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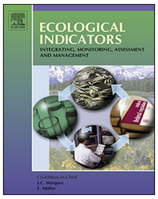

Evaluating anthropogenic landscape alterations as wildlife hazards, with wind farms as an example

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ABSTRACT

Anthropogenic alterations to landscape are indicators of potential compromise of that landscape's ecology. We describe how alterations can be assessed as 'hazards' to wildlife through a sequence of three steps: diagnosing the means by which the hazard acts on individual organisms at risk; estimating the fitness cost of the hazard to those individuals and the rate at which that cost occurs; and translating that cost rate into a demographic cost by identifying the relevant demographically-closed population. We exploit the conservation-oriented literature on wind farms to illustrate this conceptual scheme. For wind farms, the third component has received less attention than the first two, which suggests it is the most challenging of the three components. A wind farm provides an example of a 'spatially localized hazard', i.e., a discrete alteration of landscape hazardous to some population but of which there are some individuals that do not interact directly with the hazard themselves but nevertheless suffer a reduction in fitness in terms of their contribution to the next generation. Spatially localized hazards are identified via the third component of the scheme and are of particular conservation concern as, by their nature, their depredations on wildlife may be underestimated without an appropriate population-level estimation of the demographic cost of the hazard.

1. Introduction

Anthropogenic alterations of landscape may serve as an indicator of ecological compromise to habitats, though not in a straightforward manner. Determining the consequences for wildlife of such landscape transformation is an important component of conservation science. The implications of habitat loss and fragmentation have received considerable attention (Henle et al., 2004) and contributed to important theoretical developments such as spatially structured population modelling (Hanski, 2002). Less overtly disruptive landscape transformations hazardous to wildlife may be diffuse and widespread to the point of ambience, notably pollutants such as the historic worldwide occurrence of DDT in avian food webs (Hickey, 1969). Discrete alterations of landscape may also pose risks to wildlife. Notably, structures threaten collisions, particularly of birds (Drewitt and Langston, 2008; Loss et al., 2014a), and clusters or networks increase that risk. Networks of power lines pose the additional risk of electrocution (Drewitt and Langston, 2008; Loss et al., 2014b), while networks of roads and fences (Benítez-López et al., 2010) also constrain movement such as migrations and dispersion (Gadd, 2011).

Evaluating the danger posed to wildlife by landscape alteration can be a subtle conservation challenge. A discrete, but common, landscape alteration may be treated as an ambient risk when evaluating the implications for a regionally defined 'population' of interest. For example, counts of the annual mortalities of birds (or of a particular species) resulting from collisions with buildings or power lines might be converted into an additive component of per capita mortality rate based on estimates of the number of birds (of the species of interest) within some, politically or geographically defined, region. While such computations, and comparisons between them, may aid conservation (Loss, 2016), they have a poor biological basis if the 'population' is not a demographically closed population or if the risk posed by the landscape alteration is not the same for all individuals in the 'population'.

Our objective in this essay is to outline a conceptual scheme with a biological basis for evaluating the risk posed to wildlife by landscape alterations, focusing on discrete transformations of landscape. Hereafter, an alteration of landscape that is identified as posing such a risk will be called a 'hazard'. The scheme consists of three components: (1) identifying those features of a landscape alteration that act as the agents of risk and their modes of action on individuals interacting with the landscape alteration, which provides the foundation for identifying a landscape alteration as a 'hazard' and is essential for possible

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mitigation; (2) quantifying the reduction in fitness to those individuals directly interacting with the hazard, and estimating a rate of occurrence, which may take the form of annual counts of hazard-induced fatalities; (3) converting the rate obtained in (2) into a demographically meaningful per capita vital rate, which involves identifying the relevant population that pays the cost. The meaning of 'direct interaction' in (2) will be a byproduct of (1). The third component addresses the issue raised in the previous paragraph of measuring the impact of a hazard by, say, an annual mortality count, which is demographically ambiguous. We propose that the relevant population for estimating demographic cost is the smallest, demographically closed population containing the individuals interacting directly with the hazard, which we shall call the 'hazard's demographic population'. A further ingredient of the third component is determining whether the risk and fitness costs vary across individuals in this population, which, if so, adds to the subtlety of (3). We believe that organizing the evaluation of landscape alterations as spatial hazards into this scheme facilitates this important conservation task by clearly separating aspects of the problem into components that are conceptually distinct. The scheme will thereby aid planning, implementation, and assessment of such an evaluation.

As a byproduct, we formalize a notion of a particular kind of discrete alteration of landscape as follows. By a spatially localized hazard (SLH), we shall mean a hazard for which there are individuals in the hazard's demographic population that never interact directly with the hazard (never enter the spatial extent of the hazard) yet suffer a reduction in individual fitness indirectly (as measured by their contribution to future generations). The third component is essential for the identification of an SLH and alerting scientists/managers to the existence of individuals that are a less visible yet integral part of assessing the overall demographic cost of the hazard.

We emphasize that whether a particular hazard is best treated as ambient or discrete will depend on the spatial scale relevant to the organisms of interest. For an isolated (perhaps sessile) population of organisms existing within the spatial extent of the hazard, the hazard may be best treated as ambient, while for another, more widely distributed, and perhaps more mobile, organism, the same hazard may be discrete and even an SLH, though not necessarily so. Thus, the identification of a hazard as discrete, and more specifically an SLH, depends on both the hazard itself and the organisms interacting with it. The third component of the conceptual scheme underscores that the nature of the hazard itself and the population at risk might only become apparent through analysis, rather than being a priori evident.

Our formulation of the SLH concept was motivated by a study of the impact of the wind farm in the Altamont Pass Wind Resource Area (APWRA), California, on golden eagles *Aquila chrysaetos* (Hunt et al., 2017). As wind farms are an increasingly common component of renewable energy production and result in considerable deaths of birds and bats (Kunz et al., 2007a,b; Drewitt and Langston, 2008; Pagel et al., 2013; Smith and Dwyer, 2016), we will illustrate the conceptual scheme by exploiting the literature on wind farms, which will suggest that the third component of the scheme has received much less attention than the first two, no doubt due to its difficulty. Of course any potential hazard, such as the APWRA, and species interacting with it will have their own peculiarities and require analyses specific to that instance. It is for this reason we emphasize here a conceptual scheme. Nevertheless, we shall use the golden eagle study to illustrate how the scheme can be tailored to a specific application.

For wind farm literature, we first conducted a search using the terms 'spatial hazard', and 'wind farm' in the search engine Web of Science. To be abreast of ongoing publications, we examined emails notifying Table of Contents for the following journals: *Biological Conservation*, *Conservation Biology*, and *Journal of Applied Ecology*, and, less formally, perused *Journal of Raptor Research* and *Condor*. We then used a recursive procedure of examining the literature cited in each publication we found. We do not claim our literature is exhaustive, but we believe that it is at least representative through 2017 of the published literature on wind farms as it relates to our paper. Our review of this literature is integrative in that we cite publications within the context of our conceptual scheme. As noted above, we formulated our conceptual scheme based on our experience studying a golden eagle population in and around a wind farm in California and prior to conducting our literature search and review. We were prepared to modify our scheme if the literature indicated it was inadequate but did not find that to be the case.

2. Identifying the agents of a landscape hazard and their mode of action

For the remainder of this essay, we have in mind a discrete alteration of the landscape that is considered to pose a risk to some organism, some individuals of which interact with the potential hazard. By the 'agents' of the hazard, we mean identifiable interactions between hazard and individual expected to result in fitness costs to that individual, while 'mode' of interaction refers to features that govern the interaction.

The primary hazard agent posed by wind farms (other than habitat loss, Villegas-Patraca et al., 2012; Smith and Dwyer, 2016) appears to be fatal collisions of birds and bats with moving blades (Kunz et al., 2007a,b; Drewitt and Langston, 2008; Smith and Dwyer, 2016), though avian collisions with static components of wind farms (Drewitt and Langston, 2008) and internal soft-tissue damage in bats from air decompression (Kunz et al., 2007b) also occur.

While coincidental factors such as weather may contribute to wind farm deaths (Arnett et al., 2008), especially for migrating and flocking species, the study of why and how collisions between birds and bats with moving rotors occur has most usefully focused on intrinsic features of the wind farm and the species concerned. Intrinsic features of wind farms (Arnett et al., 2008, 2011; de Lucas et al., 2008; Horn et al., 2008; Kikuchi, 2008) include geographical location relative to existing flight paths, e.g., migratory routes, the landscape features on which the wind farm is imposed, the spatial layout of the wind farm itself, characteristics of the turbines such as height, length and speed of the blades, wind-farm lighting, and natural attractants within the farm such as prey (ground prey for raptors; flying insects for insectivorous bats). Intrinsic features of the vulnerable species (Kunz et al., 2007a,b; Kikuchi, 2008; Smallwood et al., 2009) include flight behaviour (e.g., flocking versus solitary; hunting/foraging flight, Horn et al., 2008; territorial display; species-specific flight characteristics, Hoover and Morrison, 2005, De Lucas et al., 2008; time of day) and morphology affecting flight (body weight and size; wing length, loading and aspect ratio; tail length; De Lucas et al., 2008); vision (binocular versus peripheral vision acuity, Martin, 2012); seasonal behaviour (migratory behaviour, Hüppop et al., 2006; Arnett et al., 2008); differences in life stage (e.g., floater versus breeder; subadult versus adult, Hunt et al., 2017); and the natural distribution and abundance of populations in relation to wind farm location and their environs (de Lucas et al., 2008). Nevertheless, wind-turbine-induced deaths of migratory tree bats were not adequately explained by such factors indicating that wind-farm-induced deaths are not yet understood for all organisms at risk (Jameson and Willis, 2014; Cryan et al., 2014).

Identification of the hazard agent and study of its mode of action can lead to modelling of the agent and its action, or at least to hypotheses and predictions, e.g., of collision risk in wind farms (reviewed by Marques et al., 2014; see also: Kikuchi, 2008; Noguera et al., 2010; Eichhorn et al., 2012; Ferrer et al., 2012; New et al., 2015) that may result in mitigation (Drewitt and Langston, 2008; Arnett et al., 2013; Marques et al., 2014; Martin et al., 2017; May et al., 2017). This modelling has focused primarily on the probability of single incidents, either of a single individual colliding with a turbine or of a flock colliding with a wind farm, but Wiens et al. (2017) employed individual-based population modelling in a spatially explicit context to assess the consequences of increasing wind farm development in southern California and propose pre-emptive mitigation.