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Underpinning the precautionary principle with evidence: A spatial concept for guiding wind power development in endangered species' habitats

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ABSTRACT

The precautionary principle is an essential guideline in decision making, particularly for regulating novel developments with unknown or insufficiently proven environmental impact. However, due to the inherent component of uncertainty it has been widely criticized for being "unscientific", i.e. hindering progress without sufficient evidence. The consequential postulation, that precautionary measures are only justified if the addressed threats are plausible and the measures reasonable, calls for methods to guide action in the face of uncertainty. Using the example of species conservation versus wind-farm construction, an expanding development with hypothesized – but unexplored – effects on our model species the capercaillie (*Tetrao urogallus*), we present an approach that aims at compensating the lack of knowledge about the threat itself by making best use of the available knowledge about the object at risk. By systematically combining information drawn from population monitoring and spatial modelling with population ecological thresholds, we identified areas of different functionality and importance to metapopulation persistence and connectivity. We integrated this information into a spatial concept defining four area-categories with different implications for wind power development. Highest priority was assigned to areas covering the spatial and functional requirements of a minimum viable population, i.e. sites where the plausibility for threat is highest, the uncertainty as regards importance for the population is lowest, and thus the justification for precautionary measures is strongest. This gradated approach may also enhance public acceptance, as it attempts to avoid either error-minimization bias (i.e. being too restrictive or permissive) the precautionary principle is frequently criticized for.

Introduction

The precautionary principle is an established guideline applied to environmental policy and considered a fundamental tool for sustainable development (Cooney, 2004; Kriebel et al., 2001; Myers, 1993). It is based on the idea of "better safe, than sorry", in more detail described as "when an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically" (Raffensperger & Tickner, 1999). The precautionary principle is usually applied when decision makers have an obligation to respond while there are indications of a negative impact, which are expected to be serious or irreversible and when there exists scientific uncertainty to the nature and severity of the threat (LILC, 2000; Prato, 2005). As this often applies to new developments, which are in potential conflict with species conservation, the precautionary principle has become a common element in environmental impact assessments in relation to endangered species. Nevertheless, the precautionary principle is often criticized for being not entirely "science based" (i.e. even though an activity or development has not been shown to be harmful it might still be prohibited) and is therefore accused of hindering progress or innovation (Kriebel et al., 2001; Sandin, Peterson, Hansson, Rudén, & Juthe, 2002).

The recent increase of wind energy use in Central Europe and the consequential necessity to evaluate wind farm projects with regard to conservation targets provides a good example of how the precautionary principle is applied in the field of endangered

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species protection. There are three main effects wind turbines may have on wildlife: firstly, increased mortality due to collisions; secondly, habitat fragmentation or reduced population connectivity when animals avoid passing through wind turbine areas; and thirdly, habitat loss due to construction works and avoidance of the disturbed area. Both birds and bats are known to collide with wind turbines causing increased adult mortality (Drewitt & Langston, 2008; Johnson et al., 2002; Kuvlesky et al., 2007; Langston & Pullan, 2003; Rydell et al., 2010). Although in most cases the effects at population-level are unclear (Stewart, Pullin, & Coles, 2007), increased adult mortality in long lived, slow reproducing species can rapidly affect population numbers (Sæther & Bakke, 2000). Moreover, a wide range of animal species have been shown to avoid areas around wind turbines, effectively causing habitat loss or acting as barriers to movement (Bach & Rahmel, 2004; Drewitt & Langston, 2006; Pearce-Higgins, Stephen, Langston, Bainbridge, & Bullman, 2009). Yet, the effects of wind turbines on wildlife seem to be highly species and site specific and the mechanisms behind certain effects remain poorly understood (Anderson et al., 2008; Kuvlesky et al., 2007). Besides, most studies on this subject are case studies, making it difficult to draw general conclusions. This lack of knowledge induces policy makers to apply the precautionary principle, which usually results in defining buffer zones around sites with ascertained species presence, for example nesting sites, where wind turbines are prohibited (Bright et al., 2008). The extent of this buffer zone is often based on expert opinion (Bright et al., 2008) and is therefore highly debated. Moreover, this approach is static and often based on data collected in a short time-window (e.g. a single breeding season), thus neglecting spatial and temporal fluctuations as well as minimum required areas or functional connectivity at the population level. One may argue that the lack of knowledge precludes a more complex approach. However, even if the effect of wind turbines on a species is unknown, evidence-based information on species' habitat selection and spatial requirements is often largely available or can be generated with relatively low effort from existing data sources. We state that this knowledge should be applied to determine prohibition zones for wind turbine development and advocate that the precautionary principle is used to protect viable populations of species and not only individuals. Here we provide an approach illustrating how a systematic combination of available data and knowledge can be applied to minimize – within the framework of the precautionary principle – the potential impact of wind power development on an endangered species population, even though knowledge about the actual effects of wind turbines on the species is lacking. Using the example of capercaillie (*Tetrao urogallus*) in the Black Forest, Germany, we identified areas of different functionality and importance with regard to reproduction, metapopulation persistence and connectivity, which were combined with population-related thresholds to define area categories with different levels of vulnerability and consequential implications for wind power development.

Methods

Model species

Due to its specific habitat and extensive area requirements, and its high sensitivity to human disturbance, the capercaillie is considered an indicator of undisturbed mountain forest ecosystems rich in structural diversity (Cas & Adamic, 1998; Klaus et al., 1989; Simberloff, 1998; Storch, 1995) and an umbrella species for the underlying species community (Pakkala, Pellika, & Lindén, 2003; Suter, Graf, & Hess, 2002). The same attributes, along with a limited dispersal capacity, renders the species highly vulnerable to habitat degradation and fragmentation. In Central Europe capercaillie is listed in most national red data books and in Annex I of the EU Birds Directive (EU Directive 2009/147/EC on the conservation of wild birds, The European Parliament and the council of the European Union, 2009), and its presence was one of the main criteria for the designation of special protected areas (SPA) for birds in the Natura 2000 network. However, the proportion of the capercaillie range that is covered by protected areas is far from sufficient to support self-sustaining, viable populations in most countries (Storch, 2007).

As the Central European populations are mostly confined to mountain regions, with distributions largely overlapping the areas suitable for wind energy development, capercaillie became a focal species for impact regulations. However, although a wide array of knowledge is available on behaviour and habitat requirements, it is still unclear how the species is influenced by wind turbines. The main impact is expected from turbine construction and operation triggering avoidance behaviour and thus effective habitat loss (González & Ena, 2011; Horch, Bruderer, Keller, Mollet, & Schmid, 2003; Horch, Graf, Liechti, Mollet, & Schmid, 2006; Langston & Pullan, 2003), but none of these effects have been scientifically proven yet. The only published study on the Cantabrian subspecies *T. urogallus cantabricus* shows a significant decrease of capercaillie signs in winter, one year after turbine construction (González & Ena, 2011). As capercaillie is highly sensitive to human presence (Thiel, 2007), road construction in the forefront of wind-turbine erection, followed by an increased human use of the area, is highly likely to reduce habitat suitability (Thiel, Jenni-Eiermann, Braunisch, Palme, & Jenni, 2008). Moreover, being a prey species to raptors, the flickering shadows elicited by the turbines blades may affect vigilance behaviour, a hypothesis that requires further research (Lovich & Ennen, 2013). Capercaillie are known to collide with many different man-made structures (Baines & Andrew, 2003; Baines & Summers, 1997; Bevanger & Brøseth, 2004; Catt et al., 1994) and occasional collisions with wind turbines have been reported from Sweden (Göran Rönning, pers. comm.). Despite case studies suggesting negative effects of wind turbines on capercaillie, it is impossible to draw general conclusions at the population level. In the case of the small and fragmented Central European capercaillie populations however, any additional impact may affect long-term population viability, which is why the precautionary principle is applied to handle conflicts between wind turbine construction and capercaillie protection.

Study area

The study area encompassed the Black Forest (i.e. the ecoregions "Black Forest" and "Baar-Wutach", Aldinger et al., 1998), a forested mountain range of about 7000 km^2 in south-western Germany. It was selected as it hosts the largest Central European capercaillie population outside the Alps (Storch, 2007) and, at the same time, is one of the Federal State's primary regions for wind energy development due to favourable wind conditions along the mountain ridges. The capercaillie population is distributed over 520 km^2 in the forested regions of the highest altitudes (Braunisch & Suchant, 2006), isolated from neighbouring populations (Storch and Segelbacher, 2000) and forms a metapopulation system consisting of four main subpopulation clusters (Segelbacher, Manel, & Tomiuk, 2008) (Fig. 1a). Since the beginning of the 20th century the population has declined greatly, from an estimated 3000–4000 males (Suchant in Lieser & Roth, 2001) to a low of 250 males counted in 2003. Since then the population has slightly recovered to approximately 300 males, which translates to a conservatively estimated minimum size of 600 individuals (Braunisch & Suchant, 2006), which exceeds only marginally the estimated size of a minimum viable population (MVP) of 500 birds (Grimm & Storch, 2000). Consequently, the loss or isolation of any sub-population is expected

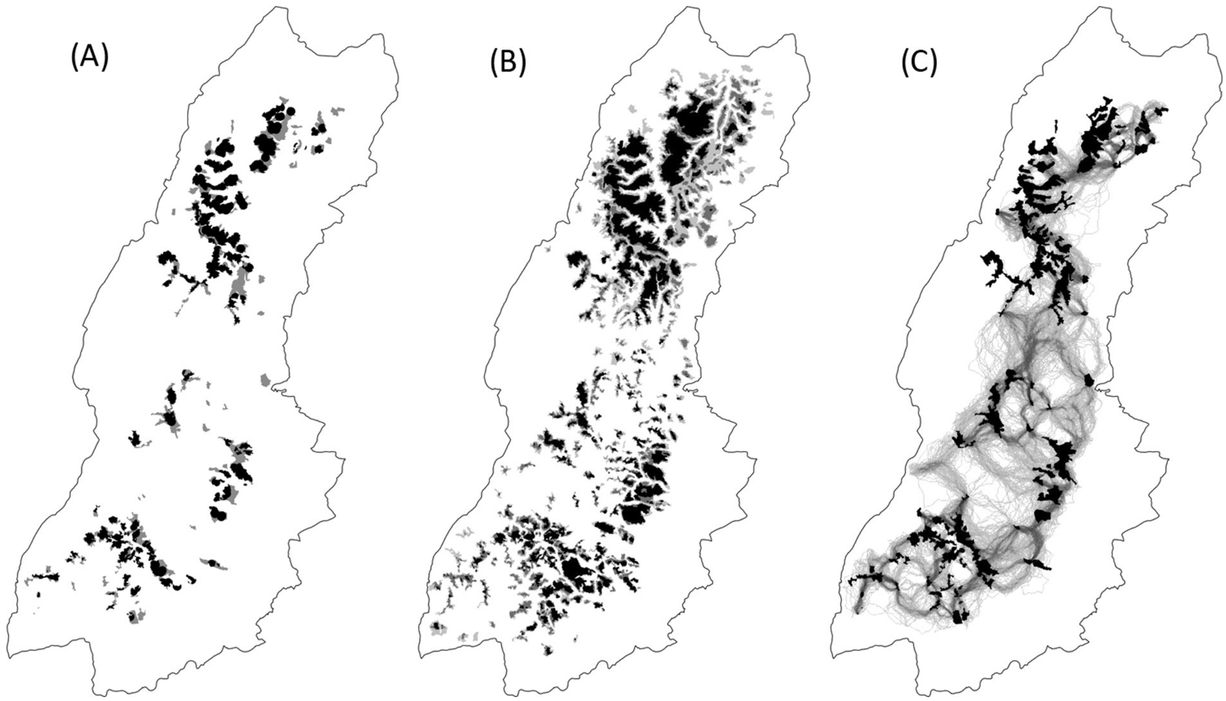

Fig. 1. Spatially explicit fundamentals integrated in the concept: (A) capercaillie distribution (grey) with core areas of reproduction (black), (B) long-term habitat potential in three classes: high (black), moderate (dark grey), low (light grey), and (C) corridors consisting of 100 paths (grey) offering the best conditions for inter-patch dispersal between capercaillie patches (black), redrawn from: Braunisch et al., 2010, modified.

to increase considerably the overall extinction risk (Braunisch, Segelbacher, & Hirzel, 2010; Braunisch & Suchant, 2006).

Spatially explicit sources of information

To define the zones where wind turbine construction potentially interfere with the target of capercaillie conservation, we developed a spatially explicit planning concept (in the following referred to as "spatial concept") that aims at the preservation of a long-term viable capercaillie metapopulation. It is, therefore, not targeted exclusively on areas of current species occurrence and reproduction, but also includes – based on the spatial requirements of a viable population – a network of habitat patches that, due to their size, quality and spatial configuration, meet the species' demands as regards both habitat suitability and inter-patch connectivity. For this, we combined three main sources of spatial information on (1) species distribution, (2) habitat potential and (3) habitat connectivity obtained from species monitoring and spatial modelling. As they have been already published elsewhere and a detailed description of the methods would be beyond scope we provide only a brief outline here and refer to the appendices and the original publications for more detailed information.

Species distribution and core areas with reproduction

Data on current capercaillie distribution were obtained from a long-term capercaillie monitoring programme which consists of two components: First, a systematic, annual survey of lekking places; and second, a year-round collation of data from all available sources, such as incidental direct observations and indirect evidence (feathers, faeces) provided by hunters, foresters, birdwatchers as well as data collected in research projects (Braunisch & Suchant, 2006). Every five years, the minimum capercaillie distribution was at a scale of 1:25,000 based on all available data from the preceding 5-year period (Fig. 1a). Capercaillie patches were defined as 'occupied' when at least three proofs (direct or indirect) with a maximum distance of 1 km to each other had been recorded within the preceding 5-year period. For the delineation of a capercaillie patch the minimum polygon encompassing these observation points was drawn, aligning the patch boundaries to lines evident on the ground (i.e. forest-field boundaries, trails, streams, etc.) with a deviation of 100 m from the minimum polygon tolerated (for details see: Braunisch & Suchant, 2006). In addition, locations relevant for reproduction were extracted from the database, i.e. all lekking sites and locations of nests or chicks. For this study, data from a 10-year period (2000–2010) were considered.

Habitat potential

Areas relevant for long-term occupancy were identified based on the concept of the "Landscape Habitat Potential" (Suchant, Baritz, & Braunisch, 2003), which quantifies the capacity of the prevailing landscape conditions to support the natural development of suitable habitat and vegetation structures for a species and, at the same time, to provide sufficient framework conditions for species' inhabitation. We used species presence data (N = 1600) from forest patches with continuous occupancy (at least 20 years as identified by the monitoring programme) and an Ecological Niche Factor Analysis (Hirzel, Hausser, Chessel, & Perrin, 2002; Hirzel, Le Lay, Helfer, Randin, & Guisan, 2006) to model the probability of long-term capercaillie presence as a function of the prevailing environmental conditions, notably climate and soil conditions, topographic and land use characteristics forest distribution and fragmentation as well as human infrastructure. The resulting map shows the sites (occupied or non-occupied) which offer suitable landscape framework conditions for long-term capercaillie presence and thus represent the area generally available for a metapopulation (Fig. 1b, for details see: Supplementary Appendix A, Braunisch & Suchant, 2007, 2008).

Habitat connectivity

To localize the "corridors" between the habitat patches that were most important for maintaining metapopulation

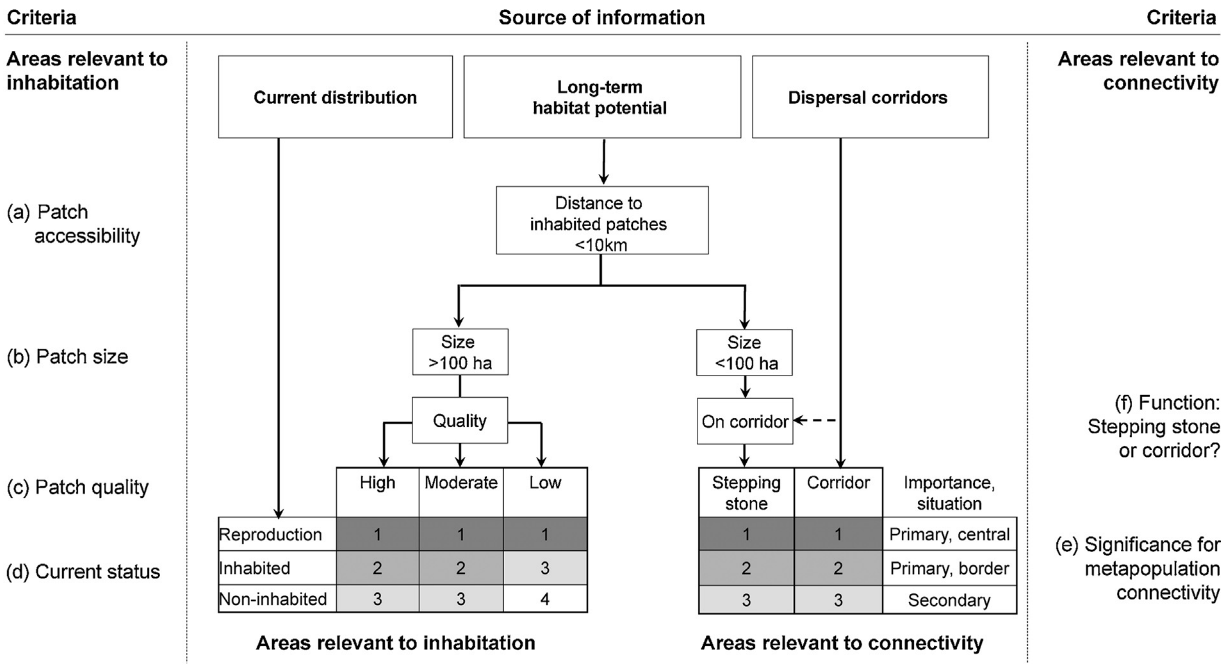

Fig. 2. Stepwise evaluation of areas relevant to capercaillie metapopulation persistence and connectivity. Information on current distribution, long-term habitat potential and dispersal corridors were combined with population-related thresholds as regards patch accessibility (a), patch size (b), patch quality (c), current inhabitation status (d), significance (e) and function (f) for metapopulation connectivity, resulting in four area-categories (1–4) with different implications for wind turbine construction. Thresholds were derived from (a) Storch and Segelbacher (2000), (b) Moss et al. (1991) and Moss (1994), (c and f) Braunisch and Suchant (2007), (d) Braunisch and Suchant (2006), and (e) Braunisch et al. (2010).

connectivity, we developed a model that detected species-specific dispersal patterns from population genetic structure (Braunisch et al., 2010). Pairwise relatedness (Lynch & Ritland, 1999) between 213 individuals of the capercaillie population was correlated with the intervening landscape structures, while controlling for isolation by distance, in order to identify the landscape variables that either promoted or impeded gene flow. The results were used to generate a spatially explicit landscape permeability map that allowed identifying dispersal corridors that offered the relatively best conditions for individual movements between subpopulations. Corridors were calculated between the centroids of all inhabited patches located more than 1 km from the next neighbour. First, between each pair of neighbouring patches, 1000 random paths were calculated and path with the highest permeability was retained. Repeating this procedure 100 times resulted in 100 partly overlapping paths forming a corridor (Fig. 1c, for details see: Supplementary Appendix B, Braunisch et al., 2010). The model was evaluated using both data partitioning and independent observation data of dispersing birds.

Spatial concept: combining spatial information with ecological thresholds

To delineate areas with different importance and functionality for the capercaillie population which then translate into different implications for wind energy development, the three data sources were evaluated with regard to population related target values and combined in a stepwise manner. Thereby we distinguished between areas relevant for capercaillie inhabitation and population connectivity.

Areas relevant for species inhabitation

Areas relevant for capercaillie inhabitation were classified according to the following criteria, with the letters corresponding to the steps illustrated in Fig. 2:

(a) *Patch accessibility*: Habitat patches within a metapopulation network must be within the birds' reach. The seasonal movements of adult birds are an average of 1–2 km and median dispersal distances of juveniles are generally less than 10 km (Patthey, Signorell, Rotelli, & Arlettaz, 2012; Storch & Segelbacher, 2000). Areas with habitat potential were thus only considered if they were within 10 km of the nearest occupied capercaillie patch (Braunisch & Suchant, 2006).
(b) *Patch size*: Moss, Picozzi, and Catt (1991) and Moss (1994) quote a minimum patch size of 100 ha as a precondition for capercaillie inhabitation. Only patches achieving this minimum size were deemed relevant for inhabitation, while smaller patches were evaluated for their function as stepping stones (see Fig. 2f).
(c) *Patch quality*: The capercaillie meta-population in the study area amounts to 600 birds. The area required by a capercaillie population of this size depends on habitat quality. With an average proportion of 30% suitable habitat, as determined for the capercaillie habitats in the Black Forest, a minimum area of 60,000 ha is required (Suchant & Braunisch, 2004). The area with habitat potential was thus classified into three quality levels: The 60,000 ha with the highest potential formed level 1, the remaining area with moderate and low potential was subdivided using equal habitat potential intervals and attributed to the levels 2 and 3.
(d) *Current inhabitation status*: For the final classification of areas with regard to the potential conflict with wind energy development, the areas with habitat potential were intersected with the current capercaillie distribution (Braunisch & Suchant, 2006), and four categories were formed reflecting different levels of importance (Fig. 2): A particular emphasis was put on the core areas with reproduction. These were defined by drawing a 1 km radius around each lek site and each ascertained location of reproduction as obtained from the monitoring data. The distance of 1 km was chosen because most females breed within 1 km of a lekking site (Wegge & Rolstad, 1986). Furthermore an exclusion zone of 1 km is generally advised for

capercaillie habitats (LAG-VSW, 2007). To avoid exclusion of wind power in areas irrelevant for capercaillie inhabitation, only areas with habitat potential (levels 1–3), within the 1 km radius was classed as first priority (category 1). Second highest priority was given to areas occupied by capercaillie with high or moderate habitat potential (category 2). These were followed by unoccupied areas with moderate potential or occupied areas with low potential (category 3). The remaining areas, which were neither occupied nor served as potential habitats with long-term relevance (i.e. low or no habitat potential) were classed in category 4.

Areas relevant for metapopulation connectivity

The areas relevant for metapopulation connectivity were obtained from the corridor model (Braunisch et al., 2010). A distinction was made between 'stepping stone habitats' and 'corridors' (see Fig. 2):

(e) *Relative significance for metapopulation connectivity*: The corridor model (Braunisch et al., 2010) provided a raster map, showing the relative suitability of the landscape for interpatch movement between subpopulations. In homogeneous landscapes, this resulted in broad corridors, whereas narrow corridors where obtained where the landscape conditions provided only one suitable connection (Fig. 1c). Moreover, most habitat patches were connected by several possible pathways. To preserve a functional network connecting all inhabited capercaille patches, the primary connection that offered the relatively best conditions for dispersal between the core areas with reproduction of neighbouring habitat patches was selected. A central band of 1 km minimum width was delineated and assigned to category 1. The remaining corridor area was classed as category 2. Secondary corridors of minor quality and importance were assigned to category 3.

(f) *Function – stepping stone or corridor*: Patches with moderate to high habitat potential smaller than 100 ha (see Section "Areas relevant for species inhabitation"(b)) located on a corridor were classed as 'stepping stones', and assigned to the corresponding category of the corridor.

Potential conflict areas with wind energy development and management implications

Each location of the study area was thus assigned to one of the four categories (Fig. 3). Whereas in category 1-sites there is a high probability that negative effects of wind turbine construction may interfere with both reproduction and population connectivity, a stepwise decreasing conflict potential can be expected for sites of category 2 and 3. In category 2 current distribution areas without ascertained reproduction as well as corridors of secondary importance are concerned, while category 3 sites mainly encompass unoccupied, potential habitats which, however, serve as a buffer zone around core habitats and allow population fluctuations and recolonization processes in the metapopulation system (see Braunisch & Suchant, 2007). In category 4 areas negative effects can largely be ruled out. Applying the precautionary principle, we translated these categories into management recommendations: Representing the core areas of the distribution, wind energy development should be banned from category 1 sites. For sites of the categories 2 and 3 we recommended a mandatory, detailed on-site assessment of the population situation at and around the foreseen turbine locations before deciding whether the project should be declined or whether impacts could be minimized by an optimized planning and adequate compensation measures. No further restrictions are required in category 4 sites. Finally, to provide an

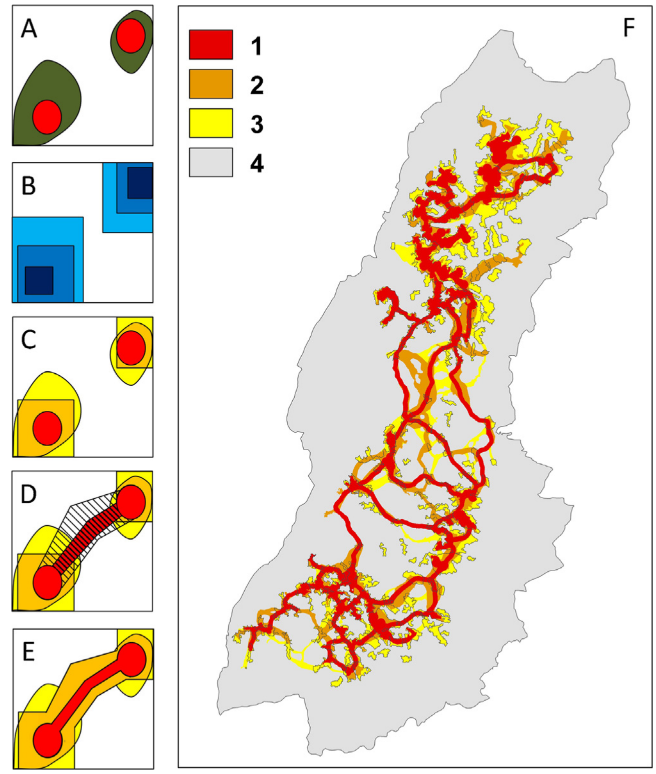

Fig. 3. Spatial planning concept illustrating four area-categories with different levels of importance for the capercaillie metapopulation and consequential restrictions for wind energy construction (right panel). The categorization resulted from combining different sources of spatial population information with ecological thresholds as described in Fig. 2, the successive steps are schematically illustrated (left panel): The current capercaillie distribution (green) and core areas with reproduction (red, A) were intersected with the long-term habitat potential (three levels: high = dark blue, moderate = medium blue, and low = light blue) (B), resulting in a map showing areas relevant for capercaillie inhabitation (C). This was then combined with the results of a corridor-model (hatched, D) to form the final categories 1–4 (E and F).

applicable planning tool which allows a direct appraisal of prospective turbine sites in the study area, without revealing the precise locations of vulnerable key habitats (i.e. lek sites), the resulting map was intersected with the areas profitable for energy development, i.e. where the average annual windspeed at 100 m above ground exceeded 5.25 m/s, as extracted from the wind atlas of Baden-Württemberg .

Comparison with prevailing guidelines

Existing guidelines for wind energy planning in Germany recommend a radius of 1 km around capercaillie reproduction sites from which wind energy development should be banned (LAG-VSW, 2007). We compared the areas under protection resulting from this approach with the areas relevant for capercaillie (i.e. categories 1–3) as obtained by our spatial concept with regards to both, areas irrelevant to capercaillie that would be protected as well as areas with metapopulation functionality that would not fail to receive a protection status.

Results

Basic information: species distribution, habitat potential and connectivity

According to the prevailing climate, topography, land-use and site conditions, 181,770 ha of the study area offered a potential for long-term capercaillie inhabitation, were located within 10 km

Table 1
Size and proportion of the areas (a) relevant for capercaillie inhabitation, (b) relevant for metapopulation connectivity, (c) with current capercaillie distribution and (d) suitable for wind energy development that are allotted to the area-categories (1–4) with different implications for wind turbine construction. Highest priority is given to areas of category 1, where wind turbine construction is generally banned. In categories 2 and 3 detailed impact assessments are required, while in category 4 no further restrictions apply. WE: wind energy development.

Area category	Relevant for inhabitation		Relevant for connectivity		Current distribution		Suitable for WE	
	ha	%	ha	%	ha	%	ha	%
1	54,747	47.66	20,250	33.79	37,055	71.74	20,783	26.22
2	20,816	18.12	23,262	38.81	14,067	27.24	8639	10.90
3	39,313	34.22	16,421	27.40	528	1.02	9997	12.61
4	–	–	–	–	–	–	39,835	50.26
Total	114,876	100.00	59,933	100.00	51,650	100.00	79,254	100.00

distance to inhabited areas and of sufficient size to support capercaillie occupancy. 35% (63,280 ha) thereof offered a high, 29% (53,730 ha) a moderate and 36% (64,760 ha) a low habitat potential. Capercaillie was distributed over 51,650 ha. Based on the locations of 107 lekking sites and 1070 locations of reproduction (nests or chicks) 37,055 ha (72%) thereof were classed as core areas relevant for reproduction. 108 dispersal corridors were calculated between the capercaillie patches. Depending on the landscape structure, corridors often deviated considerably from the straight connection between the patches' centroids and frequently crossed spatially isolated, unoccupied habitat patches, 49 of which were classified as "stepping stones". Detailed results on current distribution status, habitat potential and inter-patch connectivity as well as on model performance and evaluation results can be obtained from (Braunisch et al., 2010; Braunisch & Suchant, 2006, 2007).

Prioritization of areas in relation to regulations for wind energy development

Within the study area 114,880 ha were identified as currently or potentially relevant for capercaillie inhabitation (Fig. 2), 48% (54,750 ha) thereof were attributed to category 1, the remaining 18% and 34% were classed as category 2 and 3 respectively (Table 1). Of the area currently inhabited by capercaillie 72% fell in category 1, 27% in category 2 and the remaining 1% in category 3. In addition, areas relevant for connectivity (i.e. corridors and embedded stepping-stone habitats) comprised 59,930 ha, with 34%, 39% and 27% thereof falling in categories 1, 2 and 3 respectively. On the corridors 62 "stepping stone" habitat-patches with an average size of 45 ha (SD: 27 ha) were identified. The remaining 542,750 ha (76%) of the study area were attributed to category 4.

Assuming a predicted average annual windspeed of at least 5.25 m/s at 100 m above ground level as threshold for profitability, 79,250 ha (11%) of the study area were potentially suitable for wind energy development. Capercaillie conservation aspects had to be considered on 50% of these areas, with 26% being allotted to category 1, 11% to category 2 and 13% to category 3.

Comparison with prevailing guidelines

Applying the prevailing recommendations of applying a 1 km-buffer zone around the reproduction sites would have resulted in 60,330 ha where turbine construction would be prohibited. According to our spatial concept, 51,289 ha (i.e. 85% thereof) were also classified as relevant for capercaillie (Table 2, Supplementary Appendix C, Fig. C1), the remaining 9040 ha (15%) however, would be protected although they are neither currently inhabited nor characterized by a function as potential habitat or connectivity element. By contrast, 123,520 ha would not receive any protection status, although relevant for the population, mainly with regard to population connectivity.

Discussion

Despite being criticized for various reasons (Sandin et al., 2002), the precautionary principle is an essential element in environmental decision-making and species protection (Kriebel et al., 2001). As illustrated by our case example, it is characterized by four dimensions (Sandin, 1999): (1) there are indications of negative effects which might be irreversible (e.g. extinction of the local capercaillie population) (threat dimension); (2) the mechanism and the severity of the impact is unknown (uncertainty dimension); and (3) the decision makers, i.e. the local government, have the obligation to take measures (action dimension); as (4) the target species is endangered and under protection by international law (command dimension). While the latter two dimensions are usually well-supported by a legal framework, the inherent lack of scientific evidence in the former two (Sandin, 1999) provokes the criticism the precautionary principle would "stifle progress without good reason", thus being "excessively risk-aversive" (Resnik, 2003) if not "unscientific" (Brombacher, 1999; Resnik, 2003). The consequential postulation, that precautionary measures can only be justified if the threats they address are plausible and the measures reasonable (Resnik, 2003; Sandin, 2004) calls for coherent methods to guide action in the face of uncertainty (Raffensperger & Barrett, 2001). We addressed this challenge by illustrating how a lack of knowledge

Table 2
Metapopulation-based versus observation-based approach: Comparison of the spatial concept with the currently prevailing recommendations of banning turbine construction within a 1 km-buffer zone around capercaillie reproduction sites. A: Attribution of the area within the buffer zone ("protected") to the categories of the spatial concept, B: area outside the buffer zone ("not protected") but relevant for capercaillie according to the spatial concept, either for inhabitation or metapopulation connectivity. An illustration of divergence between both approaches is provided in Supplementary Appendix C, Fig. C1.

	(A) Protected		(B) Not protected, but relevant					
	Total		Total		For inhabitation		For connectivity	
	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)	Area (ha)	(%)
Relevant	51,289	85.01	123,520	100.00	54,321	43.98	69,198	56.02
Thereof:								
Category 1	42,726	70.82	32,272	26.13	0	0.00	32,272	26.13
Category 2	4426	7.34	39,653	32.10	17,738	14.36	21,915	17.74
Category 3	4138	6.86	51,595	41.77	36,583	29.62	15,012	12.15
Not relevant (category 4)	9040	14.99						

about the threat itself may be partially compensated by making best use of the available knowledge on the object at risk: based on a systematic combination of evidence-based spatial information, we qualified the relative importance of sites for metapopulation functionality and translated this information into gradated management implications that strictly protect minimum requirements at the population level, while not being overly restrictive in less relevant sites.

Plausibility of threat: potential effects of wind energy on the target species

Wind turbines can threaten wildlife populations by causing un-compensable extra mortality through collisions, by generating habitat loss or disturbance, potentially affecting reproduction or triggering behavioural responses such as changes in habitat use or movement patterns. In capercaille, as in other grouse species, collisions have been mainly reported with turbine towers, since the species' flight altitude is usually below the rotor-swept zone. Although collision risks are often underestimated as victims are predated before they are found (Korner-Nievergelt et al., 2011), we consider this impact minor compared to other potential effects.

The surface of the construction area of the wind turbines is usually not large (0.2–1 ha, MKULNV, 2012) and therefore not considered a major factor of habitat loss (Drewitt & Langston, 2006; Langston & Pullan, 2003), except in the case of spread out wind parks (Langston & Pullan, 2003). Yet, avoidance of otherwise suitable areas close to the turbines can cause indirect habitat loss (Drewitt & Langston, 2008). The presence of the turbines (e.g. rotor movement, noise, shadow flickering), the increase of human use in the area due to construction of paths and roads and maintenance personnel may inflict a "disturbance effect", defined here as any action or object causing a change in animal behaviour or physiology, without necessarily incurring fitness costs. However, such effects have been shown to be highly species and site specific, which obstructs their transferability (Drewitt & Langston, 2008; Gill, Sutherland, & Watkinson, 1996; Kuvlesky et al., 2007). Studies on different grouse species also showed diverging results: for capercaillie reduced numbers of males at lekking sites near a newly established wind park have been observed in Austria and reported from Sweden (Göran Rönning, pers. comm.), and also the closely related black grouse (*Tetrao tetrix*) showed dramatic decreases in number of lekking males in a wind park area in Austria (Zeiler & Grünschachner-Berger, 2009). LeBeau, Beck, Johnson, and Holloran (2014) found indications of reduced brood survival of greater sage grouse (*Centrocerus urophasianus*) near wind turbines, and female greater prairie chickens (*Tympanuchus cupido*) seemed to adjust their space use near a wind park in the United States (Winder et al., 2014). On the contrary, no significant effects on habitat use, behaviour or reproduction have been found for willow ptarmigan (*Lagopus lagopus*) in Norway (Bevanger et al., 2010) and the closely related red grouse (*Lagopus lagopus scotica*) in Scotland (Pearce-Higgins et al., 2009).

Finally, there are indications that birds adjust their flight path to fly around wind turbines which can elicit extra energy costs (de Lucas, Janss, & Ferrer, 2004; Dirksen, Winden, & Spaans, 1998; Farfán, Vargas, Duarte, & Real, 2009; Plonczkier & Simms, 2012). Turbines might even function as a barrier between roosting, feeding or breeding grounds (Drewitt & Langston, 2006; Farfán et al., 2009; Langston & Pullan, 2004) and – at the landscape scale – reduce population connectivity (Andrén, 1994; Fahrig, 1997, 2003; Hanski & Gilpin, 1997; Lande, 1993). Due to their relatively heavy body weight and proportionally small wing size capercaillie, as all members of the grouse family, are considered "poor flyers" (Rayner, 1988), and inter-patch movements mostly occur in a stepwise manner from hilltop to hilltop. Dispersal has been shown to be affected by landscape features, with open areas, roads and settlements reducing the probability of inter-patch dispersal (Braunisch et al., 2010), which makes it likely that turbine constructions may have a similar effect. Since the genetic differentiation between the four main subpopulations in the study area (Fig. 1a) already suggests isolation effects (Segelbacher et al., 2008), accumulations of turbines placed on the primary connecting corridors may further contribute to reducing metapopulation connectivity.

Reasonability of measures: spatial prioritization and management implications

Most studies addressing the effects of wind-turbines on wildlife are temporally and spatially restricted, i.e. quantify collision rates (Conway & Danby, 2014; Everaert & Stienen, 2007; Musters, Noordervliet, & Ter-Keurs, 1996) or effects on local habitat use (Leddy, Higgins, & Naugle, 1999; Meek, Ribbands, Christer, Davy, & Higginson, 1993; Reichenbach & Steinborn, 2006; Steinborn & Reichenbach, 2011; Winder et al., 2014). Although a proven impact on single individuals or subpopulations must not necessarily imply a threat at population level, studies addressing effects on the population scale are as scarce as challenging (Bellebaum, Korner-Nievergelt, Dürr, & Mammen, 2013; Carrete, Sánchez-Zapata, Benítez, Lobón, & Donázar, 2009; Schaub, 2012). This may explain why most spatial planning concepts also focus on the protection of local occurrences or even single breeding pairs, e.g. by defining buffer zones around observation locations from which wind energy is banned (Bright et al., 2008; LAG-VSW, 2007). Our concept, by contrast, aims at preserving the spatial requirements of a viable metapopulation, thereby distinguishing between sites of different functionality, i.e. reproduction, inhabitation and connectivity. Moreover, we provide a gradated evaluation of the relative importance of each site in the study area which translates into different levels of restrictions for wind energy development. This evaluation was based on three main criteria: current situation, long-term potential and functionality: Whereas the current species distribution, and particularly the core areas of reproduction are taken into account with high priority, high priority is also given to sites where the prevailing climate, topography and land-use conditions support the natural development of suitable habitat, i.e. sites which have a higher probability of being of long-term relevance to the population (Braunisch & Suchant, 2007). With this approach we do not only indirectly account for fluctuations in distribution area or reproduction sites, thereby preventing a stepwise erosion of temporarily unoccupied but long-term species-relevant sites, we also perform an "ecological cost–benefit assessment", as secondary habitats which are prone to deteriorate without active habitat management are ranked lower – unless they are crucial for reproduction or metapopulation connectivity.

The approach has some methodological challenges, though. While information on habitat potential or corridor locations is based on spatial models evaluating landscape conditions, and thus can be expected to remain valid unless substantial transformations of land-use patterns occur, the information on current capercaillie distribution, mating and reproduction sites is expected to fluctuate over time which calls for a periodical re-assessment. Moreover, since this information is mainly based on voluntary data of ornithologists, hunters and forestry personnel, a consistent data quality has to be secured in the monitoring framework. For prioritization the spatial information was evaluated using target values based on population-related thresholds. These, however, were partly adopted from studies conducted in other regions, which may challenge their transferability. Particularly, population viability analyses strongly depend on local reproduction and survival rates with a high variability in outcome. Although the conditions in the Bavarian Prealps (South-Eastern Germany) largely resemble those in the Black Forest the MVP-results can only represent a rough estimate. While performing a sensitivity analysis (i.e. varying each threshold within the range its potential values) would have been out of scope, as the regional variance is largely unknown, one has to be aware that – if not the relative ranking – so the classification and absolute amount of area attributed to the four categories may have changed with changing the quantitative targets.

Approximately 500 birds are considered as an MVP of capercaillie (Grimm & Storch, 2000), which – under the prevailing habitat conditions – require a minimum area of 50,000 ha (Suchant & Braunisch, 2004). According to our concept 54,750 ha is classed as category 1, i.e. a sufficient amount of habitat for an MVP is under strict protection from wind energy development, supplemented by an additional protection of the primary corridors connecting these habitats. The other sites, i.e. category 2 and 3 are mainly situated like buffer areas of stepwise decreasing importance around the highly protected core areas, thus representing a “safety zone” where wind energy is not generally banned, but has to undergo a thorough evaluation process which includes the appraisal of the site-specific conditions in the field. With this approach we assign highest priority (and restrictions) to sites where the plausibility for threat is highest, the uncertainty as regards functional importance for the population is lowest, and thus the justification for precautionary measures is strongest. This gradated approach may also enhance the acceptance among planners, authorities and conservationists, as it represents an attempt to avoid either error-minimization bias the precautionary principle is often criticized for (Dorman, 2005): i.e. either being too restrictive (thus minimizing the type-2 error of wrongly rejecting the hypothesis that wind energy poses a threat) or being too permissive in favour of turbine construction (by overemphasizing the minimization of the corresponding type-1 error).

Application in wind farm planning

The resulting map allows authorities and planners a rapid and standardized first appraisal at a high resolution. Thereby it does not only indicate where wind turbine construction plans will face restrictions (i.e. category 1) and where no further constraints apply (category 4), but provides a gradated estimation of the planning risk: Whereas in category 1 sites wind energy construction is generally banned, development plans in category 2 and 3 have to be submitted to a systematic, in situ impact assessment following a standardized procedure. It includes (1) a repeated control for lekking activity before and during the mating season, (2) a thorough search for indicators of reproduction (i.e. feathers, faeces and chicks) along transect lines in late summer, as well as the mapping of (3) habitat quality and (4) evidence of species presence at systematically distributed sampling plots using the method described in Storch (2002). Data shall be collected within the capercaillie-relevant areas of the respective category up to 1 km distance from the construction site. Based on the resulting local situation in terms of habitat suitability and habitat use in relation to the construction site, potential impacts shall be estimated and the mitigation potential through a modification of the turbine positioning appraised. In addition, the compensability shall be determined and compensation measures quantified. Whereas new evidence of mating or reproduction will lead to the decline of the project, habitat loss may be compensated through habitat improvement measures. These measures should primarily be implemented in areas with habitat potential but low current suitability with regard to forest structure or within corridors. Inside the compensation area – the extent of which is determined by the importance and size of the habitat concerned – target values for structural key parameters (see Suchant & Braunisch, 2004) must be reached and maintained during the operational life of the wind turbine. Given the differences in relative importance between the two categories, projects planned in category 2-sites inherently face a higher risk of being rejected than those in category 3 sites, mainly encompassing un-occupied, potential habitats or marginal parts of the distribution area where impacts are more likely to be compensable.

Although our spatial concept is not legally binding, planners and authorities are currently using it as official planning document. Thereby, the perceived plausibility played a major role for accepting the precautionary concept: While we observed a consistent public agreement for banning turbine construction from the core areas of reproduction, the advice not to construct wind turbines on primary dispersal corridors elicited resistance. Although the majority of corridor areas is per se not suitable for wind energy development (i.e. crossing valleys or settlements where turbine construction is either not profitable or subjected to other restrictions), and population connectivity has been proven to be crucial for metapopulation persistence in the Black Forest (Segelbacher et al., 2008), it is difficult to convince public, planners and authorities that wind turbines should not be constructed in “stepping stone” habitats where the species has not been sighted for many years and the habitat is of low quality. To raise acceptance and promote adequate implementation, the concept was publicly presented and an implementation guideline, as well as the digital map showing the different categories, was made accessible on a website (www.windenergie.fva-bw.de).

Our concept refers only to one species though. Although capercaillie counts among the main focal species in relation to wind energy development in Central European mountain forests, and its key habitats largely overlap with those of other conservation relevant species (Braunisch et al., 2013), planners usually need to consider a wide range of potentially vulnerable species. Developing similar concepts for species with complementary spatial and functional requirements and integrating them into a single planning tool would facilitate an adequate and timely consideration of conservation targets in the rapidly spreading development.

Conclusions

The precautionary principle is a vital element to decision making in the field of conservation management, but public acceptance will strongly depend on the coherence of argumentation underlining the plausibility of threat and the reasonability of the measures (Resnik, 2003). We thus strongly advocate including scientific knowledge when defining precautionary measures, if not available on the threat itself, so on the object at risk. We illustrate this on the example of capercaillie conservation versus wind farm construction. By systematically combining information drawn from population monitoring and spatial modelling with ecological thresholds we delineated zones representing the spatial and functional minimum requirements of a viable population (category 1) plus a necessary safety interval (categories 2 and 3) with different importance for preserving population persistence and connectivity and consequential implications for wind energy development. From this exercise we draw the following general recommendations for applying the precautionary principle in this field:

(1) precautionary measures should focus on the relevant ecological unit, i.e. target viable populations and not local occurrences or individual animals,
(2) they should consider population dynamics processes, e.g. fluctuations in occupancy as well as population connectivity, instead of merely relying on a temporal snapshot of occurrence data,
(3) they should be based on a differentiated risk appraisal, with the estimated probability and severity of threat on the population resulting in gradated management implications or restrictions,

(4) which, however, must ensure at least the minimum requirements of a viable population until further knowledge is available.

Since precautionary measures always represent as an interim solution, regular revisions measures based on up-to-date knowledge will be crucial for promoting the precautionary principle as a valuable and justified basis for weighing ecological risks in conservation and landscape planning.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jnc.2015.01.003.

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