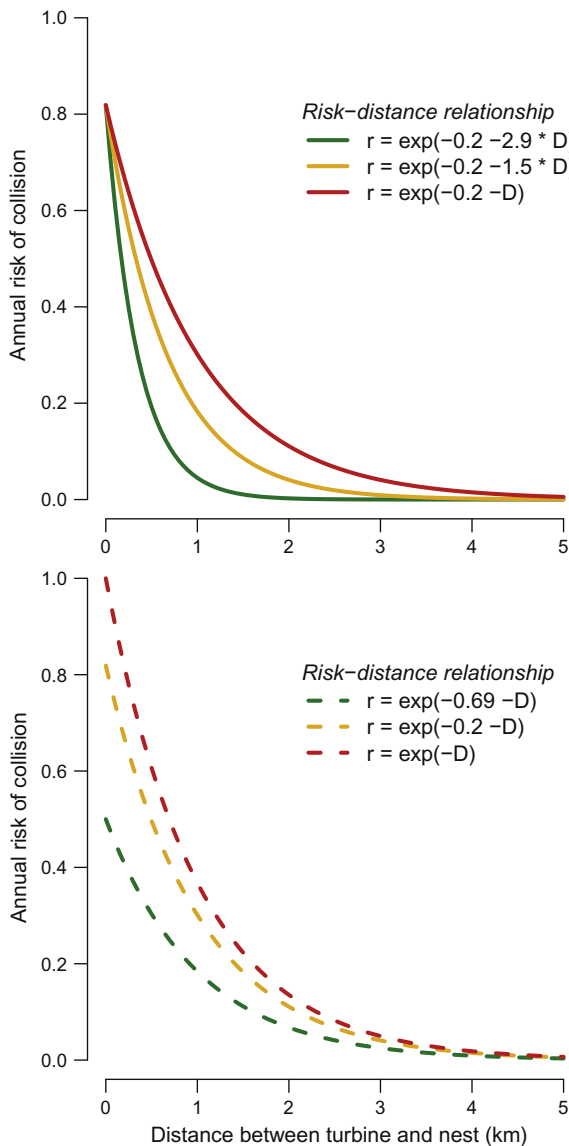

Fig. 2. Relationship between the risk of a kite to collide with a wind turbine in relation to the distance between the locations of the kite's nest and the wind turbine. Shown are the five risk–distances relationships used in this paper. In the upper panel the slope of the relationship varies, in the lower panel the intercept of the relationship varies.
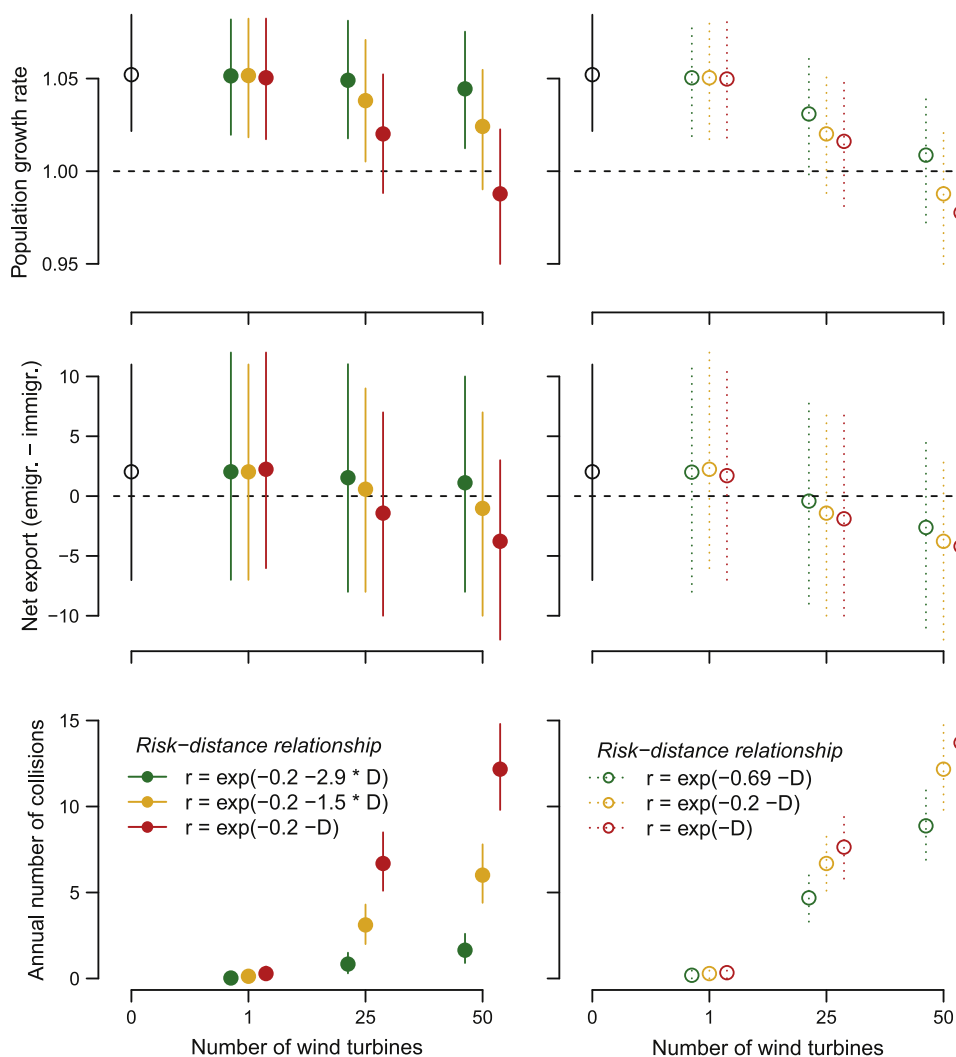
Fig. 3. Impact of a variable number of wind turbines on the growth of the red kite population in the core area, on the annual net export of individuals in the last study year (number of emigrants minus the number of immigrants) and on the total number of red kites that are killed annually by the collision with a wind turbine. Shown are these relationships for three risk–distance relationships that have the same intercept but different slopes (left panel) as well as for three risk–distance relationships that have different intercepts but the same slope (right panel). Given are the mean and the 95% confidence intervals.

increasing number of turbines and with increasing risk–distance relationship (Supporting information in Appendix C, Table C1).

3.2. Impact of the aggregation of turbines

Next I assessed the impact of aggregating a fixed number of 50 wind turbines in a variable number of wind farms. In all of these scenarios the amount of produced energy was similar. The population growth rates declined with decreasing aggregation of turbines in wind farms (Fig. 4). The risk–distance functions affected the estimated population growth rates, yet the more turbines were aggregated, the less important became the risk–distance function. When all 50 wind turbines were aggregated in one wind farm, the population growth rate was at least 4.6% (95% CI: 1.5–7.6), and thus not much lower compared to the situation without wind turbines. The net export of individuals was positive on average when the wind turbines were aggregated, but eventually became negative with decreasing degree of aggregation depending on the risk–distance function used. This suggests that by a varying degree of aggregation of the same number of wind turbines into wind farms, the kite population may turn from a source into a sink population.

The annual number of fatal collisions increased with decreasing aggregation (Fig. 4). When all 50 wind turbines were aggregated in a single wind farm, the annual number of fatal collisions was clearly lower than when 25 wind turbines were placed singly (Figs. 3 and 4). The age-specific survival probabilities declined with decreasing aggregation of wind turbines, and this was particularly evident for the adults (Supporting information in Appendix C, Table C2).

3.3. Sensitivity analysis

Changing nearest neighbour distances, dispersal parameters and natural mortality resulted in different kite population growth rates, but the impact of a variable number of wind turbines and their spatial distribution on population growth remained qualitatively the same (Supporting information in Appendix A). The initial simulations have shown that the kite population can grow in the presence of 50 wind turbines provided that the turbines are aggregated (Fig. 4). That the population increases in this situation depends on the assumed natural mortality of the red kites and is therefore not generally true. If natural mortality is higher, the
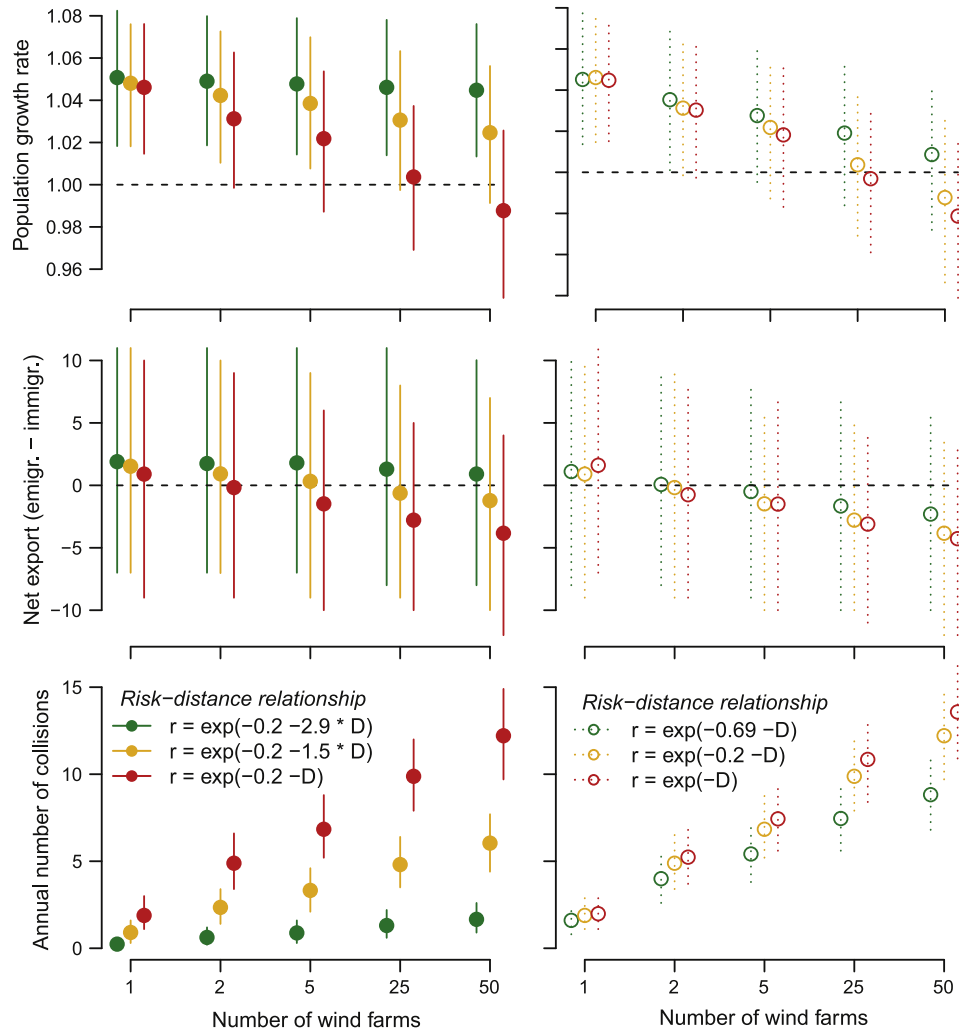
Fig. 4. Impact of a variable number of wind farms when the total number of wind turbines is fixed to 50 on the growth of the red kite population in the core area, on the annual net export of individuals in the last study year (number of emigrants minus the number of immigrants) and on the total number of red kites that are killed annually by the collision with a wind turbine. Shown are these relationships for three risk–distance relationships that have the same intercept but different slopes (left panel) as well as for three risk–distance relationships that have different intercepts but the same slope (right panel). Given are the mean and the limits of the 95% confidence intervals.

population can decline in the presence of 50 turbines even if they are aggregated (Supporting information in Appendix A, Fig. A1). If the intercept of the risk–distance function varies randomly, the results remain qualitatively the same as if there is no spatial heterogeneity in collision risk (Supporting information in Appendix A, Fig. A4).

4. Discussion

My simulations revealed clear effects of both the number of wind turbines and their spatial configuration on the growth of a red kite population: the larger the number of wind turbines and the more they were spread out in the landscape, the more depressed the population growth rate became. It is possible to turn the population in the core area from a source to a sink population and finally to a declining population by simply increasing the number of wind turbine locations. These results were qualitatively insensitive to our model assumptions about dispersal behaviour, population density (nearest-neighbour distance), baseline (natural) survival probabilities or spatial heterogeneity in collision risk. Quantitatively, but not qualitatively, was the result dependent on the assumed risk–distance relationship.

The assumed risk–distance relationship had a strong effect on the resulting population growth rate. If the slope of the negative exponential function was steep, an increasing number of wind turbines had a less strong negative effect on the population growth rate of kites than when the slope was flat. A flat slope corresponds to large home ranges of red kites and then the aggregation of wind turbines was very efficient to minimise the impact on red kite population growth. This is a general result: Bird species having larger home ranges are likely to be much more negatively impacted by an increasing number of wind turbine locations than species with small home ranges.

The variation of the intercept of the risk–distance relationship is related to the collision risk of birds that are situated very close to the wind turbine, and thus is akin to the variation in the danger of different wind turbine types. Many studies have shown that features of wind turbines such as rotor height and diameter, rotor speed, illumination or habitat and topography around wind turbines affect the collision risk (de Lucas et al., 2008; reviewed in Drewitt and Langston, 2006). My simulations showed that the reduction of the collision risk from say 0.8 to 0.5 had a strong effect on population growth, and thus there is some scope to reduce the impact of wind turbines by an appropriate construction or operating schedule (e.g., remain inactive during the breeding season).

The collision risk of birds at wind turbines is usually assessed with collision risk models of Band et al. (2007). A limitation of these models is that their accuracy to predict collision risk greatly depends on avoidance rates (Chamberlain et al., 2006), which are poorly known. The risk–distance relationship is an extension of a collision risk model in that it relates the collision risk to the distance between a wind turbine and the nest (or activity centre) of a bird. There is poor empirical knowledge about the risk–distance relationship. The only study of which we are aware of is the one by Rasran et al. (2011). They derived the collision risk in relation to the distance between the wind turbine and the nest location based on empirical knowledge of home range use of 13 red kites that were tracked with radio telemetry and by the consideration of an avoidance rate of 98% that was derived in another study (Whitfield and Madders, 2006). The uncertainty due to the lack of empirical knowledge of the avoidance rate and due to the relatively small sample size is large. Quantitatively the function of Rasran et al. (2011) corresponds to $r = \exp(-0.2 - 2.9 * D)$, thus to the least risky function included in my simulation. My simulations showed that the impact of the actual parameter values of the risk–distance relationship increases as wind turbines become more numerous and decreases the more they are aggregated in wind farms. In the light of the large uncertainty in the risk–distance relationship and its strong impact, I advocate for the application of the precautionary principle (Cooney, 2004), and strongly suggest that the number of wind farm locations must be as small as possible. Only if more knowledge about the risk–distance function becomes available, it will be possible to make better predictions about the quantitative effect of the variation of the number of wind turbines and on the tolerable number.

My simulation model needed assumptions that I have not evaluated with a sensitivity analysis. First, I have not included environmental stochasticity. The predicted growth rates are therefore too high, if environmental stochasticity is occurring (Tuljapurkar and Orzack, 1980), but I do not think that this would affect my results qualitatively. Second, my model only considered females, and thus I assumed that the number and fates of males had no effect on the population growth at all. In reality, it is unlikely that a brood is raised successfully if one of the partners dies during the breeding period. Since I have not included this condition in the simulation model, my result is likely too positive, that is, the impact of wind turbines is underestimated. Third, I assumed that there is no avoidance effect of wind power plants consisting of multiple turbines. It is possible that the collision risk at wind turbines that are aggregated in wind farms is lower compared to wind turbines that are single, because large plants may be more conspicuous or more scary to the birds and may be avoided to some degree (Desholm and Kahlert, 2005). If an avoidance effect due to large farms is occurring in red kites as well, the positive effect of aggregating wind turbines in wind farms revealed by my study will in reality be even stronger than predicted. Fourth, I assumed that the spatial distribution of red kites is random, implying that the habitat quality across a large area is identical. In reality this will not be the case, the spatial distribution of red kite territories is not random across large areas. Habitat quality varies spatially resulting in areas of high and areas of low kite density. As long as there is no spatial correlation between the location of red kite nests and the location of wind turbines, a non-random distribution of kites will not affect the relationship between kite population growth and the number of wind turbine locations, but the uncertainty of the prediction increases. Fifth, I assumed that there is no spatial correlation between the location of kite nests and the location of wind turbines. If there is a negative correlation, that is, if wind turbines are preferably constructed in areas where kites do not occur, the number and aggregation of wind turbines will have no or little effects on the red kite population growth. Yet, if there is a positive

spatial correlation, the negative impact of wind turbines on kite population growth will be stronger than what was found here (Carrete et al., 2012). However, even then the aggregation of wind turbines is better than no aggregation. Kites that are living close to an aggregation of wind turbines will be strongly negatively impacted, but other kites that are living far away from the few aggregations are safer.

Most red kites are migratory and therefore it is likely that they are additionally impacted by wind turbines that are placed along the migratory routes or in the wintering areas. These impacts were not considered explicitly in our simulation. The distribution and number of wind turbines along migration routes and in the wintering areas are potentially important as well, in particular if they are placed at specific points where many individuals concentrate on migration such as mountains passes. The impact of the spatial distribution of wind turbines along migration routes and in the wintering areas on red kite population growth depends on the level of migratory connectivity (Webster et al., 2002) and how similar the migration routes are between individuals. If migratory connectivity is low and the migration routes were very variable between individuals, I expect a lower impact at the population level. Red kites often show a different spatial distribution during the non-breeding season than during the breeding season, they are not territorial anymore and gather at large roosts. Thus, their spatial distribution is often clumped. In this situation, the wind turbines should only be built far away from roosts to have the least impact of red kite population growth. The seasonally differential spatial behaviour of red kites poses a real challenge for the spatial distribution of wind turbines that minimises the impact on red kite populations.

My simulation study required several simplifying assumptions which are not all met in reality and consequently real red kite populations would not exactly behave according to the reported results. The estimated figures (e.g. population growth rate) cannot be taken as and equated with empirical findings. Yet, the simulations are useful to demonstrate potential changes of the population development when impacting factors such as the number or the location of wind turbine locations alter. In order to assess empirically how red kite and other bird populations react after the construction of wind turbines, it is essential that integrated population monitoring (Baillie, 1991) over large areas is performed.

4.1. Planning of wind turbine locations

Wind energy production must deal with many challenges in order to be efficient and to minimise its impact on biodiversity. Besides decisions about the architecture of wind turbines and the management of the surroundings, a crucial point is the location of future plants. Obviously, wind turbines need to be at places where strong and reliable winds prevail. Locations where birds concentrate (e.g. migration points, roosts, breeding colonies) should be avoided, because wind turbines at such locations can potentially affect many individuals of a population. A recent study has shown that the number of birds killed can vary a lot at very small spatial scales, such that within a wind farm some wind turbines are much more dangerous than others (Ferrer et al., 2012; Martinez-Abrain et al., 2012). Factors such as local topography or turbine rotor blades seem to be important for the collision risk. Therefore, small scaled impact studies are required when a new wind farm is planned. My simulation study shows that the population growth of a focal species decreases with increasing number of wind turbine locations. The critical number of wind turbine locations that a focal population can sustain in the sense that its growth rate does not become negative depends on the demography of the specific population. The identification of this tolerable

number is analogous to the setting of the hunting bag of a harvested population with the goal of a sustainable harvest (Dillingham and Fletcher, 2008; Lebreton, 2005). My study suggests that it is necessary to assess the impact of a planned wind turbine in addition at a much larger spatial scale than what is currently done in order to be ecological relevant and to avoid more environmental damage. Assessment at a larger scale needs to consider the impact of extant turbines as well as of turbines that are planned in the same region. Ideally, the spatial scale needs to be as large as possible (Masden et al., 2010), it should have at least the spatial scale of a self-sustaining population of the target species (Schaub et al., 2006), which, in the case of the red kite, might be several hundred km^2.

Acknowledgements

Appendices A, B and C. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2012.06.021.

References

Aebischer, A., 2009. Der Rotmilan. Haupt Verlag, Bern.
Baillie, S.R., 1991. Integrated population monitoring of breeding birds in Britain and Ireland. Ibis 132, 151–166.
Band, W., Madders, M., Whitfield, D.P., 2007. Developing field and analytical methods to assess avian collision risk at wind farms. In: de Lucas, M., Janss, G., Ferrer, M. (Eds.), Birds and Wind Power. Lynx Edition, Barcelona, pp. 259–275.
Barrios, L., Rodriguez, A., 2004. Behavioural and environmental correlates of soaring-bird mortality at on-shore wind turbines. J. Appl. Ecol. 41, 72–81.
Bright, J., Langston, R.H.W., Bullman, R., Evans, R., Gardner, S., Pearce-Higgins, J.W., 2008. Map of bird sensitivities to wind-farms in Scotland: a tool to aid planning and conservation. Biol. Conserv. 141, 2342–2356.
Carrete, M., Sanchez-Zapata, J.A., Benitez, J.R., Lobon, M., Donazar, J.A., 2010. Large scale risk-assessment of wind-farms on population viability of a globally endangered long-lived raptor. Biol. Conserv. 142, 2954–2961.
Carrete, M., Sanchez-Zapata, J.A., Benitez, J.R., Lobon, M., Montoya, F., Donazar, J.A., 2012. Mortality at wind-farms is positively related to large-scale distribution and aggregation in griffon vultures. Biol. Conserv. 145, 102–108.
Chamberlain, D., Rehfish, M.R., Fox, A.D., Desholm, M., Anthony, S.J., 2006. The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models. Ibis 148, 198–202.
Cooney, R., 2004. Better safe than sorry? The precautionary principle and biodiversity conservation. Oryx 38, 357–358.
Dahl, E.L., Bevanger, K., Nygard, T., Roskaft, E., Stokke, B.G., 2012. Reduced breeding success in white-tailed eagles at Smola windfarm, western Norway, is caused by mortality and displacement. Biol. Conserv. 145, 79–85.
de Lucas, M., Janss, G.F.E., Whitfield, D.P., Ferrer, M., 2008. Collision fatality of raptors in wind farms does not depend on raptor abundance. J. Appl. Ecol. 45, 1695–1703.
Desholm, M., Kahlert, J., 2005. Avian collision risk at an offshore wind farm. Biol. Lett. 1, 296–298.
Dillingham, P.W., Fletcher, D., 2008. Estimating the ability of birds to sustain additional human-caused mortalities using a simple decision rule and allometric relationships. Biol. Conserv. 141, 1783–1792.
Drewitt, A.L., Langston, R.H.W., 2006. Assessing the impacts of wind farms on birds. Ibis 148, 29–42.
Dürr, T., 2009. Zur Gefährdung des Rotmilans *Milvus milvus* durch Windenergieanlagen in Deutschland. Informationsdienst Naturschutz Niedersachsen 29, 185–191.
Eichhorn, M., Drechsler, M., 2010. Spatial trade-offs between wind power production and bird collision avoidance in agricultural landscapes. Ecol. Soc. 15, 10.
Ferrer, M., de Lucas, M., Janss, G.F.E., Casado, E., Munoz, A.R., Bechard, M.J., Calabuig, C.P., 2012. Weak relationship between risk assessment studies and recorded mortality in wind farms. J. Appl. Ecol. 49, 38–46.
Garvin, J.G., Jennelle, C.S., Drake, D., Grodsky, S.M., 2011. Response of raptors to a windfarm. J. Appl. Ecol. 48, 199–209.
Kiesecker, J.M., Evans, J.S., Fargione, J., Doherty, K., Foresman, K.R., Kunz, T.H., Naugle, D., Nibbelink, N.P., Niemuth, N.D., 2011. Win–win for wind and wildlife: a vision to facilitate sustainable development. PLoS One 6, e17566.
Knott, J., Newbery, P., Barov, B., 2009. Action plan for the red kite *Milvus milvus* in the European Union.
Kuvlesky Jr., W.P., Brennan, L.A., Morrison, M.L., Boydston, K.K., Ballard, B.M., Bryant, F.C., 2007. Wind energy development and wildlife conservation: challenges and opportunities. J. Wildlife Manage. 71, 2487–2498.
Lebreton, J.D., 2005. Dynamical and statistical models for exploited populations. Aust. N. Z. J. Stat. 47, 49–63.
Martinez-Abrain, A., Tavecchia, G., Regan, H.M., Jimenez, J., Surroca, M., Oro, D., 2012. Effects of wind farms and food scarcity on a large scavenging bird species following an epidemic of bovine spongiform encephalopathy. J. Appl. Ecol. 49, 109–117.
Masden, E.A., Fox, A.D., Furness, R.W., Bullman, R., Haydon, D.T., 2010. Cumulative impact assessments and bird/wind farm interactions: developing a conceptual framework. Environ. Impact Assess. Rev. 30, 1–7.
Newton, I., Davis, P.E., Davis, J.E., 1989. Age at first breeding, dispersal and survival of red kites *Milvus milvus* in Wales. Ibis 131, 16–21.
Pullen, A., Sawyer, S., 2011, Global wind report – annual marked update 2010 Brussels.
R Development Core Team, 2004. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna.
Rasran, L., Grajetzki, B., Mammen, U., 2011, Berechnungen zur Kollisionswahrscheinlichkeit von territorialen Greifvögeln mit Windkraftanlagen.
Saether, B.E., Bakke, O., 2000. Avian life history variation and contribution of demographic traits to the population growth rate. Ecology 81, 642–653.
Schaub, M., Ullrich, B., Knötzsch, G., Albrecht, P., Meisser, C., 2006. Local population dynamics and the impact of scale and isolation: a study on different little owl populations. Oikos 115, 389–400.
Smallwood, K.S., 2007. Estimating wind turbine-caused bird mortality. J. Wildlife Manage. 71, 2781–2791.
Stewart, G.B., Pullin, A.S., Coles, C.F., 2007. Poor evidence-base for assessment of windfarm impacts on birds. Environ. Conserv. 34, 1–11.
Tuljapurkar, S.D., Orzack, S.H., 1980. Population dynamics in variable environments. 1. Long-run growth rates and extinction. Theor. Popul. Biol. 18, 314–342.
Webster, M.S., Marra, P.P., Haig, S.M., Bensch, S., Holmes, R.T., 2002. Links between worlds: unraveling migratory connectivity. Trends Ecol. Evol. 17, 76–83.
Whitfield, D.P., Madders, M., 2006. Deriving Collision Avoidance Rates for Red Kites *Milvus milvus*. Natural Research Ltd., Banchory, UK, 3.