Cumulative impact assessments and bird/wind farm interactions: Developing a conceptual framework

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A B S T R A C T

The wind power industry has grown rapidly in the UK to meet EU targets of sourcing 20% of energy from renewable sources by 2020. Although wind power is a renewable energy source, there are environmental concerns over increasing numbers of wind farm proposals and associated cumulative impacts. Individually, a wind farm, or indeed any action, may have minor effects on the environment, but collectively these may be significant, potentially greater than the sum of the individual parts acting alone. EU and UK legislation requires a cumulative impact assessment (CIA) as part of Environmental Impact Assessments (EIA). However, in the absence of detailed guidance and definitions, such assessments within EIA are rarely adequate, restricting the acquisition of basic knowledge about the cumulative impacts of wind farms on bird populations. Here we propose a conceptual framework to promote transparency in CIA through the explicit definition of impacts, actions and scales within an assessment. Our framework requires improved legislative guidance on the actions to include in assessments, and advice on the appropriate baselines against which to assess impacts. Cumulative impacts are currently considered on restricted scales (spatial and temporal) relating to individual development EIAs. We propose that benefits would be gained from elevating CIA to a strategic level, as a component of spatially explicit planning.

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1. Introduction

Cumulative impacts originally gained status in the United States’ National Environmental Policy Act (NEPA) and were later incorporated into the Environmental Impact Assessment (EIA) Directive (85/337/EEC) of the European Community. Cumulative impact assessments provide information to inform the management of developments so resultant impacts do not exceed specified threshold levels (Canter and Kamath, 1995). Whilst all individual projects or actions affect their environment, the combined or cumulative effects of multiple actions can be greater than the sum of the individual parts (Canter and Kamath, 1995). Increasing numbers of proposed developments create greater pressures on the environment, making cumulative impacts a pressing issue. Such is the case for wind farms in the UK, where concerns have been raised over the negative impacts of increasing numbers of wind farms on bird populations (Stewart et al., 2007).

Although cumulative impacts are increasingly included within environmental impact assessments, the quality remains far from adequate (Piper, 2001). Most UK assessments fail to sufficiently incorporate cumulative impacts; only 48% of the statements reviewed by Cooper and Sheate (2002) mentioned the term ‘cumulative impacts’ and of those, only 18% provided a discussion on the topic. Explanations for the lack of consideration of cumulative impacts in EIA reports include the absence of guidance on the requirements of cumulative impact assessment and the lack of a comprehensive definition (Bérubé, 2007; Canter and Kamath, 1995; Thatcher, 1990).

Cumulative impact assessment remains a mystery to most EIA practitioners (Duinker and Greig, 2006; Smith, 2006) therefore changes are required in the way assessments are approached and delivered, if any utility is to be derived from the process. “We need revolution in how we undertake cumulative impact assessment, not evolution” (Duinker and Greig, 2006). One obvious barrier to effective assessment of cumulative impacts is the lack of clarity in discourse between the relevant parties i.e. developers, statutory bodies, non-governmental organisations (NGOs) and scientists. Practitioners remain uncertain about the legislative requirements and also the data required for assessments. Such confusion is not a problem unique to cumulative impact assessment. For example, in a review of ecosystem stability, Grimm and Wissel (1997) emphasised that...
although “human concepts can be signposts through the confusing complexity of nature” these concepts themselves can cause confusion. In this paper, we propose a conceptual framework to promote a more transparent and efficient cumulative impact assessment process, to further understanding of the impacts of wind farms on bird populations.

2. Legislative background

Consideration of cumulative impacts is required under the EC Directive (85/337/EEC) on EIA, implemented in the UK under the Town and Country Planning (Environmental Impact Assessment) Regulations 1999. The regulations refer to cumulative impacts in the screening of projects (Schedule 3) “the characteristics of development must be considered having regard, in particular, ... the cumulation with other developments” and in the inclusion of information in environmental statements (Schedule 4) “a description of the likely significant effects of the development on the environment, which should cover the cumulative effects of the development...” (Town and Country Planning Regulations Assessment of Environmental Effects Schedule 4 Part 1). These regulations in themselves create confusion: Schedule 3 defines cumulative impacts as an accumulation of impacts across developments, Schedule 4 refers to cumulative effects as effects that accumulate within a development over time.

The Habitats Directive (92/43/EEC) also refers to cumulative impacts and is implemented in the UK through the Conservation (Natural Habitats & c.) Regulations. The regulations state that where an appropriate assessment should be undertaken, “The effects considered should be those of the plan or project, either alone or in combination with other plans or projects already carried out or proposed, on the habitats and species of international importance...”. Cumulative effects also appear in the Strategic Environmental Assessment (SEA) Directive (2001/42/EC) on the assessment of certain plans and programmes on the environment. The Directive requires information to be provided on “the likely significant effects... including cumulative and synergistic effects... on the environment.”

Despite the Directives requiring assessment of cumulative effects, no appropriate definition of cumulative effects, or indeed guidance on methods of assessments, are provided in the legislation, creating an uncertain regulatory environment for practitioners. Documents discussing cumulative impacts or explicitly defining the term ‘cumulative impact’ are also rare (RPS, 2007) and the only available definition is found within the EU “Guidelines for the Assessment of Indirect and Cumulative Impacts as well as Impact Interactions” (Hyder, 1999). Cumulative impacts are defined as “Impacts that result from incremental changes caused by other past, present or reasonably foreseeable actions together with the project” (Hyder, 1999).

3. Deconstructing cumulative impacts

How can we improve on the current process of cumulative impact assessment? In this section we provide insight on the concepts (impact, actions, and scale) within Hyder’s (1999) cumulative impact definition and suggest how these ideas can direct data collection and analysis for a cumulative impact assessment.

3.1. Impact

A cumulative impact assessment is intended to estimate the impact of a planned action on a receptor, in combination with other actions. We define an environmental receptor as any ecological or other feature that is sensitive to, or has the potential to be affected by, an action. Of primary importance is the identification of environmental receptors at risk from the proposed action. For example, which guilds, species and/or individuals are to be considered in the assessment and why?

3.1.1. Species or guilds

An action could affect any species occurring in the impact area. When confronted with the decision to approve a wind farm location it may be necessary to consider the variation in effect dependent on species. Red-throated divers Gavia stellata and common scoters Melanitta nigra were found within the Horns Rev offshore wind farm area pre-construction but were almost totally absent post-construction (Petersen et al., 2006), although common scoters have since begun to forage between the turbines. In contrast, some long-tailed ducks Clangula hyemalis at Nysted offshore wind farm have occurred between the turbines, but at lower densities than prior to construction (Petersen et al., 2006). The extent and nature of effective habitat loss may therefore differ between species. Not only the behaviour, but also the ability to withstand effects may differ between species. Short-lived migratory species may show high reproductive capacity that buffers them, under normal circumstances, against the very high rates of mortality experienced during their annual migrations. Such species may be relatively robust to enhanced mortality levels in a way that is not the case for long-lived species, where even small increases in death rate will rapidly impact on population size because of low reproductive output. It is also important to consider ecosystem functioning and the trophic relationships between species, i.e. the processes and interactions that occur within an ecosystem. The presence or absence of a species, especially a top predator, may affect the abundance of their prey and ultimately the composition of the ecosystem (Mills et al., 1993).

Which species should be considered? Ideally, a broad range of species would be included in a cumulative impact assessment but rarely is it logistically or financially viable to consider all species occurring within a region. Species selection requires value to be placed on the environment and the receptors within. Value can be assigned to species by various methods (Bandara and Tisdell, 2005; Ekins, 2003; Patterson, 2002; Turner et al., 2003). However, the EU Directive on the Conservation of Wild Bird Species (EC birds Directive 79/409/EEC) already assigns value to bird species via its species Annexes, e.g. Annex I lists critical species subject to special conservation measures whilst species in Annex II and III can be hunted. All species on the Birds Directive Annex I must be included in a cumulative impact assessment, as they are considered of particular value and awarded the greatest level of protection. We recommend that the list of species should not end with Annex I. Other species that practitioners should include in assessments are those for which the area is important for a specific life stage, whose characteristics make them especially vulnerable i.e. flying at turbine height, are named in the citation of adjacent protected areas or have low reproductive output (King et al., 2009).

3.1.2. Individuals or stages

An action can potentially affect a single individual or an entire population, dependent on the ecology of the species. For example golden eagles Aquila chrysaetos are largely sedentary, territorial birds so a development may only affect the pair whose territory encompasses the wind farm. Alternatively, a development may affect an entire population. Between 200 000 and 300 000 migrating common eiders Somateria mollissima (breeding in Estonia, Finland and eastern Sweden) may interact with the Nysted wind farm off the Danish coast during passage to and from their wintering grounds in the Wadden Sea (Petersen et al., 2006). Individuals of the same species may also represent different values; death of a territorial breeding adult of high quality may have a greater direct impact than the loss of a sub-adult that lacks the capacity to breed in a territorial population. Between individuals, the level of the effect may also vary as a function of state (starving versus satiated) (Kaiser et al., 2006) and personality (risk averse versus risk prone).

For a comprehensive assessment, all individuals within a population, at all stages within the lifecycle should be considered. However,
resources available for assessments are often limiting so a comprehensive assessment is not always possible. In these situations we recommend that only the stages and individuals most likely affected should be included. To make consistent decisions on the stages/individuals to include requires a repeatable design protocol, which practitioners can follow but such protocols are not available. Therefore we suggest that consistency and repeatability would be enhanced by the development of a standard design protocol for deciding appropriately representative receptors to include in cumulative impact assessments.

3.1.3. Processes

Impact is often assumed to be synonymous with effect but the two have distinct meanings. An impact is the ultimate change due to an effect, with the effect being the proximate response of an individual to an action. Fox et al. (2006) highlighted the ways in which processes such as habitat use, can be affected in the wind farm context. Birds colliding with turbines represent a direct impact on population size (through additional mortality) but what of other effects? For example, birds may avoid the immediate vicinity of a wind farm post construction, where the effect is displacement from feeding habitat, resulting in effective habitat loss. The impact of the wind farm may thus be a reduction in local abundance by displacement of individuals to other areas. However, these birds may be displaced to already occupied or otherwise unsuitable habitat elsewhere, and this displacement may cause loss of condition amongst these individuals, reductions in reproductive output or even reductions in survival. Equally, a wind farm may be perceived by a bird as a barrier, necessitating additional flight to avoid the obstacle, thus causing the bird to expend excess energy, again potentially affecting its breeding success and survival. In this way an effect (avoidance response) ultimately contributes to an impact (reduced population size), suggesting changes in population abundance as a potential common currency or metric for impact assessment. The challenge is to assess these indirect effects along with the direct impacts and the difficulty lies in translating an effect, or cumulative effects, into their ultimate impacts. But this is a difficulty pervasive to almost all environmental science: how does physical environment influence population abundance? Our quantitative understanding of this link is often poor, and while we lack a currency to compare what are essentially chalk and cheese, combining impacts and effects in realistic cumulative impact assessments will remain a serious problem.

Theoretically abundance is an ideal metric but it is also often difficult to measure with sufficient accuracy to detect statistically significant changes before there is a real probability of a substantial ecological change so it may be more practical to measure the effects of an action on a process. Effects are more easily detected and quantified than impacts, but it requires an understanding of how the processes are ultimately linked if the impact is to be estimated through the application of population modelling. For all species, the causal linkages between actions such as wind farms, population processes (effects) and changes in abundance (impacts) are currently unknown and a better basic understanding of these links remains a fundamental challenge for ecologists.

In contrast, estimates of collision risk can be quite robust. In this respect, the Baltic/Wadden Sea population of common eider provides an example of cumulative processes. Out of 235 000 passing eiders at Nysted, modelling showed with 95% certainty that 0.018–0.020% would collide with the turbines (less than 1 bird/turbine/year) (Desholm, 2006). Therefore the wind farm has an impact by directly adding to mortality rate, to a degree which can be predicted with confidence and verified by remote sensing. However, eiders are known to avoid wind farms, incurring an additional energetic cost to navigating around the turbines (Desholm and Kahlert, 2005; Masden et al., 2008) that may affect breeding condition and consequently affect the reproductive output of the population. Both the direct mortality and the results of indirect energetic costs will impact the population, but in this case, whilst the former is well documented, the population impacts of additional energy costs incurred by avoidance remain unknown. With such unknowns, the problem of assessing cumulative impacts as defined by Hyder (1999) is intractable and would require individual-based modelling at the scale of the flyway population along with knowledge of avian ecology, energetics and food resources that is not available at present, nor likely to be in the near future, in order to link the effects with population impacts. This problem is not one solely of cumulative impact assessment but of ecology in general, however, it does mean that there is a discrepancy between the data and knowledge required for a comprehensive cumulative impact assessment, and that which is available.

One solution would be to concentrate on a restricted number of processes. Different processes influence changes in population size to a greater or lesser extent, and the identification of these processes is important for effective population management (Benton and Grant, 1999). It is possible to predict the processes most likely affected by an action, based on the ecology of a species, for example eiders generally fly below rotor height and strongly avoid wind farms (Desholm and Kahlert, 2005) so are less likely to be affected by collision than by increased energetic costs. For some species the importance of different processes has already been established (RPS, 2007).

Predictions about the future impacts of wind farms on birds require prior knowledge of the effects on processes, but this evidence-based approach is generally absent from studies which are often methodologically weak with few long term impact assessments (Stewart et al., 2007). We recommend the Before-After Control-Impact (BACI) design as an ideal framework upon which to base data collection before and after the construction of a development in order to understand the effect of an action upon a receptor. Although we recognise that the BACI design is not flawless, with potential for dispute over the comparability of control and impact sites, it is nonetheless the best method currently available, and a considerable improvement on many current practices. We also suggest that the assessment of cumulative impacts would benefit from increased availability of post-construction monitoring data, therefore more stringent regulations are required on the collection and dissemination of such data (Langston et al., 2006).

3.2. Actions

An action is any event that perturbs a receptor with a resultant effect. A cumulative impact can therefore be thought of as the impact associated with increasing numbers of actions and their resultant effects. According to Hyder’s (1999) definition, a thorough cumulative impact assessment should be exhaustive and include all actions affecting a receptor. For example, when assessing the additional mortality incurred by a population of small passerines due to a wind farm, the list of other actions to be considered would include overhead power lines, tall buildings, windows, cars, cats, storms, etc. The actions may be homotypic or heterotypic (Irving et al., 1986) and may, or may not, have a specific consenting process (RPS, 2007). Actions such as climate change have no specific consenting process, but impact on a receptor. Such actions might then be considered background sources of impact nonetheless. Although the effects and impacts of these actions may be more difficult to assess due to the lack of a definite location of the action, it remains important to include them in assessments as they contribute to cumulative impacts, according to Hyder (1999). Inclusion of climate change in an assessment also allows the impact associated with other actions i.e. wind farms, to be viewed in the context of climate change (Stewart et al., 2007). Therefore, with the inclusion of all actions, it is possible to make comparisons between the impacts of different actions. For example, after a comparison of different actions affecting seabird populations, Wilcox and Donlan (2007) suggested that the removal of invasive predators from breeding islands would be a more effective means of...
increasing seabird population growth rate per dollar than fisheries closures and by catch reduction strategies. It may therefore be possible to compare the relative impacts of actions, for example a comparison between the relative impacts of hunting mortality, that of a wind farm, and of climate change on the Baltic/Wadden Sea population of common eiders.

Which actions should be included in a cumulative impact assessment? A comprehensive assessment should include all actions, past, present and future, with future being defined as those actions in planning when considering consented projects, and reasonable projections for non-consented actions such as fishing activity or climate change. Climate change is an action often excluded from assessments on the basis that it is impossible to disentangle the effects of human actions against those of climate change due to the variability and uncertainty linked with climate change. However, if climate change itself is considered an action, then the associated variability can be explained. For example, Rolland et al. (2008) assessed the combined effects of fisheries and climate on the endangered black-browed albatross, Thalassarche melanophris, concluding that the population dynamics were affected both by climatic conditions and fisheries. Although the Hyder (1999) definition dictates that all actions potentially affecting a receptor should be exhaustively included within a cumulative impact assessment, such an assessment is often logistically impractical. In these situations, the question of which actions to include in an assessment remains unanswered and decisions have to be made on the basis of expert opinion. Due to the necessity of expert evaluation and with the aim of consistent decision making, we propose that cumulative assessments would be better tackled once at a strategic level, rather than many times by different practitioners for individual project-based EIAs.

3.3. Scale

Not only is it necessary for types of actions to be defined within an assessment but also, the specific identity of actions. Therefore, it is crucial that the boundaries of space and time be defined so that actions can be identified and any scale effects can be ascertained (Burris and Canter, 1997; Canter and Kamath, 1995; João, 2002; Stewart et al., 2007).

3.3.1. Space

It is fundamental to determine the area to be included in an analysis and it must be large enough to cover the processes likely affected (Krebs, 2002). If an action affects a whole population, including only a sub-sample of the population in the assessment will not estimate the true effect. For example, post-construction of a wind farm, mortality of a receptor may increase due to collisions with the turbines. Consequently, the global population may be reduced but if new individuals move into the area due to a released constraint of density dependence, the local population may appear the same with the local area acting as a population sink. Considering only the local population, in this case, would underestimate the extent of the impact. Conversely, local sub-populations may be affected by different actions and this should be allowed for in the assessment of impact at the global scale. For example, a widespread species such as the chaffinch Fringilla coelebs migrates in a broad front rather than on a specific route. A single wind farm will therefore only affect a restricted portion of the population, and multiple wind farms will affect a different set of birds in turn. Contrast this with the same set of wind farms but located along a migration corridor; all wind farms now affect the same set of birds. Space use and the spatial scale at which the receptor is considered (local population or global population) are vital to the accurate assessment of impacts.

Another consideration is that although a receptor may not be present in the immediate vicinity of the action year-round, it may be linked to the action during discrete life stages. An example of this is the interaction of eiders with the Danish wind farm, Nysted. If the effects of the wind farm are only assessed in Danish waters then the receptor will be defined as the Danish population of eiders. However, the Wadden Sea/Baltic population migrates through the area of the wind farm twice a year, and therefore actions that affect the population along the flyway should also be included in the assessment. When considering larger spatial scales it may however be problematic because species often move across international boundaries; it therefore requires cooperation to assess all of the actions that affect these populations.

If a species of concern is using the area around an action for any period of time then the ideal spatial scale for an assessment would be the area used by the global population of the species of interest. Thus the extent would include all actions that the species would interact with during all stages of a life cycle. Although the spatial extent of assessment may be the global range of a species, the main areas of interest are those of past, present or future actions. Therefore, during data collection, field effort will be concentrated around these areas. Spatial boundaries therefore need to be defined at these smaller action-based scales, for example, when assessing collision mortality. If a bird collides with a wind turbine it can either be killed instantaneously or injured. If killed, it will drop to the ground in the vicinity of the turbine, however, if injured the bird may die some distance from the turbine. Consequently, the estimated mortality rate will change with the area included in the corpse search around the turbine. The greater the area included in the search, the more birds are likely to be found, however, the cause of death becomes less certain and difficult to verify as the distance from the turbine increases. Accuracy of assessments at the local action-based scale is vital to the accuracy of cumulative impact assessments at the global scale. For a given cumulative impact assessment, it may be sufficient to consider only the current range of a species however under certain circumstances additional areas may need to be incorporated. For example, the extent to which habitat loss will impact a species is dependent on the availability of suitable, but currently unutilised habitat. If a golden eagle territory is bounded by another, the ability of the eagle to expand its range in the face of reduced habitat will be constrained (McGrady et al., 1997; Whitfield et al., 2007a).

The ideal spatial scale of assessment may be the global range of a population but if large-scale data collection and analysis proves impossible, we recommend the use of smaller bio-geographic units. One such unit, if considering terrestrial birds in Scotland would be the natural heritage zones used by Scottish Natural Heritage (Whitfield et al., 2007b). A similar unit for the marine habitat of the North Atlantic could be ICES sea areas. Although often arbitrary, such units are already well established and may have associated data archives. However, as mentioned in Section 3.3.2, there is a lack of standard protocols for decision making on matters such as selecting appropriate scales of assessment therefore we highlight this as a target for effort in the future.

3.3.2. Time

The temporal boundaries of a cumulative impact assessment must be appropriate both for the processes likely to be affected and also the species ecology. Temporal scale should be considered because the effect of an action may show a temporal trend with a population more susceptible at specific times of the year, for example during the breeding season or the over-wintering period. This can be seen in the Nysted wind farm example of Section 3.3.1 with eiders being affected by collision mortality from Nysted only during their annual migration, i.e. twice a year. Another reason to consider the temporal scale of assessment is that effects are not always realised immediately, leading to delayed temporal variation. One potential cause of such a lag is breeding biology and the age of maturity of individuals with effects only being realised once individuals have entered the breeding population. For example, golden eagles do not secure a mate and...
enter the breeding population until 4 or 5 years old (Watson 1997) therefore effects may be unobserved for at least 5 years. Serious consideration should be given to the inclusion of such lags when measuring effects because there is the potential for impacts to remain undetected (RPS, 2007).

“The identification of the effects of past actions is critical to understanding the environmental condition of the area.” (US Council on Environmental Quality, 1997). When setting the baseline against which to assess impacts a practitioner should consider whether the current condition is an adequate representation of the non-effected environment and if not, what data should be included to allow the differentiation between noise within the system and an impact due to the action. Assuming data availability, McCold and Saulsbury (1996) advocate, “The appropriate baseline for considering the significance of cumulative impacts is the time when the valued environmental component was most abundant”, though this may not always be true. The population of northern fulmar, Fulmarus glacialis around the British Isles provides one such example. This population has increased both its range and abundance since the mid-18th century (Mitchell et al., 2004). Availability of offal and discards from commercial fisheries has been implicated as a contributing factor to the growth in numbers and distribution, therefore it may not be fitting to use these elevated abundances as a baseline value because the increase is a function of anthropogenic activities (Mitchell et al., 2004). Another view is that the baseline should be the most recent state of the receptor. Although this may not be the true and naturally occurring state of the receptor, it is argued that it is the most feasible to assess. The problem arises when no standard baseline measure exists for a receptor, but rather the baseline is considered the state of the receptor at the time of individual assessments (IEEM, 2008). This lack of historical data integration is known as the “shifting baselines” syndrome (Pauly, 1995) and over time can lead to the degradation of a receptor. However, very rarely are sufficient time-series data available to adequately assign baselines. Therefore compromises have to be made, for instance the Ramsar Convention on Wetlands designations, adopts the last five years of reliable data to determine the benchmark/baseline.

Temporal variation may also occur over the lifetime of the action because the behaviour of the receptor changes in response to the action; birds may initially exhibit avoidance behaviour towards wind turbines but over time the response may change. At the Danish wind farm, Horns Rev, red-throated divers and common scoters were found within the wind farm area pre-construction but were almost totally absent immediately post-construction. Five years after construction, scoters have now moved back within the wind farm and occur at similar densities inside the wind farm area to outside, yet divers persist in their absence (IB Krag Petersen pers. comm.). Similarly, habituation has been observed in pink-footed geese, Anser brachyrhynchus at terrestrial wind farms in Denmark (Madsen and Boertmann, 2008).

The temporal scale of an assessment should be defined in terms of the available baseline data, the species ecology, and also the lifetime of the actions of interest. The data collection and assessment should include seasons relevant to the environmental receptor of interest and the analysis of the data should allow for any potential time lags in effects. For example, an assessment for a wind farm (operational lifespan of 15 years) affecting golden eagles (breeding age of 5 years), may include a predictive model that has a temporal scale of 20 years. The concept of time lags is also important when designing post-construction monitoring for an action. If temporal lags in effects are expected then the scale of the monitoring program should encompass these lags and continue long enough to assess whether predicted impacts have been realised. The baseline data against which to compare these impacts should not be the state of the receptor at the time of assessment and data collection as over time, this will lead to shifting baseline syndrome (Pauly, 1995). Instead, it should include a series of data long enough to detect underlying variability in the system, against which to compare effects and impacts caused by the action. There is a lack of guidance available for practitioners on choosing appropriate baselines and so with each practitioner independently deciding on an appropriate baseline, the process is ad hoc. We therefore suggest that if all assessments are to be comparable and free from shifting baseline syndrome it requires a strategic decision to be made at the policy level about the value of species, appropriate baseline levels and acceptable target population sizes.

4. Formalising the framework

Throughout this paper we have described ways to consider the assessment of cumulative impacts and the concepts within the Hyder (1999) definition. In this section we present our discussion in terms of a formalised equation in an effort to further clarify thinking on the matter. Models and formulae are often useful as a tool to simplify concepts and identify the essential elements of a problem, in an effort to find solutions. Although simplistic, our formulation further highlights the different elements that should be incorporated into a cumulative assessment. As Box and Draper (1987) stated, “All models are wrong, but some are useful.”

4.1. The framework as a function

A function is a mathematical concept that describes the relationship between variables, such as abundance of golden eagles and number of wind farms. Therefore, the impact of the jth action ($A_j$), for example a wind farm, on the jth receptor ($R_j$), for example a golden eagle population, at location $x$, at time $t$ can be defined by a function ($I$):

$$I(A_i, R_j, x, t)$$

Having defined the impact of a specified action on a specified receptor at a particular space-time location, it is now possible to consider the cumulative impact of a set of actions ($A$), for example wind farms, forestry and persecution, on a set of receptors ($R$), for example adult and juvenile golden eagles, over an area, or set of areas, ($\Omega$), accumulated over a defined time period comprising the past, present, and future. The cumulative impact ($CI$) can be expressed as a multiple integral of the impact function ($I$):

$$CI = \sum_{i=1}^{A} \sum_{j=1}^{R} \int_{x=0}^{x=\Omega} \left( \int_{t_0}^{t_1} I(A_i, R_j, x, t) dt \right) dx$$

4.2. Defining the sets

In Eq. (2), actions ($A_i$) and receptors ($R_j$) are discrete values taken from sets, $A$ and $R$, respectively. These sets should be selected, as discussed in Section 3, to ensure inclusion of all relevant actions and receptors. Space ($x$) is represented as $x$-y locations in a 2-dimensional plane within a bounded area ($\Omega$), however space could instead be represented as a set of areas. Time ($t$) is divided into two periods, past ($t_0$) to present ($t_1$) and present to some defined point in the future ($t_1$). Inclusion of past impacts prevents temporal creep from adopted baseline standards as discussed in Section 3.3.2. The projection into the future should be made over appropriate time horizons based on the operational life-span of the action and the receptor ecology (Section 3.3.2).

4.3. Assumptions

For clarity of presentation, a simplifying assumption of Eq. (2) is that the impacts are additive, with no interactions between receptors.
and/or actions. This is certainly violated in most situations. When considering the receptor for example, the behaviour of individual birds towards a wind farm may not be independent. Many species exhibit flocking behaviour, so the response of many individuals may be dependent on that of a few key individuals. It is also possible that for effects such as disturbance, the response is likely to be non-linear with threshold characteristics. A small disturbance may have limited impact but a more extensive or prolonged disturbance event may have a disproportionately large impact. Interactions are also possible between actions. It has been suggested that wind turbine structures in the marine environment may provide habitat for some life stages such as juvenile fishes. Furthermore, it is possible that no-take marine protected areas could be developed in association with the footprints of offshore wind farms, thus positively affecting species which are negatively affected by other actions elsewhere (Linley et al., 2007). Simplicity of presentation dictated the exclusion of interaction terms from Eq. (2) however these terms should be introduced where required.

5. Conclusion

“The natural world is in crisis; wild living resources are being depleted at increasing rates, the ecosystems upon which they depend are generally perturbed, and the consumption of resources by a growing human population generally increases” (Mangel et al., 1996). As human actions increasingly influence the environment, it is important to monitor and assess these anthropogenic-induced changes. Increasing numbers of wind farms seem to be inevitable given the international legal responsibility to reduce CO2 emissions but there remains much concern over the impacts on bird populations. With increasing numbers of wind farms comes concern not only over isolated environmental effects but also the cumulative environmental impacts and despite awareness of the issue, there seems to be a lack of understanding and research in the area of cumulative impact assessment.

The cumulative impact assessment process is inadequate and unsatisfactory with few EIAs even considering cumulative impacts. Bad practice is not restricted to the UK, but widespread across Europe and North America (Burris and Canter, 1997; Duinker and Greig, 2006; Wärnbäck and Hilding-Rydevik, 2008). The absence of effective assessments of cumulative impacts is a function of the current lack of guidance (Cooper and Sheate, 2002), and particularly the absence of a comprehensive definition. Without a clear definition it is not possible to ensure an assessment that demonstrates adequate consideration of all aspects of the ecosystem including spatial and temporal scale. Therefore there is an urgent need for legislation and statutory authorities to offer clarity on the requirements of cumulative assessment. Similarly, without explicit statements of which components have been considered in a cumulative assessment, it is difficult to draw conclusions from the data. The framework we suggest provides a means by which to explicitly highlight and include actions, impacts and scales in any cumulative impact assessment. By explicitly stating the actions and receptors included (or more importantly, those not included) in an assessment, and the scales at which these have been considered, it is possible to reduce uncertainty surrounding the assessment. If data collection has to be compromised i.e. the spatial scale reduced from global to local, due to limited financial resources, it can be identified using the framework we describe. However, practitioners are still lacking a means by which to make consistent decisions on the reduced sets of actions and receptors to include, and the scales at which to consider them, in a cumulative impact assessment. Until a standard method is devised it is unlikely that cumulative impact assessments will provide any more value than at present.

A comprehensive cumulative impact assessment relies on the availability of data for actions. In a competitive business such as energy supply, acquiring information from other developers about potential actions, sufficient to conduct a thorough cumulative assessment is difficult, if not impossible. Ludwig et al. (2001) suggested, “Wicked problems, such as the planning of wind farms, require innovative policy but also innovative methods of arriving at the policy”. We propose that the innovation required is the elevation of cumulative impact assessment from the individual project to the strategic level. Under the EIA Directive, cumulative impact assessments are conducted at a project level by developers; elevating the process to a more strategic level may relieve some of the problems of data availability and confidentiality, with an assessment being the responsibility of a regulatory body rather than the individual project developer. With a more strategic approach, greater data acquisition would also be possible, as resources would be pooled for one assessment rather than for many. Strategic assessments already occur within the EU in the form of the strategic environmental assessment (SEA) and for offshore wind farm developments, the SEA is intended to inform cumulative impact assessments. Therefore, the infrastructure is more readily available and would only need modification. It has been suggested that when capability and resources for assessing cumulative impacts are limited, a greater proportion of effort should be assigned to minimise the impacts of single actions (MacDonald, 2000). The recommended shift in policy would see cumulative impact assessment integrated into strategic planning levels as part of the process of spatially explicit planning, making available the resources of developers to minimise the impacts of single actions through environmental impact assessments.

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