APPENDIX A11.4

POPULATION MODELLING

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Appendix A11.4: Population Modelling

Introduction

Deterministic population models have been developed for red-throated diver, whimbrel, curlew, golden plover, dunlin, arctic skua and great skua. This appendix describes how the models were developed; the assumptions made and discusses the value and limitations of the models to inform the windfarm design and assessment processes. It is worth emphasising at the start that the model results do not accurately mimic the likely future trajectory of the populations. Building models that could do this was not possible due to the various limitations of the input parameters, together with a lack of understanding of density dependence and stochastic factors for the populations of interest. Rather, the models seek to inform by comparing different scenarios, and show how the numbers might change in a hypothetical population with no spare carrying capacity, no density dependence and no stochasticity. Of course the absence of all these, together with imperfect estimates of population parameters means that the models lack realism, but that does not mean they are not helpful or informative. They are useful as they allow the magnitude of predicted adverse effects to be visualised and seen in the context of existing circumstances, and allow for different scenarios to be easily compared. However, model results need to be interpreted with caution and should be used alongside other evidence in forming a judgement on the likely effects of the proposed windfarm.

The model outcomes are sensitive to the baseline conditions in terms of a population's rate of decline or increase and, if stable the extent of spare capacity (i.e. excess potential recruits) or density dependence. After discussion with SNH and RSPB it was agreed that deterministic models should be developed for baseline conditions where the production of young surviving to recruitment age exactly equals adult mortality, i.e. the baseline model population is exactly balanced (neither increasing nor declining) and has no spare capacity. Comparing windfarm scenarios that have any adverse effects whatsoever against a balanced baseline situation (no windfarm) with no spare capacity inevitably results in a negative change in the modelled population. In reaching a conclusion about the likely affects of the windfarm the results of the modelling (Figs 1-8) need to be considered alongside information on the actual status of the Shetland population and the likely extent of spare population capacity.

Basic model

The models although having many steps are in fact very simple in their basic workings. They consist of a series of years representing the life of the windfarm with the first year representing conditions before the windfarm is commenced. The modelling calculations start by supplying a seed breeding population size, representing the size of the regional breeding population at the start. In the first modelled year the seed animals produce a number of fledged young (number of breeding birds multiplied by baseline productivity rate) and (afterwards) are subject to natural mortality (no. breeding birds multiplied by baseline annual adult mortality rate). At the start of the following year (taken to be the start of the breeding season) the size of the new breeding population is calculated from the number of surviving established breeding birds from the previous year plus recruitment of new breeding birds. The number of new recruits is determined from the number of young produced in an earlier year multiplied by appropriate survival rates over the intervening period. In species that breed at 1-year old (i.e. the year after they were a chick) the recruits come from the previous year's productivity. However, most species have delayed maturity (i.e. they breed for the first time when two or more years old) and so there is a lag of up to several years between the year of production and the year of recruitment. This lag is set to equal the average age of first breeding for the species under consideration. These basic steps are repeated for successive years and give a time series of the population size.

The models were constructed using Excel. In all cases except whimbrel they consider the effect of the windfarm on the Shetland population. In the case of whimbrel they consider the effect on the UK population (though over 95% of the UK population breeds in Shetland).

Ringing studies of breeding waders show that they exhibit strong site fidelity. Typically, established breeders return to the same location each year and young birds breeding for the first time return to within a few kilometres of their hatching location. Site fidelity has been incorporated into the models for wader species and arctic skua by assuming that birds breeding in Central Mainland (where the windfarm is located) remain breeding there throughout their lives and that first-time breeders are recruited from young that hatched in Central Mainland (Table 1). This is was achieved by building two independent models for these species, one considered Central Mainland birds only and the other the rest of the population (Table 1), and summing the results to give the overall population size. This creates a weaker site fidelity affect than is expected to occur in reality and is therefore likely to be conservative. Incorporating site fidelity effectively spatially limits the effects of the windfarm to Central Mainland and thereby slightly reduces the overall effect on the wider population.

Incorporating the effects of the windfarm

The effects of the windfarm are included in a model by creating perturbations to the baseline conditions. Three types of perturbation were incorporated:

- Loss of production caused by disturbance;
- Loss of breeding pairs caused by displacement;
- Additional mortality caused by collisions with operating turbines.

Disturbance is included in the model as an effect that temporarily causes breeding birds to fail to produce young, but the birds themselves are not displaced. With the exception of some red-throated diver scenarios, this effect is assumed to be limited to the construction period (Table 1). Birds within a certain threshold distance of infrastructure are assumed to be affected but this varies between species (see Table 1). Again with the exception of divers, the affects on any one pair are assumed to be limited to a single year and overall the affects of disturbance are assumed to be spread equally across the construction period (Table 1).

Displacement is included in the model as a one-off affect occurring at the start of the windfarm operational stage. The magnitude of displacement varies between species (refer to species accounts in ES text). The value depends on the strength of displacement considered likely multiplied by the number of pairs that were found within a certain distance (again, this varies with species) of the proposed windfarm infrastructure during baseline surveys. Whether or not displacement affects the population size depends on whether displaced pairs are allowed to successfully resettle somewhere else or are effectively lost from the population. Both these scenarios were modelled though which is considered to be the more likely varies between species (see Table 1). If displaced birds are not allowed to resettle they are assumed to be completely lost from the population and, of course, have no production of young.

Collision mortality is included in the models only during years when turbines are operational. CRM estimates (Technical Appendix A11.3) the number of birds killed annually assuming baseline conditions prevail. Should the numbers of birds present on the windfarm change then there is expected to be a directly proportional change in the number of collisions each year. For this reason collision mortality in the model is inputted as a proportion of the population size rather than a constant. For example, if the Central Mainland population is 1000 birds and CRM estimates that two of these are predicted to be killed in a year, then collision mortality is included in the model as 0.2%. Collision mortality is assumed to be additional to natural mortality and to only affect breeding birds (with the exception of red-throated divers, where both immature and breeding birds are both assumed to be affected) (Table 1). Collision mortality is assumed to occur during the breeding season and therefore birds killed by collision are assumed to have no production that year. For several species (merlin, golden plover, curlew) this assumption is unlikely to be fully met as some flight activity was also recorded in the winter, a time when the birds present were unlikely to be of local origin i.e. migrants rather than Shetland breeders.

Input parameters

The basic model described above requires supplying values for several input parameters: initial population size, average age-of-first-breeding and annual rates for productivity, adult mortality, juvenile mortality and immature mortality. Unfortunately knowledge of these parameters is imperfect and in some cases almost completely unknown. Furthermore the parameters can vary with time (including stochastic effects) and interact with one another (e.g. density dependence). This therefore inevitably causes problems into how well the available information can be used to predict the size of likely population change for a given scenario.

The approach regarding what input parameter values to use was largely determined by what was available. The parameter values and other information used in models are presented in tabular form (Tables 2-9). Information on population size is generally relatively well known, though in some cases the information was not as up to date as ideal. Information on other parameters comes from detailed studies. Baseline survey work on the Viking study area over recent years has quantified annual productivity for red-throated divers and merlin only (refer to Technical Appendix A11.1). For other species values for mean productivity were taken from other studies including where necessary, those conducted away from Shetland. The national BTO ringing programme and individual population studies involving colour-ringed individuals provided information on survival rates. For most species there are reasonably good estimates of adult survival rates and the age-of-first-breeding. However, typical survival rates for immature cohorts and productivity for some species are generally poorly known. However, provided other parameters are known and it is assumed that the population is balanced (i.e. potential recruitment equals adult mortality) then these can be calculated by inference.

Presentation and interpretation of model results

In all cases the results presented are likely to be pessimistic because:

1. collision rate estimates are likely to be too high as a result of using an avoidance rate in CRM below the true value;
2. the effects of density dependence and spare capacity were not accounted for and these factors naturally tend to buffer a 'healthy' population towards a broadly stable situation.

Whether or not the predicted adverse effects of the windfarm will translate into real population changes of the magnitude indicated by the simple determinate models will depend on whether the average per annum 'decline' rate value can be absorbed by a population's natural tendency to over produce, i.e. its spare capacity. It would be naïve to suggest that this can be reduced down to a single average value (e.g. the spare capacity is 'x'% p.a.) as the situation is complicated by density dependence. However the concept of spare capacity is a useful one albeit one that is hard to quantify and precisely define. Some insight into roughly what the likely magnitude of any spare capacity must be can be gained from the rate at which bird populations typically increase when recovering from a set back (such as a hard winter). It is would be normal for recovering bird populations to show average annual increase rates of a few percent per annum and rates of up to 10% would not be unusual for more productive species. It is suggested that the magnitude of the average annual modelled rates of change should be viewed in this context. All species that show either long term stability or are known to have increasing populations are likely to have some spare capacity. In contrast, species which are in long term decline clearly do not have spare capacity (though density dependent process are still likely to operate) and therefore predicted adverse windfarm affects on these species are much more likely to translate into real detrimental effects on their population size. The only species of concern for which there is good evidence of long term (and ongoing) decline are whimbrel and arctic skua. For this reason these species are believed to be especially sensitive to any adverse effects from the windfarm, as these have the potential to exacerbate the existing situation.

The results are presented as time-series graphs for a number of modelled scenarios (Figs. 1-8). The graphs for each species are presented in a consistent way and in most cases show the same scenarios presented using the same colour scheme. In all cases the green line represents the no windfarm situation for a hypothetical balanced baseline population. This is a flat line in all cases (for the reasons described earlier, models were constructed using these baseline conditions for easy comparison). All other scenarios shown are based on the same baseline conditions perturbed by the assumed windfarm effects stated.

The three red lines indicate alternative models varying in how displacement is treated (an in the case of red-throated diver disturbance leading to reduced breeding success also). The red line and scenario label shown in bold is considered to be the most likely scenario for that species and is the one used in the ES assessment (though others are also discussed for some species). Of the three red lines the solid one indicates the scenario in which displaced birds are lost all together from the population. The dashed red line illustrates the scenario in which displaced birds are not lost but successfully settle outwith the windfarm; this is only considered likely for species where there is evidence of surplus habitat (e.g. whimbrel and skua species). The dotted red line shows the scenario where no displacement is assumed to occur. This is usually the ‘worst’ scenario because the penalty of no displacement is that flight activity in the near vicinity of turbines is assumed to be higher (twice as high), and (according to the deterministic model) the affects of the additional collisions over time more than offsets the benefit of fewer pairs displaced.

The solid blue line illustrates the same scenario as the solid red line but flight activity data for CRM collision rate estimates was not corrected for distance detection bias. The blue line is included to show what affect applying this correction has and to facilitate comparison with other windfarms where detection bias was not applied.

For the sake of clarity, the model results do not include consideration of benefits to the populations that will stem from the Viking Habitat Management Plan (Appendix A10.9).

Red-throated diver

The three scenarios illustrated in red in the results graph (Fig. 1) are very similar to one another. The difference in these scenarios concerns whether or not disturbance is assumed to occur to pairs nesting at the few breeding lochans <500 m from wind farm infrastructure. If this does occur it is estimated that this would affect 2.2 pairs on average per year (see ES text on operational disturbance) and could result in either reduced breeding performance (dashed red line) or displacement (dotted red line) in which case displaced birds are assumed to be lost from the population altogether. If birds are displaced there is assumed to be a corresponding reduction in overall flight activity across the windfarm (by 12%) and hence slightly reduced collision losses. The solid red line indicates the scenario for negligible disturbance to pairs nesting <500 m wind farm infrastructure, something that in practice could be facilitated by strategic screening of roads and turbines, although in many cases this is unlikely to be necessary.

The average annual decline rate for all of the red scenarios is ca. 0.25% p.a. It is highly likely that this can be comfortably absorbed by the population's spare capacity given that the species has a long term stable population size. Red-throated diver populations are able to grow surprisingly rapidly, as shown by the ca. 10% increase in Central Mainland between 2009 and 2010 and large increases in Western Scotland (Dillon *et al.,* 2009).

Merlin

Of all the species for which modelling was undertaken a simple deterministic model was perhaps least suited to the data on merlin due to the small number of individuals in the regional population. Apart from the biological unlikelihood that Shetland operates as an effectively closed population, basing a model on fractions of individuals killed by collision in a year where in reality events must involve whole individuals adds to the over-simplification. These concerns will tend to make the model results more sensitive to change and therefore probably more conservative. Notwithstanding these concerns, the model results indicate that the three red scenarios have the potential to cause a moderate decline in merlin numbers if not absorbed by spare capacity (Fig. 2). At most the decline would be in the order of 0.3 -0.5% p.a. but true rates are likely to be substantially lower due to the low avoidance rate used in CRM to estimate collision deaths and the likely existence of spare capacity in the population.

The alternative red scenarios differ in how the pair using Territory C (this is the only territory where recent nest site locations have been close (ca. 300 m) to a proposed turbine) respond to the wind farm. It is considered most likely that they will not be displaced from the territory but will nest further away from the turbine (there is suitable heather for this to occur). The reason why the scenario illustrating the situation for pair C birds continuing to nest in the same place (dotted red line) causes a greater population change than the other scenarios is that if the birds nest close to a turbine they are assumed to have a slightly elevated risk of collision (details in ES).

Golden plover

The most likely scenario for golden plover is considered to be that where displaced birds are lost from the population (solid red line) (Fig. 3). At worst this could result in a average decline rate of 0.34% p.a. However, the actual magnitude of the affect on the regional population is likely to be smaller because collision estimates are likely to be too high (due to low avoidance rate) and there is likely to be spare capacity. Furthermore, approximately a one third of the flight activity recorded for golden plover was outside the breeding season when migrant birds from other populations are likely to be present. This would mean that not all collision deaths of golden plover are from the Shetland breeding population.

Dunlin

The modelling results show that the magnitude of decline rate could occur as a result of windfarm effects is very low (ca. 0.04% p.a.) (Fig. 4). Furthermore the magnitude of the modelled decline rate is likely to be overestimated due to use of an implausibly low (98%) avoidance rate in the CRM to estimate collision deaths. The Shetland dunlin population is apparently stable and is therefore likely to have some spare capacity. It is likely that this is able to absorb the small adverse effects of the windfarm and mean that there will be no detectable effect on the population.

Whimbrel

The most likely scenario is considered to be that illustrated by the dashed red line, where displaced birds are allowed to resettle elsewhere, as there is likely to be ample surplus breeding habitat available (Fig. 5).

The magnitude of the adverse effect predicted by the windfarm is likely to be overestimated due to use of an implausibly low (98%) avoidance rate used in the CRM to estimate collision deaths.

However, this is a declining species and so there is unlikely to be any spare capacity to buffer adverse effects. Therefore, any adverse effects are likely to exacerbate the current unfavourable situation. The size of the modelled decline caused by the windfarm (likely to well below 0.23% p.a.) is very low in the context of the size of the existing long term decline rate of 2.5% p.a., a difference in excess of ten fold.

Curlew

The most likely scenario is considered to be that illustrated by the solid red line, in which displaced birds are lost from the population (Fig 6). The model estimated that the average rate of decline caused by windfarm effects for this scenario is 0.25% p.a. However, the actual change to the regional population caused by the windfarm is likely to be smaller because collision estimates are likely to be too high (due to use of a implausibly low avoidance rate in CRM) and, given the apparent stability of the population, the likely existence of some spare capacity.

There is uncertainty over the size of the Shetland curlew population, different surveys, some using different methods, estimating anything from 2300 to 3975 pairs (Pennington *et al.,* 2004). The figure of 2300 pairs was used in the population model. Doing so tends to make the magnitude of model changes conservative, i.e. larger.

Arctic skua

The modelling results show that the three red line scenarios are similar and so it is relatively unimportant to the conclusions how displacement is treated (Fig. 7). The most likely scenario is considered to be that illustrated by the dashed red line, where displaced birds are allowed to resettle elsewhere. Not only is there is likely to be ample surplus breeding habitat available but there is evidence from studies in Shetland that some birds change breeding site (Pennington *et al.,* 2004).

The magnitude of the adverse effect predicted by the windfarm is likely to be overestimated because of the use of an implausibly low avoidance rate used in CRM to estimate the number of collision deaths. However, this is a declining species and so there is unlikely to be any spare capacity to buffer adverse effects. Therefore, any adverse effects are likely to exacerbate the current unfavourable situation. The size of the modelled decline caused by the windfarm (likely to well below 0.08% p.a.) is negligible in the context of the pre-existing long term decline rate of around 5% p.a., a difference in excess of a sixty fold.

The models results illustrated are based on an annual adult survival rate of 80% (O'Donald 1983). However, since preparing the models evidence has come to light that adult survival rate is substantially greater at around 87.2% (Davis in prep, cited in Ratcliffe *et al.,* unpublished RSPB report). This would mean that the annual average young production required to achieve an exactly balanced population is 0.28 chicks per adult per annum. The models were rerun with these revised values for the survival and production parameters. This made only a very small difference to the results and does not alter the conclusions. For example, the average annual decline rate for the dashed red line changed from 0.081 to 0.085% p.a.

Great skua

The most likely scenario is considered to be that illustrated by the dashed red line, in which displaced birds are allowed to resettle elsewhere (Fig. 8). The average rate of decline caused by the windfarm effects for this scenario is estimated by the modelling at 0.05% p.a. However, the actual magnitude of the affect on the regional population is likely to be smaller because collision estimates are likely to be too high (due to low avoidance rate) and there is likely to be spare capacity. For all scenarios, the magnitude of the possible effect on the population caused by the windfarm is small in comparison to the average rate of 1.8% p.a. for population growth in recent decades.

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Table 1. Model assumptions for all wader species; arctic and great skua; red-throated diver and merlin.

Assumption/Species	**Details**	**Met or violated**
Adult site fidelity		
All species	Established adults return to same area for duration of their life (unless displaced by proximity of windfarm infrastructure)	Likely for vast majority of individuals.
Natal philopatry 1		
All wader species and arctic skua	All 1st-time breeders are recruited from Central Mainland production only.	Likely for vast majority of individuals. Good evidence of strong natal philopatry (e.g. Jackson, 1994).
Red-throated diver, merlin and great skua	All 1st-time breeders are recruited from Shetland population.	Met. Evidence for strong natal philopatry lacking for these species.
Natal philopatry 2		
All wader species and arctic skua	1st-time breeders settle randomly i.e. within Central Mainland vacant habitat within and outside windfarm is equally likely to be occupied.	Assumption likely to be conservative as close proximity to a turbine might deter settlement. i.e. less likely to settle close to turbines.
Red-throated diver, merlin and great skua	1st-time breeders settle randomly i.e. within Shetland, vacant habitat within and outside windfarm is equally likely to be occupied.	Assumption likely to be conservative as close proximity to a turbine might deter settlement. i.e. less likely to settle close to turbines.
Collision risk 1		

All wader and skua species	Only birds with territory centres within the median nearest-neighbour-distance (for that species) of a turbine are at risk.	Broadly likely given individuals of these species are likely to largely confine their activity to vicinity of their territory.
Red-throated diver	Risk to flying birds corresponds to the detailed assessment of spatial variation across the site (Appendix A11.1 Map C6a & b).	Likely based on detailed mapping of diver flight traffic over the site.
Merlin	Risk to flying birds is split between birds hunting away from their nests (assumed to be approximately uniform across site) and additional activity within 400 m of nest site.	Broadly likely.
Collision risk 2		
All species except red-throated diver	All collision deaths are breeding adults.	Likely that this is nearly so. No good evidence of non-breeding immatures being present on breeding habitat but there may be some. If so a few collisions might be of non-breeding immatures (especially for great skua), in which case the assumption tends towards being pre-cautionary.
Red-throated diver	Collisions deaths affect breeding adults and non-breeding immatures in proportion to the respective amount of flight activity estimated for each during baseline surveys.	Likely. Baseline surveys distinguished activity by the two groups enabling separate CRM estimates for breeding and non-breeding components of the population.
Collision risk 3		
All species	A collision death causes loss of breeding production by that individual that year. (Does not apply to non-breeding divers).	Likely that this is broadly so. Collisions during chick-rearing may not lead to loss of an individual's production. This is likely to be offset by collisions at egg stage that also cause loss of the year's

		production by a dead individual's mate.
Disturbance 1		
All wader and skua species except whimbrel	During construction phase, breeding performance of birds within 250 m of infrastructure reduced by 50% for 1 year.	Theory. Likely to be conservative
Red-throated diver, merlin and whimbrel	Unaffected by construction disturbance.	Measures undertaken under the Bird Protection Plan will prevent disturbance of breeding WCA Schedule 1 species
Displacement 1		
All wader and skua species	Some breeding birds with territory centres relatively close to turbines are displaced. Magnitude of effect varies with a species assumed assume 50% displacement within 200 m of roads and 100 m of tracks. Lapwing assume 25% displacement)	Likely to some extent though uncertainty regarding the effective distance and percentage of birds. Evidence in Pearce-Higgins *et al., J. Ap Ecol*., 2009, suggest marked displacement. Evidence from other studies of negligible displacement of golden plover and curlew (see ES text).
Red-throated diver	Up to 2.2 pairs p.a. displaced (see ES text for details)	Likely as windfarm layout avoids proximity of breeding sites.
Merlin	One pair (Territory C) at risk of displacement, but only in years when territory occupied.	Quite likely as recent nest sites in Terr C are within 400m of a proposed turbine.
Displacement 2		

All species except red-throated diver	Displacement of birds from close to turbines leads to a 50% reduction in at-risk flight activity and this causes a corresponding reduction in estimated collision mortality. (no reduction for divers as no evidence to support it).	Reduction in 'at risk' flight activity due to displacement is inevitable but the magnitude of reduction is uncertain Fig. 3a in Pearce-Higgins, 2009 provides some evidence that reduction in density close to turbines (say <150 m), where flying birds are at potential risk of collision, is much greater than the average reduction up to 500 m away. This suggests that the reduction in at-risk flight activity is also much greater; a 50% figure is likely to be conservative.
Displacement 3		
Whimbrel and arctic skua.	Displaced birds successfully settle elsewhere in Shetland as vacant habitat is apparently available.	Probably broadly met. Evidence of vacant habitat caused by recent declines in population. Alternative also modelled.
Red-throated diver, golden plover, curlew, dunlin, great skua, merlin.	Displaced birds do not successfully settle elsewhere in Shetland as all habitat likely to be occupied. They are therefore effectively lost from the population.	Probably broadly met. No evidence of widespread vacant habitat. Great skua possibly an exception to this as population has been increasing and colonising new areas over past decades. Alternative also modelled.

Table 2. Red-throated diver parameter values and other information used in population model

Parameters	Value	Source	Certainty	Comment
Age of first-breeding	5 years	David Okill pers. com.	High	
Mean productivity (chicks fledged per breeding pair)	0.732	6-year mean for Central Mainland (Viking baseline studies).	High	
1st year survival rate (fledging-1 year old)	Unknown (0.72)	0.72 is calculated value to exactly balance mortality. True value likely to be greater.	Moderate	
2nd , 3rd, 4th year survival rates (p.a.)	Unknown (c 0.86)	Assumed same as adult survival (informed guess).	Moderate	
Adult survival rate	c. 0.86	BTO (adult ringing recoveries).	High	
Pairs affected by construction disturbance (T127 layout)	0	Viking surveys (Appendix A11.1).	High.	Measures under BPP will be put in place to prevent disturbance.
Pairs assumed displaced by windfarm (T127 layout)	0	Viking surveys, (Appendix A11.1).	Moderate.	Windfarm designed not to cause disturbance of breeding divers.
Pairs, Central Mainland	45	Viking surveys, (Appendix A11.1).	High	Increasing.
Pairs, Shetland	407	2006 survey, Dillon *et al*. 2009, Smith *et al* 2009	High	

Shetland status	Stable, locally increasing	Dillon *et al.,* 2009 & Viking surveys. Gibbons *et al* 1997	High	Substantial non-breeding population. Recent increase in Central Mainland, at least.
Natural breeding adult deaths per year	Ca. 114	Based on survival rate above.	High	
Natural non-breeding bird deaths per year (ages 1,2,3,4 yrs)	Ca. 94	Based on survival rate above.	Moderate	
Collision deaths of breeding adults (Year 1, T127)	1.4	CRM prediction (from Tech. Appendix A11.3).	CRM prediction, likely to be too high as avoidance rate likely to exceed 98%.	Scenario = 98% avoidance, DDC applied. No displacement assumed.
Collision deaths of non-breeding birds (Year 1, T127)	2.8	CRM prediction (from Tech. Appendix A11.3).	CRM prediction, likely to be too high as avoidance rate likely to exceed 98%.	Scenario = 98% avoidance, DDC applied. No displacement assumed.

Table 3. Merlin parameter values and other information used in population model

Parameters	Value	Source	Certainty	Comment
Age of first-breeding	1	Lieske *et al.,* 1997.	High	
Mean productivity (chicks fledged per breeding pair)	0.725	Viking studies (5-year mean).	High	
1st year survival rate (fledging-1 year old)	0.483	Calculated value to exactly balance mortality.	Moderate	
Adult survival rate	0.65	Lieske *et al.,* 2000.	High	
Pairs affected by construction disturbance (T127 layout)	0	Viking surveys (Appendix A11.1).	High.	Measures under BPP will be put in place to prevent disturbance.
Pairs assumed displaced by windfarm (T127 layout)	Up to 1	Viking surveys (Appendix A11.1).	Moderate.	Windfarm designed not to minimise disturbance of breeding merlins. Only one pair within 500 m, and this not present in all years.
Pairs, Central Mainland	10	Viking surveys (Appendix A11.1).	High	Increasing slowly.
Pairs, Shetland	20	Pennington *et al.,* 2004, SBR 2008. Ellis & Okill 1990.	High	Likely to be an underestimate, as many areas not surveyed.
Shetland status	Recent recovery,	Pennington *et al,* 2004, NRP monitoring in Central Mainland, Ellis & Okill	High	Numbers on Mainland probably as high now as in the mid-1970s, no.s

	stable or increasing slowly	1990.		on smaller islands remain low.
Natural breeding adult deaths per year	Ca.14	Based on survival rate above.	High	
Collision deaths of breeding adults (Year 1, T127)	0.11	CRM prediction (from Tech. Appendix A11.3).	CRM prediction, likely to be too high as avoidance rate likely to exceed 98%.	Scenario = 98% avoidance, DDC applied, 50% reduction for displacement.

Table 4. Golden plover parameter values used in model

Parameters	Value	Source	Certainty	Comment
Age of first-breeding	1 year	Cramp and Simmons, 1983.	High	
Mean productivity (fledglings per pair)	Unknown (0.9)	0.464 is calculated value to exactly balance mortality.	Low	
1st Yr survival rate (fledging-1 yr)	Unknown (0.4)	informed guess.	Low	
Adult survival rate	0.82	Piersma, 2005;Pearce-Higgins and Yalden 2003, 88% survival but small sample size and only 2 years data.).	Moderate	
Pairs affected by construction disturbance (T127 layout)	29	Viking surveys (Appendix A11.1)	High	50% of pairs within 250 m all infrastructure (T127 layout).
Pairs assumed displaced by windfarm (T127 layout)	18	Viking surveys (Appendix A11.1).	High	50% displacement within 200 m of turbines and additional 25% displacement within 200-500 m of turbines and 100 m of tracks.
Pairs, Central Mainland	212	Viking surveys (Appendix A11.1).	High	
Pairs, Shetland	1450	Pennington *et al.,* 2004	Moderate	
Shetland Status	Apparently stable	BTO BBS surveys 2002 - 2008 (SBR 2008).	Moderate	

Natural adult deaths p.a.	522	Based on 0.82 survival rate.	Moderate	
Collision deaths (Year 1, T127 layout)	17.8	CRM prediction (Appendix A11.3).	CRM prediction, likely to be too high as avoidance rate likely to exceed 98%.	Scenario = 98% avoidance, DDC applied, 50% reduction for displacement

Table 5. Dunlin parameter values used in model

Parameters	Value	Source	Certainty	Comment
Age of first-breeding	2 years	Jackson 1988.	High	
Mean productivity (fledglings per pair)	Unknown (0.96)	0.96 is calculated value to exactly balance mortality.	Low	Productivity highly variable (Jackson 1988, Jackson and Green 2000).
1st Yr survival rate (fledging-1 yr)	Unknown (0.5)	informed guess.	Low	
2nd Yr survival rate (fledging-1 yr)	Unknown (0.81)	informed guess, same as adult survival.	Moderate	
Adult survival rate	0.81	Jackson, 1988.	High	
Pairs affected by construction disturbance (T127 layout)	17.5	Viking surveys.	High	50% of pairs within 250m all infrastructure (T127 layout).
Pairs assumed displaced by windfarm (T127 layout)	4.5	Viking surveys (Appendix A11.1).	High	50% displacement within 200m of turbines and additional 25% 100 m of tracks.
Pairs, Central Mainland	100	Viking surveys (Appendix A11.1).	Moderate	Difficult to survey accurately.
Pairs, Shetland	1700	Pennington *et al.,* 2004.	Moderate	Difficult to survey accurately.
Shetland Status	Apparently stable	BTO BBS surveys 2002 - 2008 (SBR 2008).	Moderate	
Natural adult deaths p.a.	646	Based on survival rate above.	High	

Collision deaths (Year 1, T127 layout)	1.1	CRM prediction (Appendix A11.3).	CRM prediction, likely to be too high as avoidance rate likely to exceed 98%.	Scenario = 98% avoidance, DDC applied, 50% reduction for displacement.

Table 6. Whimbrel parameter values and other information used in population model

Parameters	Value	Source	Certainty	Comment
Age of first-breeding	3 years	Grant, 1991.	High	
Mean productivity (fledglings per pair)	Unknown (0.62)	0.62 is calculated value to exactly balance mortality.	Low. True value likely to be lower as popltn. known to be declining.	
1st Yr survival rate (fledging-1 yr)	Unknown (0.50)	informed guess.	Low	
2nd & 3rd Yr survival rates	Unknown (0.88)	informed guess, same as adult survival.	Moderate	
Adult survival rate	0.88	Grant, 1991 estimated 0.89, but true value likely to be lower given short study period and recent declines.	Moderate	
Pairs affected by construction disturbance (T127 layout)	0	Viking surveys (Appendix A11.1).	High. Measures under BPP will be put in place to prevent disturbance.	Mean of 2.7 pairs within 250m all infrastructure, T127 layout.

Pairs assumed displaced by windfarm (T127 layout)	5.5 (mean)	Viking surveys, 5 year mean (Appendix A11.1).	Moderate	50% displacement within 200m of turbines and additional 25% displacement within 200-500 m of turbines and 100 m of tracks.
Pairs, Central Mainland	56	2009 survey.	High	
Pairs, Shetland	Ca. 290	2009 survey.	High, but additional work in 2010 indicates numbers may be a little greater.	
Status, Shetland	Declining, (locally stable)	Several surveys. Rate of decline averages ca -2% p.a. over past two decades.	High, but additional work in 2010 indicates that mean rate of decline numbers may be a little less.	Central Mainland numbers have shown only a small decline compared to other sub-regions.
Pairs, UK	Ca. 300	2009 survey	High, but see above.	
Natural adult deaths p.a.	Ca. 72	Based on survival rate above	High	
Collision deaths (Year 1, T127)	2.3 birds/yr	CRM prediction (Appendix A11.3)	CRM prediction, likely to be too High as avoidance rate likely to exceed 98%.	Scenario = 98% avoidance, DDC applied, 50% reduction for displacement.

Table 7. Curlew parameter values used in model

Parameters	Value	Source	Certainty	Comment
Age of first-breeding	2 years	Cramp and Simmons, 1983	High	
Mean productivity (fledglings per pair)	Unknown (0.706)	0.706 is calculated value to exactly balance mortality. Field study estimates vary greatly but are mostly <0.5 fledglings /pr suggesting 0.706 is too high (which means survival rates too low). (Berg 1992, Grant *et al.,* 1999, Grant 2002, Jensen and Lutz 2007.).	Low	
1st Yr survival rate (fledging-1 yr)	Unknown (0.5)	0.5 is informed guess (BWP suggests 36 – 47% but likely to be biased low).	Low	
2nd & 3rd Yr survival rates	Unknown (0.85)	Informed guess, same as adult survival	Moderate	
Adult survival rate	0.85	0.85 is the approximate mean of several estimates. Estimates range from 0.82 to 0.88 (Berg, 1994; Ylimaunu *et al.,* 1987; Evans, 1991).	Moderate	
Pairs affected by construction disturbance (T127 layout)	61	Viking surveys (Appendix A11.1).	High	50% of pairs within 250 m all infrastructure (T127 layout)
Pairs assumed displaced by windfarm (T127	37.5	Viking surveys (Appendix A11.1).	High	50% displacement within 200 m and 100 m of tracks.

layout)				
Pairs, Central Mainland	456	Viking surveys (Appendix A11.1).	High	
Pairs, Shetland	2300	Several surveys, but estimates vary. (Pennington *et al*).	Moderate	
Shetland Status	Apparently stable	BTO BBS surveys 2002 - 2008 (SBR 2008).	Moderate	
Natural adult deaths p.a.	690	Based on 0.85 survival rate.	High	
Collision deaths (Year 1, T127 layout)	8.5	CRM prediction (Appendix A11.3).	CRM prediction, likely to be too high as avoidance rate likely to exceed 98%.	Scenario = 98% avoidance, DDC applied, 50% reduction for displacement.

Table 8. Arctic skua parameter values used in model

Parameters	Value	Source	Certainty	Comment
Age of first-breeding	4 years	O'Donald 1983.	High	
Mean productivity (fledglings per pair)	Unknown (1.14) *Alternative (0.55)*	1.14 is calculated value to exactly balance mortality. *(*Ratcliffe *et al.,* unpub., estimate*)*	Moderate	1.14 is likely to be higher than the true average value in recent years. Actual rate is highly variable year to year (Ratcliffe *et al* unpub.).
1st yr survival rate (fledging-1 yr)	0.69	O'Donald, 1983 (0.68); Furness, 1987 (0.70).	High	
2nd & 3rd Yr survival rates	Unknown (0.8) *Alternative (0.872)*	informed guess, same as adult survival. (Davis in prep cited in Ratcliffe *et al.,* unpub.).	Moderate	
Adult survival rate	0.80 *Alternative (0.872)*	O'Donald 1983. (Davis in prep cited in Ratcliffe *et al., 2009*).	Moderate	
Pairs affected by construction disturbance (T127 layout)	6.5	Viking surveys (Appendix A11.1).	High	50% of pairs within 250 m all infrastructure (T127 layout).
Pairs assumed displaced by windfarm (T127 layout)	3.4	Viking surveys (Appendix A11.1)	High	50% displacement within 200 m of turbines and 100 m of

				tracks.
Pairs, Central Mainland	50	Viking surveys (Appendix A11.1).	High	
Pairs, Shetland	ca. 600	Mitchell *et al.,* 2004, Ratcliffe *et al.,* unpub.	Moderate	
Shetland Status	Declining rapidly	Mitchell *et al.,* 2004, Ratcliffe *et al.,* unpub.	High	Rate of decline has averages ca. 5% p.a. over past 25 years.
Natural adult deaths p.a.	240 *Alternative (154)*	Based on 0.80 survival rate. *Based on 0.872 survival rate.*	Moderate	
Collision deaths (Year 1, T127 layout)	1.9	CRM prediction (Appendix A11.3).	CRM prediction, likely to be too high as avoidance rate likely to exceed 98%.	Scenario = 98% avoidance, DDC applied, 50% reduction for displacement.

Table 9. Great skua parameter values used in model.

Parameters	**Value**	**Source**	**Certainty**	**Comment**
Age of first-breeding	7 years	Ratcliffe *et al.*, 1998.	High	
Mean productivity (fledglings per pair)	Unknown (0.55)	0.55 is calculated value to exactly balance mortality.	Low	Values from field studies are Highly variable (Votier *et al.,* 2007).
1st Yr survival rate (fledging-1 yr)	Unknown (0.8)	Balmer & Peach, 1997.	Moderate	
2nd to 6th Yr survival rates	Unknown (0.89)	informed guess, same as adult survival.	Moderate	
Adult survival rate	0.89	Ratcliffe *et al.,* 2002.	High	
Pairs affected by construction disturbance (T127 layout)	15.5	Viking surveys (Appendix A11.1).	High	50% of pairs within 250m all infrastructure (T127 layout).
Pairs assumed displaced by windfarm (T127 layout)	13.3	Viking surveys (Appendix A11.1).	High	50% displacement within 200 m of turbines and 100 m of tracks.
Pairs, Central Mainland	104	Viking surveys (Appendix A11.1).	High	
Pairs, Shetland	6874	Seabird 2000 survey.	High	

Shetland Status	Increasing	Several surveys. Rate of increase averages ca. 1.8% p.a. over past two decades.	Moderate	Possibly now stabilised.
Natural adult deaths p.a.	1512	Based on survival rate above.	High	
Collision deaths (Year 1, T127 layout)	24.9	CRM prediction (Appendix A11.3).	CRM prediction, likely to be too high as avoidance rate likely to exceed 98%.	Scenario = 98% avoidance, DDC applied, 50% reduction for displacement.

Fig. 1. Results of deterministic population models for red-throated diver.

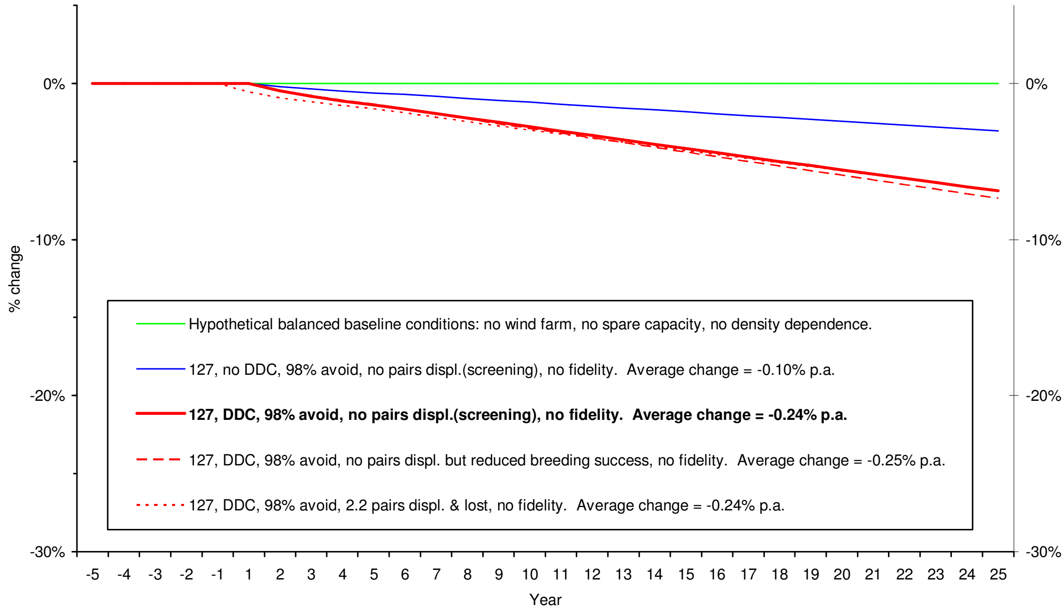

Fig. 2. Results of deterministic population models for merlin.

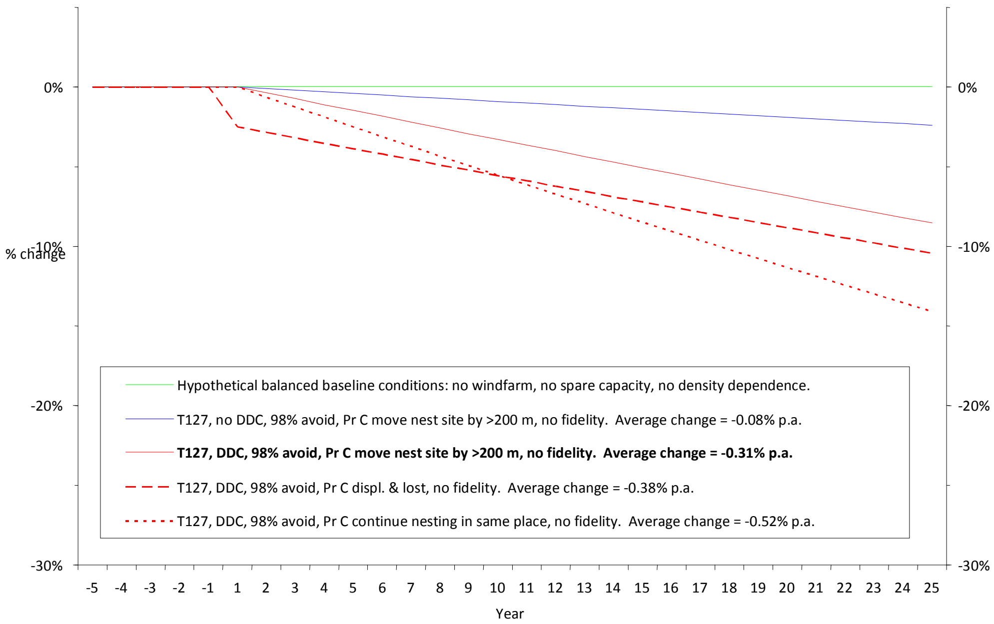

Fig. 3. Results of deterministic population models for golden plover.

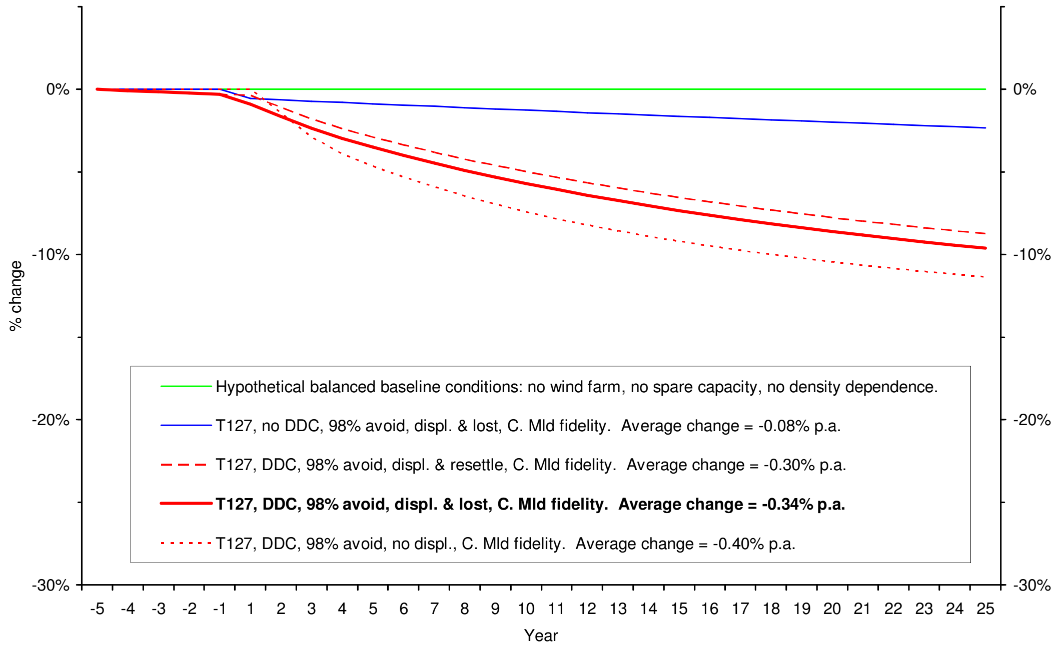

Fig. 4. Results of deterministic population models for dunlin.

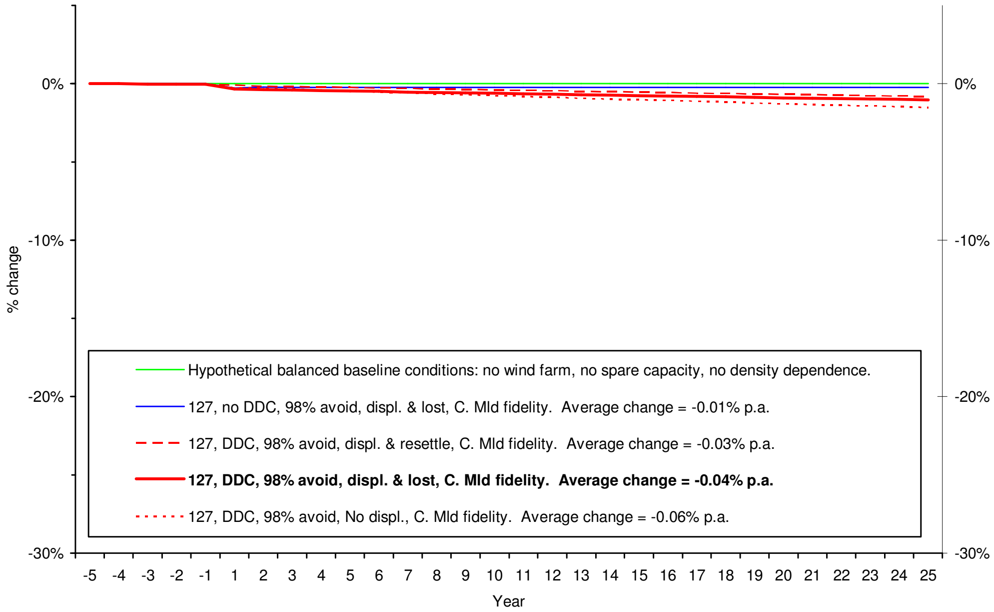

Fig. 5. Results of deterministic population models for whimbrel.

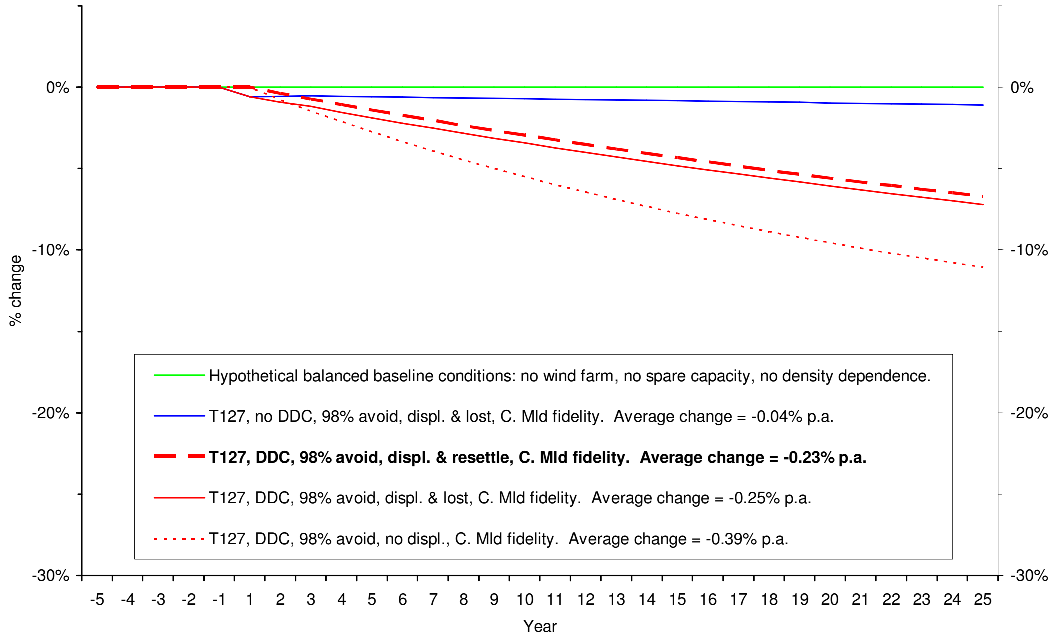

Fig. 6. Results of deterministic population models for curlew.

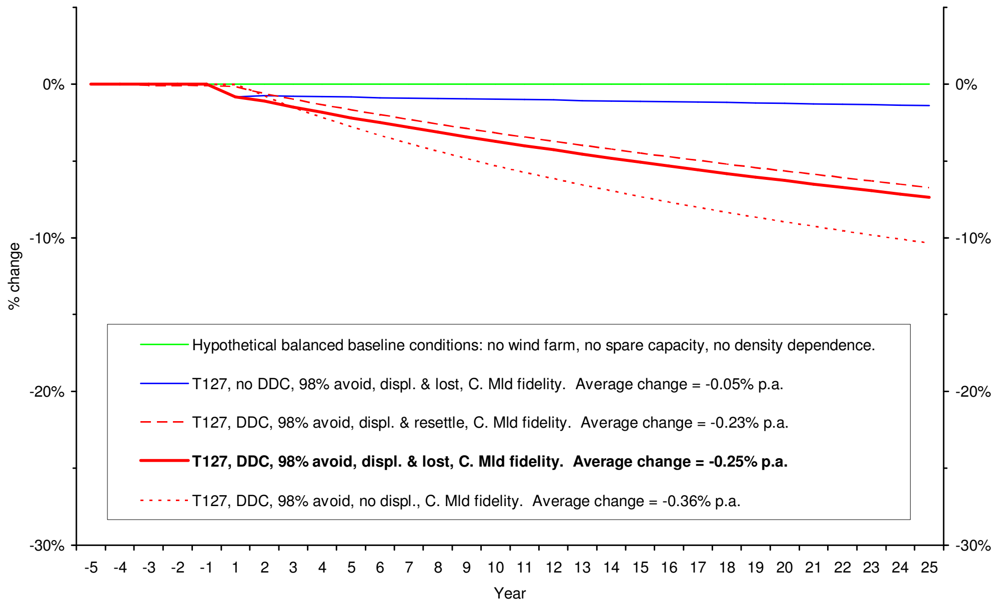

Fig. 7. Results of deterministic population models for arctic skua.

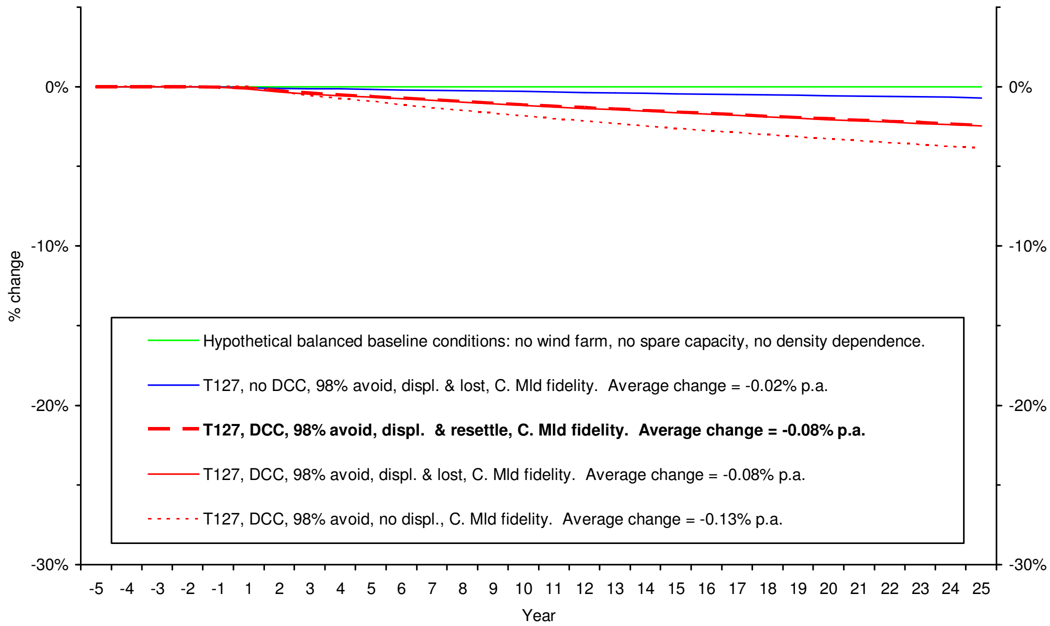

Fig. 8. Results of deterministic population models for great skua.