Greenshank collision mortality estimate based on ecological and behavioural studies

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Keywords

Greenshank; collision risk; modelling; Strathy South wind farm.

Background

This analysis was developed for the Public Local Inquiry for the proposed Strathy South wind farm. Concerned that the observed flight activity under-estimated the actual collision mortality at this wind farm, an approach was developed that used modelling of known ecology and behaviour of greenshank.

Main findings

- Using known and estimated parameters of flight activity for female greenshank, the amount of time that birds spend flying throughout the breeding season was estimated to range between 27 (low) and 320 (high) minutes each day, with an average of 140 minutes per day
- Using a simplified layout of the wind farm and an estimated dispersion of greenshank territories, the model estimated the number of territories surrounding the wind farm to be 21, with the potential for a further nine within the forested block.
- There are several key results from the modelling. Females are predicted to spend twice as much time commuting as males, and hence females have twice the commuting collision risk of males. Conversely, males spend much more time in display flight than females and are thus up to nine times more at risk of display collisions than females.
- Depending on the level of display flight activity used (low, average, high), display collisions were estimated to represent between 42% and 69% of all collision risk (low and high respectively).
- Collision estimates were assessed as being 10.11 collisions per annum (low), 12.97 (average) and 18.69 (high). This is based on an avoidance rate of 0.98. If the avoidance rate is higher, then mortality will be lower.
- In the theoretical model developed there is no requirement to account for detection rates since flight activity has been derived empirically. Thus, the 98% avoidance rate is almost certainly over-precautionary for use in the current model.
- Collision risk was assessed as being of high sensitivity to three aspects of the model. Two of these are closely linked (the use of the forestry areas for nesting territories only

and foraging occurring only outside the wind farm area) and the third was the avoidance rate.

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1. INTRODUCTION

The estimated collision risk for greenshank within the July 2013 Environmental Statement Addendum for the Strathy South proposed wind farm suffers from a number of methodological problems, most notably issues around the detection of flight activity. The purpose of this work is to corroborate (or otherwise) collision risk estimates developed as part of the 2013 Environmental Statement Addendum, by using an alternative approach, which was based on the understanding of greenshank breeding ecology and activity budgets.

2. MODELLING FLIGHT ACTIVITY BASED ON A REVIEW OF GREENSHANK BREEDING AND FLIGHT ECOLOGY

The proposed 39 turbine wind farm at Strathy South occupies an area of forested peatland within the Caithness & Sutherland SPA. Greenshank is considered to be a qualifying feature of the SPA and the peatland habitat that surrounds the forest block supports a significant proportion of the estimated number of breeding pairs within the SPA (estimated to be around 5%). The use of empirically derived data to determine collision rates can be hampered by poor detection from standard vantage point watches. Reduced detection distances will invariably mean that potential collision risk is under-estimated. This is determined in part by the fall-off in species detectability with increasing distance from a single vantage point. While this can in some cases be corrected for, there are a number of problems that make this challenging, not least the fact that failure to detect any flights (even when they do occur) cannot then be corrected for distance. Species that are cryptic, nocturnal or fly at times when fewer vantage point watches are undertaken (very early or very late) are prone to such biases. SNH believes that greenshank suffer from some of these detection-reducing characteristics and that alternative means of assessing collision risk should be explored.

The British population has been estimated at 1,080 (720 to 1,480) occupied breeding territories in 1995 (Hancock *et al*., 1997; Forrester *et al*., 2007). Caithness & Sutherland Peatlands SPA held 653 pairs in 2009 (389-917 pairs) at a breeding density of 0.73 pairs per km^2 (Bellamy & Eaton, 2010). Even in typical habitat, there is rarely more than one pair per km^2 (Nethersole-Thompson, 1951). Forrester *et al*. (2007) reported densities of 0.2 to 0.7 pairs per km^2 but they also comment that some prime habitat may hold up to two pairs per km^2. Up to 10 pairs were found in 1200 ha of North Sutherland with 52% territory occupancy, 59% hatching success and most failures due to nest predation (Christian & Hancock, 2009). One of the highest recorded breeding densities is in NW Sutherland (Nethersole-Thompson & Nethersole-Thompson, 1979). This is tabulated as 20 pairs in a 10 km square, equivalent to 0.2 pairs per km^2. However, in the text it is stated that about 20 pairs nested within a study area of 3,250 ha, which equates to about 0.7 pairs per km^2. Nests tend to be spaced about 1 km apart even where nesting density is particularly high (Nethersole-Thompson & Nethersole-Thompson, 1979). Hatching success averaged 77% in NW Sutherland (Nethersole-Thompson & Nethersole-Thompson, 1979), but survival of chicks is typically low, with mortality especially of young chicks. Productivity (chicks fledged per breeding pair) may be about 0.5 to 1 young per pair in most years (Nethersole-Thompson & Nethersole-Thompson, 1979).

A feature of the ecology of the greenshank is that birds defend several areas, and not just their nest site. Greenshanks will defend and display over mating territories in April, nesting territories in May and food territories in June, and these different defended areas can be up to several kilometres apart (Nethersole-Thompson, 1951; Nethersole-Thompson & Nethersole-Thompson, 1979).

2.1 Flight height

Flight height data are likely to suffer from problems of low detection, with low flying birds probably more likely to be undetected than high flying birds. Empirical data from vantage point surveys may therefore be biased towards higher flight estimates. RPS (2014) reported that eight out of 30 greenshank flights (27%) observed in the Strathy South vantage point watches were at potential collision height. RSPB (2013) stated of greenshank that "*we note that around a third of the flights recorded over non-forestry sites were at collision risk height*". E.ON (2010) reported greenshank flight height data at Corriemoillie as nine birds at <20 m, 15 at 20-40 m, six at 40-100 m, two at 100-150 m, and no flights above 150 m. This represents about half of flight activity at collision risk height based on flight duration. In the bands overlapping with collision risk height, 1,575 bird-seconds were spent at 20-40 m, 450 at 40-100 m, and 1,575 at 100-150 m. The total in the upper band was high due to relatively few, but prolonged, flights of individual birds undertaking display flights.

Natural Research (2006) reported on 14 greenshank flights in north Lewis in May-June 2005. Eight of the reported flights were at 10-50 m above ground, and six at 50-100 m above ground, so perhaps about half of these flights appear to have been at collision risk height, but this is difficult to assess from the height bands used, and is based on a small sample size. None were below 10 m and none were above 100 m, and none were considered to change between the defined height bands, although Nethersole-Thompson (1951) and Nethersole-Thompson & Nethersole-Thompson (1979) describe how greenshank may fly much higher than 100 m above ground and especially in display flights may gain and lose height rapidly during display. Although exact times of observations were not reported, all flights except possibly one were observed either in early morning (eight flights appear to have been observed before 08.00) or evening (five, possibly six flights appear to have been observed after 16.00). The timing of the flight activity in early morning or evening is consistent with the descriptions in Nethersole-Thompson (1951) and Nethersole-Thompson & Nethersole-Thompson (1979). Observed flights lasted up to six minutes or more, eight were described as display flights and six as commuting flights. Five of the eight display flights were at 50-100 m, whereas five of the six commuting flights were at 10-50 m.

Overall, despite the rather limited amount of flight height data, it appears reasonable to suggest that about one-third of flight activity may be at collision risk heights (i.e. 25-100 m).

2.2 Activity budget

The sustained speed of greenshanks in level-flight has been studied by radar indicating a flight speed of 12.3 m s^{-1} (Alerstam *et al*., 2007). A greenshank flight speed of about 75 km h^{-1} (20 m s^{-1}) is quoted by Meinertzhagen (1955) but such a high flight speed seems improbable. Nethersole-Thompson (1951) cites a similar flight speed but quoting Meinertzhagen as the source, so that represents the same estimate as published by Meinertzhagen. However, this old estimate seems likely to be less reliable than the radar studies reported by Alerstam *et al*. (2007).

There is a detailed, but largely qualitative, description of the breeding ecology of greenshanks in the monographs by Nethersole-Thompson (1951) and by Nethersole-Thompson & Nethersole-Thompson (1979). Those books, and other relevant literature on greenshank ecology were reviewed to obtain appropriate estimates of the activity budgets of breeding greenshanks in order to assess the amount of time spent in flight through the breeding season, the height at which flight occurs and hence the amount of time spent in flight at potential collision risk height and the likely locations of flight activity in relation to nest

site locations. Guidance on appropriate levels of flight activity to use in modelling collision risk in each month April to July was also sought by interviewing Professor Des Thompson[1].

This section is primarily based on material in Nethersole-Thompson (1951) and Nethersole-Thompson & Nethersole-Thompson (1979). Males and females take part in display flights, though females less than males. Birds defend and display over mating territories in April, nesting territories in May and food territories in June. Display flights may occur for several hours per day and may involve long chases over several kilometres; birds breeding in treeless areas and at high population density seem to spend more time in display flight. Mating territories are beside large lochs, some distance from nesting territories, and feeding territories are also some distance from nesting territories. Breeding birds usually fly at least 500 m from nest to feeding site, but often may fly 5 km, and may travel up to 14 km. In Glengarry, birds court and feed by lochs and rivers but nest in flows about 3-6 km away from these sites and 45 to 630 m higher in altitude. Display flights occur most frequently during the early part of the breeding season (April), up to pair formation. The displays involve the male flying to a height of 60 m, occasionally up to 300 m, before dropping down. Most display activity occurs between 0300 and 0700 hours (Pendlebury *et al.*, 2011). Display activity is much reduced in May while birds are incubating (D. Thompson, pers. comm.), although birds that lose the clutch may resume displaying and lay a replacement clutch.

One constraint on flight activity that can be used to set an upper limit on activity levels is the energy cost of flight, which is far higher for most birds than can be sustained for prolonged periods. Birds can only increase sustainable energy expenditure up to a limit of about four times Basal Metabolic Rate (BMR). The development of a metabolic approach to setting an upper limit to flight activity is explored here. Hale (1980) used a bioenergetics modelling approach to argue that waders harvest a much higher proportion of invertebrate production in breeding grounds than in wintering grounds, not because they eat more, but because their consumption depletes the standing stock of food to a greater extent during the breeding season. He therefore argued that energy limitation is more likely for breeding waders than for overwintering waders (Hale, 1980, Chapter 10) and that there will be strong natural selection for territorial behaviour on breeding grounds to reduce intra-specific competition for food. More recently, the energy expenditure of birds during breeding has been measured for a wide range of species by use of the doubly labelled water method (Nagy, 2005). The daily energy expenditure during breeding (known as Field Metabolic Rate FMR) is expressed by the equation FMR (kJ d^{-1}) = 10.5 $M^{0.681}$ for a large sample of bird species and with a high statistical confidence (n=95, r^2=0.938, p<0.0001) (Nagy, 2005). Although birds can expend energy at higher rates, for example by using fat stores to fuel migratory flight, such rates of energy expenditure require metabolism of stored reserves and so are not sustainable. The sustainable maximum work rate of birds (and of mammals) has been shown to be around four times BMR, a ceiling that is set by physiological constraints on energy processing (Drent & Daan, 1980; Green *et al.*, 2013). Flight costs represent a critical part of the daily energy budget of flying birds because flight costs are especially high and particularly so in birds that are larger than typical small passerines, so that the amount of time birds can spend in flight within their maximum sustainable work rate is constrained (Johnston & McFarlane, 1967; Pennycuick, 1989; 2008; Nudds & Bryant, 2000; Rogers *et al.*, 2006; Schmidt-Wellenburg *et al.*, 2007; Weber, 2009). For a species such as greenshank, where flight is by flapping flight at relatively high speed and without major use of economies of soaring, the energy cost of sustained flight is likely to be around 8-10 times BMR (Johnston & McFarlane, 1967; Pennycuick, 1989; 2008; Butler & Bishop, 2000; Nudds & Bryant, 2000; Schmidt-Wellenburg *et al.*, 2007; Weber, 2009; Gavrilov, 2011). Numerous short flights, or flight with frequent changes of direction and altitude, as in display flights or territorial or courtship chases, will have higher energy costs (Butler & Bishop, 2000; Gavrilov, 2011), possibly as much as three

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[1] Professor Des Thompson (SNH) has continued to maintain a long term study of greenshank in Sutherland, and has a very good knowledge and understanding of the species' behaviour.

times higher than sustained flapping flight (Nudds & Bryant, 2000). There is, therefore, a limit to the amount of time that a bird can spend in flight, especially display flights, and remain within the ceiling of four times BMR. Assuming that most other routine activities such as foraging, walking, preening, resting, incubating eggs, digesting food, and general maintenance behaviour costs about 2.6 times BMR (Drent & Daan, 1980; Hale, 1980; Piersma *et al.*, 2003; Rogers *et al.*, 2006), this is likely to set a maximum of no more than 3 hours per day in flight for a bird the size of the greenshank in order to keep total metabolism below the ceiling of four times BMR (Pennycuick, 1989; 2008). This was demonstrated by experimental work with starlings *Sturnus vulgaris*; breeding adult starlings declined in body mass as they were forced to spend more than two hours per day in flight, and this decline increased dramatically when birds had to spend three hours per day in flight, indicating that this work rate had exceeded a sustainable level (Drent & Daan, 1980). While birds may be able to exceed the four times BMR ceiling for a short period, this will be at the cost of depleting body stores such as fat and protein, and so would be likely to compromise survival prospects. It is, therefore, reasonable to assume that birds will generally avoid exceeding the four times BMR ceiling except in the short term and for brief periods. Some species, such as pelagic seabirds, are adapted to cope with fluctuations in foraging conditions by carrying large fat reserves even when breeding (Jacobs *et al.*, 2011), but this does not apply to the greenshank. Although greenshanks store large quantities of fat to fuel long-distance migrations (Remisiewicz *et al.*, 2014), they do not carry large reserves of fat when breeding; breeding birds (mean mass 199 g BTO Bird Facts) carry only a few grams more fat than birds remaining resident in Africa and not fuelling for migration (Remisiewicz *et al.*, 2014).

The above considerations formed the basis of the activity budget estimates used in the modelling (Table 2). These were discussed with Professor Thompson, who confirmed that they were appropriate for this purpose.

2.3   Breeding phenology

The timing of the greenshank breeding season is well documented. Males generally arrive back on the breeding grounds first, with females following soon after (Nethersole-Thompson & Nethersole-Thompson, 1979, Cramp & Simmons, 1982). Greenshanks arrive back at breeding grounds in Scotland in late March or early April (Nethersole-Thompson & Nethersole-Thompson, 1979; Thompson *et al.*, 1986; Thompson & Thompson 1991). Females normally lay four eggs, with egg laying at about 44 hour intervals (Nethersole-Thompson & Nethersole-Thompson, 1979). Clutch completion varied from year to year and among studies but was mainly around 5th to 10th May (Nethersole-Thompson, 1951; Nethersole-Thompson & Nethersole-Thompson, 1979; Thompson *et al.*, 1986), indicating that egg laying starts around 1st May. Incubation continues for 24-26 days (Nethersole-Thompson, 1951; Nethersole-Thompson & Nethersole-Thompson, 1979), and may be by both sexes although in many pairs most incubation is by the female. Changeovers at the nest generally occur in early morning and evening (often around 6 a.m. and 8 p.m.) (Nethersole-Thompson, 1951; Nethersole-Thompson & Nethersole-Thompson, 1979). During incubation, which is predominantly by females during the day, females will make two (sometimes one to four) feeding trips per day of ca 30 minutes, flying typically 2 km to feeding grounds (Nethersole-Thompson, 1951). Breeding season diet is aquatic, and mud invertebrates and fish fry are obtained from shallow waters fringing lochs or from shallows of sluggish stretches of rivers (Nethersole-Thompson & Nethersole-Thompson, 1979). However, nest sites are predominantly several kilometres from feeding sites, so birds commute between nest sites and feeding sites. Both may be defended by territorial displays.

Shortly after hatching (usually within the first two or three days), adults lead chicks away from nest sites to feeding areas which are defended but may be several kilometres from nest sites. Broods may be split between parents, or the female may desert and leave the male to rear chicks. Males will explore different possible feeding sites and will song-dance overhead

to establish territorial ownership of suitable feeding areas (Nethersole-Thompson & Nethersole-Thompson, 1979). Broods may move several kilometres from nest to feeding grounds, depending on local geography. Chicks fledge when about 29 days old (Nethersole-Thompson, 1951), so start to fly around the beginning of July. Females tend to migrate south first (early to mid-July). Shortly after chicks can fly strongly, males and fledglings migrate south (mid to end of July or early August) (Nethersole-Thompson, 1951; Thompson *et al.*, 1986).

2.4   Assumed Phenology for modelling (based on literature reviewed)

- April – pair formation, territorial displays; 30 days
- May – egg laying, incubation and hatching; 31 days
- June – chick-rearing; 30 days
- July – post-fledging period females depart on average 10th July, males and fledglings depart on average 20th July.

Table 1. Assumed phenology of activity by greenshank.

Class	Number of days present and flying over area			
	April	May	June	July
Males	30	31	30	20
Females	30	31	30	10
Fledglings	0	0	0	20

It should be noted that for convenience calendar months have been used to describe the breeding phases during which the birds may be at risk of collision. Thus, while the actual dates of arrival may vary by several days, the duration of the relevant periods (e.g. pair formation, egg laying, incubation, etc.) will remain more or less the same and consequently this will not be expected to have a large effect on the collision risk estimates.

2.5   Assumed activity budgets for modelling (based on literature review)

Greenshank sustained speed in level flight is around 12.3 m s^{-1} (Alerstam *et al.*, 2007). However, birds need to take off and land, and may need to gain height during flights between nest sites and feeding sites, so commuting flights of only 500 m to a few kilometres will average a slower speed than this, perhaps around 10 m s^{-1} for a typical commuting flight. The activity budget assumes that, during April, males commute between display sites, foraging sites and potential nest sites, typically making three return trips of around 3 km (1.5 km each way based on the typical distance between nest sites and foraging sites reported in Nethersole-Thompson (1951) and Nethersole-Thompson & Nethersole-Thompson (1979)), at an average flight speed of 10 m s^{-1}, so spend about 15 minutes flying. Around this estimate are possible minimum estimates of only 6 minutes commuting and maximum of 30 minutes commuting, based on descriptions of the minimum and maximum distances between nest sites and feeding sites reported in Nethersole-Thompson (1951) and Nethersole-Thompson & Nethersole-Thompson (1979). The large difference between the lower and upper estimates is due to high uncertainty in the evidence, and also to the indication in the literature that these values vary considerably among pairs and among locations, at least in part likely to be a result of local ecological features and the spatial scale of habitat mosaics.

Males show considerable song-flight activity in April and may chase other males and females in display flights. Such flights involve high aerial agility, but are likely to average around 10 m s^{-1}. The amount of time spent in display flight is uncertain, but may be around 90 minutes per day. A minimum of 60 minutes per day is assumed. A ceiling on all flight

activity is set by the metabolic cost which will limit this to no more than three hours total in flight per day for both commuting and display, so, allowing for up to 30 minutes of commuting, a maximum of about 150 minutes in display flight is assumed for days in April.

Females spend less time in display flight activity than males, but probably spend more time in commuting flights than males. They need to feed more intensely to obtain resources for egg formation and are likely, on average, to do this in a larger number of foraging bouts than required by males. In May, incubation requires females to commute between the nest and feeding areas, and the constraint of having to return to the nest site after each foraging bout will increase their commuting costs relative to the pre-laying period. The need to visit the nest site as well as feeding areas and to display will probably increase commuting flight activity of males in May compared with pre-laying levels in April, but display activity is known to decrease from peak pre-breeding levels so is assumed to be much less in May than in April. When eggs hatch, commuting flight costs for males and females will reduce because chicks are led towards feeding grounds within the first few days after hatching. The modelling uses an estimated 50% reduction in commuting flight activity between incubation (May) and chick-rearing (June), but assumes a small increase in the amount of display/territorial defence flight activity because movement of chicks to feeding grounds results in adult territorial behaviour (i.e. display flights) over the area being used by chicks. In July, when chicks are larger, adult flight activity associated with commuting between sites is assumed to reduce further, whereas display/territorial activity is assumed to continue but at a lower level, at half the level in June.

Fledglings begin flying in July. The literature provides very little guidance as to how much time fledglings spend in flight in the breeding areas in July before dispersing away from the area in late July. For the modelling it is assumed that fledglings spend between 0 and 60 minutes in flight per day during July, but the most likely amount seems to be towards the lower end of this range. In 60 minutes of flight a fledgling flying at an average of 10 m s^{-1} could travel 36 km. While it is known that fledglings will explore their natal area before dispersing, it seems very unlikely that fledglings would explore over such large distances on a daily basis. These assumptions result in the estimates presented in Tables 2, 3 and 4.

Table 2. Assumed flight activity budgets in terms of time spent commuting between nest sites and foraging areas, and in terms of time spent in territorial or sexual display flights, in minutes flight per day, of adult males, adult females, and fledglings.

Class	Activity budget levels	Mean minutes in flight per day (commuting to forage)				Mean minutes in flight per day (display)			
		April	May	June	July	April	May	June	July
Males	Low	6	12	6	3	60	10	30	15
	Average	**15**	**30**	**15**	**10**	**90**	**20**	**60**	**30**
	High	30	60	30	20	150	40	120	60
Females	Low	6	12	6	3	0	0	0	0
	Average	**30**	**45**	**20**	**10**	**10**	**10**	**10**	**5**
	High	60	90	45	20	30	30	30	15
Fledglings	Low	0	0	0	0	0	0	0	0
	Average	**0**	**0**	**0**	**10**	**0**	**0**	**0**	**0**
	High	0	0	0	60	0	0	0	0

Table 3. Assumed flight activity budgets in terms of total minutes flight per day, of adult males, adult females, and fledglings (based on components in Table 2).

Class	Activity budget levels	Mean minutes in flight per day (total)			
		April	May	June	July
Males	Low	66	22	36	18
	Average	**105**	**50**	**75**	**40**
	High	180	100	150	80
Females	Low	6	12	6	3
	Average	**40**	**55**	**30**	**15**
	High	90	120	75	35
Fledglings	Low	0	0	0	0
	Average	**0**	**0**	**0**	**10**
	High	0	0	0	60

Table 4. Total hours of flight activity each month over the area, per male, per female, and per fledgling. 30 days in April, 31 days in May, 30 days in June, males and fledglings present on average for 20 days in July, females present on average for 10 days in July.

Class	Activity budget level	Total hours of flight			
		April	May	June	July
Males	Low	33.0	11.4	18.0	6.0
	Average	**52.5**	**25.8**	**37.5**	**13.3**
	High	90.0	51.7	75.0	26.7
Females	Low	3.0	6.2	3.0	0.5
	Average	**20.0**	**28.4**	**15.0**	**2.5**
	High	45.0	62.0	37.5	5.8
Fledglings	Low	0.0	0.0	0.0	0.0
	Average	**0.0**	**0.0**	**0.0**	**3.3**
	High	0.0	0.0	0.0	20.0

2.6   Spatial distribution of flight activity

Greenshank breeding territories in the vicinity of the proposed Strathy South Wind Farm have been mapped from breeding bird surveys (RPS, 2014). In order to estimate collision risk we combined the assumed phenology and activity budget data with a simplified territory map overlain on a simplified wind farm plan. We have assumed territories are 1 km across and packed into the available area (Figure 1). This idealised layout covers a slightly smaller area than the actual site, however the differences are comparatively small (actual site c. 16 km^2 modelled site 14.25 km^2) and will not influence the model outputs to an appreciable amount. It is also worth stressing that the modelling was developed to assist understanding of the potential collision risks and not to replicate precisely the specific development.

A key assumption is the distance of commuting flights between nest sites and foraging areas or between foraging sites, and the distance of display flights. Nethersole-Thompson (1951) and Nethersole-Thompson & Nethersole-Thompson (1979) stress that greenshanks move between display areas, nest sites and feeding areas and that display activity occurs over all of these. The distance between nest sites, display areas and feeding areas used by individual pairs is usually more than 500 m, often 2 to 6 km, and can be up to 14 km (Nethersole-Thompson, 1951).
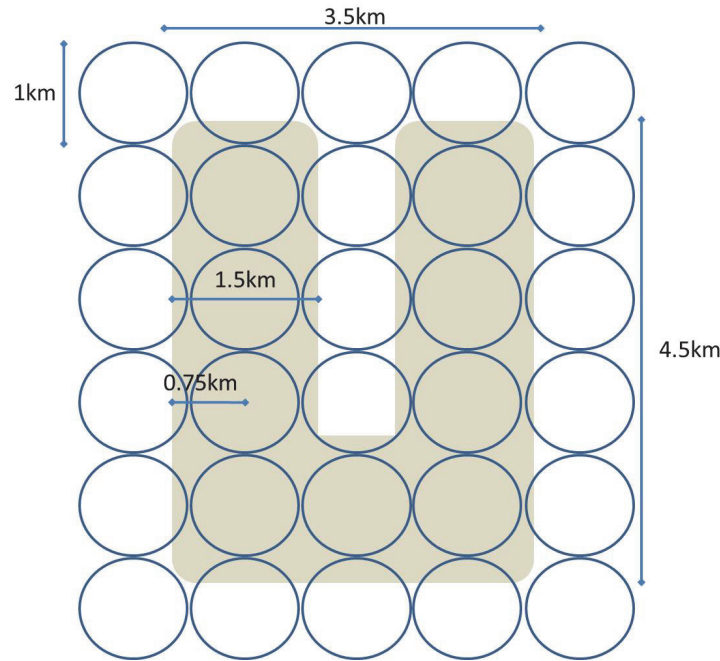
Figure 1. Simplified map of Strathy South wind farm (brown 'u' shape) overlaid with greenshank nesting territories (blue circles). The distances are approximate but have been used to estimate the proportion of flight time which may be in the vicinity of turbines.

2.7   Estimation of a theoretical collision risk

Based on the review of greenshank breeding ecology the following assumptions have been made in relation to estimating the potential collision risk at the Strathy South wind farm.

- The wind farm area is used primarily for nesting, especially within the forestry (i.e. where the turbines will be located). Mating territories are located outside the wind farm (i.e. at no collision risk). Foraging territories may be located around the edges of the forestry, but it has been assumed that no flight activity associated with foraging areas will be in the vicinity of turbines (i.e. no risk of collision).
- During **April** birds spend most of their time on mating territories, commuting three times per day to the nesting territory. Thus, each commuting flight (to/from the nesting territory) which passes through the wind farm is at risk of collision. In addition, display time at nesting territories in the wind farm area (assumed to be one third of the total display time) is at risk of collision.
- During **May** birds split their time between the nesting and feeding territories (males commute three times per day, females six times per day). Display activity only occurs at the feeding territories, therefore display flights are not at risk of collision.
- During **June and July** all the time is spent at the feeding territory, therefore no display flights are at risk of collision. No commuting occurs over the wind farm.

To generate predictions of flights at risk a simplified version of the wind farm and potential greenshank territories was developed (Figure 1). On this basis, individuals using the three nest territories in the centre of the site (within the open area) may be at risk of collision when they pass turbines during commuting flights for approximately 1.5 km. Individuals with territories in the wind farm area are at risk whilst commuting for approximately 0.75 km and during display flights above their nest territories. Territories around the outside of the wind farm are considered to be at no risk during commuting flights or display flights. (Although in theory these individuals could be at risk during display flights for a small proportion of time, this has been discounted since birds display less in forested areas.)

The collision risk of commuting flights has been estimated in terms of the number of turbines encountered per flight which will depend on the direction of flight. A precautionary maximum of two turbines per commuting flight has been assumed for flights to/from the central territories and one turbine per commuting flight for territories in the wind farm.

Display flight collision risk has been estimated in terms of time spent at risk of collision (i.e. accounting for the proportion of territories containing turbines, time spent at collision height, etc.). This has only been applied to nest territories within the wind farm area.

Final collision estimates have been adjusted using the accepted greenshank avoidance rate of 98%. However, it should be recognised that the avoidance rate used in the Band model includes some allowance for under recording of flight activity – where flight activity has been under-recorded the avoidance rate will tend to be underestimated in order to compensate (because it is based on number of collisions in relation to the number predicted which will be an underestimate if birds are cryptic). The current modelling is based on empirical evidence regarding flight activity; therefore this allowance for under-recorded time is not appropriate. Consequently use of the 98% avoidance rate can be considered highly precautionary for this assessment.

The parameters used in the scenario collision modelling are provided in Table 5.

Table 5. Greenshank and wind farm parameters used in scenario collision risk modelling.

	Parameter	Value	Notes
Greenshank biometrics	Flight speed (m s^{-1})	12.3	Alerstam *et al*. (2007). Note that in display flight a slower speed of 10 m s^{-1} has been used.
	Length (m)	0.315	Snow & Perrins (1998)
	Wing span (m)	0.69	
	Probability of collision (commuting)	0.063	From Band model
	Probability of collision (display)	0.067	
	Avoidance rate (%)	98	SNH guidance for survey based collision modelling (SNH 2010)
	Flight time at rotor height (%)	33	
Wind farm	Rotor radius (m)	52	Values taken from RPS (2014)
	Max. blade chord (m)	3.8	
	RPM	13.8	
	Blade pitch (°)	10	
	Rotor depth (m)	0.66	Calculated as: sin(blade pitch) x max. blade chord
	Wind farm operation (%)	85	
	Area of forest containing turbines (km^2)	9.47	
	Number of turbines in forest	39	

3. RESULTS

3.1 Scenario collision risk modelling

Three separate components of mortality were calculated, for:

- Commuting flights in April and May for birds with nest territories in the centre of the wind farm (not in the forest);
- Commuting flights in April and May for birds with nest territories in the forest; and,
- Display flights in April and May for birds with nest territories in the forest.

Collision risk was estimated (Tables 6 and 7) using the flight characteristics in Tables 1 to 4 and the bird and wind farm parameters in Table 5.

Table 6. Commuting flight collision risk.

Commuting collision mortality	Central territory				Wind farm territory			
	Males		Females		Males		Females	
	April	May	April	May	April	May	April	May
Days present	30	31	30	31	30	31	30	31
Max no. turbines encountered per commuting flight [1]	2	2	2	2	1	1	1	1
No. commuting flights per day	6	6	12	12	6	6	12	12
No. commuting flights per month	180	186	360	372	180	186	360	372
Collision risk per flight (pre-avoidance) [2]	0.04	0.04	0.04	0.04	0.02	0.02	0.02	0.02
Collision risk per month (pre-avoidance)	6.36	6.57	12.71	13.14	3.18	3.28	6.36	6.57
Collision risk per month (incl. avoidance)	0.13	0.13	0.25	0.26	0.06	0.07	0.13	0.13
No. territories	3	3	3	3	9	9	9	9
Collisions all territories	0.38	0.39	0.76	0.79	0.57	0.59	1.14	1.18
Total collisions	2.33				3.49			

Notes:
1 – Estimated on basis of direct flights to/from the centre of a territory to a location outside the wind farm.
2 – Calculated as: Probability of collision x Max. number of turbines encountered x proportion of flight at rotor height x wind farm operation percentage.

Table 7. Display flight collision risk. Values calculated using the low, average and high levels of activity as detailed in Table 2.

Display collision mortality	Low activity Males April	Low activity Females April	Average activity Males April	Average activity Females April	High activity Males April	High activity Females April
Days present	30	30	30	30	30	30
Assumed territory size (km^2)	1.000	1.000	1.000	1.000	1.000	1.000
Estimated no. turbines per territory [1]	4.119	4.119	4.119	4.119	4.119	4.119
Rotor swept area per turbine (km^2)	0.008	0.008	0.008	0.008	0.008	0.008
Proportion of each territory which is rotor swept	0.035	0.035	0.035	0.035	0.035	0.035
Display flight activity per day (seconds)	3600	0	5400	600	9000	1800
Display flight activity per day at nesting territory (seconds) [3]	1200	0	1800	200	3000	600
Display flight activity per month (seconds)	36000	0	54000	6000	90000	18000
Display flight activity per month at rotor height (seconds)	11880	0	17820	1980	29700	5940
Display flight activity per month at rotor height in rotor swept area (seconds)	416	0	623	69	1039	208
Collision risk per month (pre-avoidance) [2]	24	0	36	4	60	12
Collision risk per month (incl. avoidance)	0.48	0.00	0.72	0.08	1.19	0.24
Number of territories	9	9	9	9	9	9
Collisions all territories	4.29	0.00	6.44	0.72	10.73	2.15
Total collisions	**4.29**		**7.15**		**12.87**	

Notes:
1 – calculated as all turbines (39) divided by forested area (9.47 km^2)
2 – flight time per month at rotor height in rotor swept area x probability of collision
3 – assumes 1/3 of display activity occurs at nesting territory

Table 8. Summary of annual collision estimates.

Component	Commuting	Display Low activity	Display Average activity	Display High activity
Male	1.94	4.29	6.44	10.73
Female	3.88	0.00	0.72	2.15
Total	5.82	4.29	7.15	12.87
Commuting and display combined		**10.11**	**12.97**	**18.69**

4. CONCLUSIONS

Following a review of greenshank breeding and flight ecology and behaviour we developed a theoretical basis for estimating flight times at risk for this species. The breeding ecology and flight parameters were then applied to a simplified version of the proposed Strathy South wind farm in order to develop a model for estimating the potential collision risk for this species.

There are several key results from the modelling. Females are predicted to spend twice as much time commuting as males, and hence females have twice the commuting collision risk of males. Conversely, males spend much more time in display flight than females and are thus up to nine times more at risk of display collisions than females. Depending on the level of display flight activity used (low, average, high), display collisions were estimated to represent between 42% and 69% of all collision risk (low and high respectively).

Several important assumptions were made in the modelling. Table 9 lists the assumptions, provides an assessment of the strength of evidence supporting the assumption, an estimate of the precision for parameters used in the modelling and the sensitivity of the collision estimates to that assumption or parameter.

Table 9. Assumptions, evidence base, precision and sensitivity. Collision sensitivity has been categorised as low, medium or high. Medium indicates a directly proportional sensitivity (doubling the parameter value doubles the collision risk), low and high indicate that change in the parameter values has a less than proportional or more than proportional (respectively) effect on collision risk.

Assumption	Parameter value	Strength of evidence	Parameter precision	Collision sensitivity
Nest spacing	1 km	Good, based on extensive literature, although variability around this mean value is less well documented	Low	Medium – changing the number of territories in the site affects the number of individuals at risk
Proportion of flights at rotor height	0.33	Weak	Low	Medium – has a directly proportional effect on mortality (0.66 generates twice the mortality).
Flight speed (display)	10 m s^{-1}	Moderate (likely to be similar to commuting speed but possibly slightly slower)	NA	Low – affects the probability of collision on individual rotor transit but relatively large change has small effect on mortality
Flight speed (commuting)	12.3 m s^{-1}	Good (peer reviewed publication based on good sample size)	NA	
Number of return commuting trips per day (male)	3	Moderate (based on extensive study of breeding birds but with studies focused more on females)	Moderate	Medium - has a directly proportional effect on mortality (doubling number of flights generates twice the mortality)
Number of return commuting	6	Good (based on extensive study of breeding birds)	High	Medium - has a directly proportional effect on mortality (doubling number

trips per day (female)				of flights generates twice the mortality)
Simplified territory distribution	NA	Moderate, based on recorded territory maps	NA	Low – each territory contributes small amount to overall mortality, unlikely to be very different from model.
Forestry only used for nesting not foraging	NA	Moderate based on observations reported in literature	NA	High – if display flights occur over forestry during June and July mortality will increase substantially
Feeding territories outside wind farm area	NA	Moderate since wind farm area is apparently not good quality habitat for foraging	NA	High – if flights associated with feeding territories occur in wind farm the collision mortality will increase substantially
Number of turbines encountered per commuting flight (central territories)	2	Moderate – turbine spacing indicates this is reasonable	NA	Low – varying turbine numbers within reasonable range has relatively small effect on overall mortality as small number of territories affected
Number of turbines encountered per commuting flight (forestry territories)	1	Moderate – turbine spacing indicates this is reasonable	NA	Medium – varying turbine numbers within reasonable range has moderate effect on overall mortality as this affects a higher number of territories than in the central region.
Avoidance rate	98%	Weak	NA	High – value chosen as suitable for survey based flight activity. Small change (e.g. to 99%) will halve mortality

Collision risk was assessed as being of high sensitivity to three aspects of the model. Two of these are closely linked (the use of the forestry areas for nesting territories only and foraging occurring only outside the wind farm area) and the third was the avoidance rate. Of these, habitat use was based on moderately strong evidence from the literature. The consequence of these assumptions is that adult birds are only considered to be at risk of commuting flight collisions in April and May, and only birds with territories in the forest (with overlap with turbines) are at risk of display flight collisions.

Mating territories are located near large water bodies, of which there are none within the area of turbines. Therefore flight activity associated with mating territories is not considered at risk. We do not have enough information about finer scale habitat use following commencement of nesting to know if areas within the wind farm itself are used for both nesting and feeding. However, given the feeding preferences for this species it seems unlikely that birds would feed within forested areas, therefore assuming these areas are used solely for nest territories is appropriate. The location of each pair's feeding territory, if not continuous with their nesting territory, is not known. However, on the basis of the above

assumption that feeding does not occur within the forest, it seems reasonable to assume that feeding territories are located around the forest or further away. As we cannot know which route birds will take whilst commuting we have assumed that birds will travel in a straight line from central locations to ones outside the wind farm. Each flight made in this manner will potentially pass different turbines. However, the turbine layout suggests that in most cases a flight from the central (moorland) region of the site which crosses the forest would encounter a maximum of two turbines, while flights originating from territories within the forest itself would encounter a maximum of one turbine. Collision risk has been calculated on the basis of the number of potential rotor transits which could occur on each commuting flight and the subsequent collision risk. Soon after the chicks hatch the adults lead them to their feeding territories, which are assumed to be outside the wind farm and therefore not liable to result in collision risk.

Birds with nesting territories outside the forest are not considered at risk of collisions whilst making display flights since these occur over their territory and therefore no turbines will be encountered. Birds with nest territories in the forest will be at risk of collisions during display flights (in April and May). This has been calculated on the basis of the amount of time spent undertaking display flights and the proportion of this activity which could occur within the rotor swept zone assuming all areas within the territories are used at the same rate.

The evidence for the avoidance rate, particularly in relation to its use with our theoretical model, is assessed as being weak, and this parameter has a potentially large effect on the estimated collision risk.

The avoidance rate used to calculate the collision estimate was 98%. This is the SNH recommended value for this species, however its intended use is with survey based estimates of flight activity. Vantage point survey data suffer from decreasing rates of detection with increasing distance from the observer to the bird. This is rarely if ever quantified and therefore the avoidance rate used includes allowance for under-recording flight activity. In the theoretical model developed here there is no requirement to account for detection rates since flight activity has been derived empirically. Thus, the 98% avoidance rate is almost certainly over-precautionary for use in the current model. Without knowing how flight activity would typically be unrecorded during a survey it is not possible to recommend an appropriate value for the current model, although it is straightforward to adjust the collision estimates summarised in Table 8 on the basis of potential values. For example if 50% of greenshank flight activity is unrecorded during typical flight activity surveys, the non-avoidance rate should be halved (from 2% to 1% giving an avoidance rate of 99%) and the collision estimates should also be halved.

Collision risk was assessed as being of medium sensitivity to several parameters and assumptions, however only one was estimated with less than a moderate degree of confidence: the proportion of flights at rotor height. As varying this value from the 0.33 used in the model has a directly proportional effect on the collision mortality estimate (e.g. doubling to 0.66 doubles the collision mortality) it is straightforward to adjust the figures produced for other values. Therefore we suggest that while the current value is appropriate on the basis of currently available evidence, the mortality values can be updated should more data become available on which to base the estimate.

All the remaining parameters were estimated with at least a moderate level of confidence and the collision estimates have no more than a low sensitivity to the values used.

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