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Natural England Commissioned Report

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Natural England's role is to help protect and restore our natural world, and to balance nature recovery with the needs of people. Natural England's actions under the Hen Harrier Action Plan included a trial of brood management, which aimed to understand the effects of this management method on Hen Harrier populations and human-wildlife conflict. Following this trial, Natural England commissioned the British Trust to Ornithology to carry out population modelling to explore changes to Hen Harrier demography. This evidence will be used to inform future decisions on conservation actions.

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Executive summary

1. The Hen Harrier *Circus cyaneus* population in England has historically been suppressed by high levels of nest destruction and removal (killing) associated with grouse moor management. The population has undergone a sudden and rapid increase since 2018, concurrent with a trial of a new management approach. The reasons for this increase are uncertain.

2. This study uses a population modelling approach to explore the effects of changes in rates of productivity, survival, and settlement on population growth in the English population of Hen Harriers. Model outcomes are compared to the observed population trend to assess the plausibility of a range of candidate mechanisms to explain the population increase, including productivity uplift from nest-level interventions such as brood management and diversionary feeding, increased survival, and increased settlement rate. For the purpose of this study, ‘settlement’ effectively represents the rate at which breeding-age birds commence recorded breeding attempts, and therefore encompasses the potential for change both in the rate at which birds skip breeding entirely, and the rate at which breeding attempts fail prior to detection by surveyors (i.e. very soon after initiation).

3. Models were parameterised using several sources of evidence. Scenarios for productivity change were evidenced using nest record data for all recorded Hen Harrier breeding attempts in England during the period 2018 to 2024, including those at which interventions had and had not been applied. Scenarios for survival change were based on a recent study of Hen Harrier survival in Britain (Ewing *et al*. 2023). A lack of knowledge about settlement patterns both before and during the study period meant that scenarios for settlement change were harder to determine, and therefore largely exploratory.

4. Population models do not support productivity uplift from the nest-level interventions, brood management and diversionary feeding, as the sole explanation for the rapid increase in the population. Indeed, the direct effects of these interventions on population growth were relatively limited compared to the effects of change in survival or settlement rates.

5. Instead, the most parsimonious explanations for the population increase require improvements in one or both of survival rate and settlement rate. It is possible, but not likely, that survival change alone can explain the observed population growth. It is evident that some illegal killing has continued throughout the trial period; the question of whether it has reduced to some extent, and survival rates accordingly improved, cannot be addressed through a population modelling approach, but survival analysis for individuals tracked during the trial period may shed light on this.

6. It is plausible that increased settlement rates, perhaps linked to reduced disturbance immediately before and during the early part of the breeding season, could have contributed to the observed population increase. However, this possibility still requires some improvement in survival rates, as well as the pre-existence of a pool of non-breeding birds and/or supplementation by subadult breeding or immigration, to explain the sudden and rapid increase in the number of Hen Harrier breeding attempts in England. Within the context of this study, the modelled effect of increased settlement rates could also correspond to a real-world increase in the proportion of breeding attempts that persist for sufficiently long to be detected by surveyors, as opposed to failing soon after initiation (whether due to human interference or otherwise) and going undetected.

7. Either of these rates could have responded positively to environmental drivers (e.g. increased prey availability), a reduction in removal and/or nest interference by humans coincident with the availability of brood management as a tool to alleviate conflict between Hen Harriers and grouse moor management, or both, to plausibly result in the observed rapid population increase. However, equivalent increases have not occurred in the neighbouring populations of Wales or southern Scotland, making large-scale environmental drivers an unlikely explanation.

8. A substantial decline in the total number of breeding attempts between 2023 and 2024 highlights that adverse conditions (whether natural or linked to persecution) still have the capacity to slow or reverse the ongoing recovery of the Hen Harrier population in England.

1. Introduction

The Hen Harrier *Circus cyaneus* has been a species of significant conservation concern in the United Kingdom for several decades. Populations have been suppressed by illegal activities, including killing of adult and immature birds and interference with nesting attempts (Etheridge *et al.* 1997). Evidence strongly suggests that persecution continues to the present day (Murgatroyd *et al.* 2019, Ewing *et al.* 2023, RSPB 2023, 2024), with confirmed cases of active nest destruction and shooting of adult birds reported in the 2022–2023 period covered by the two most recent Birdcrime reports (RSPB 2023, 2024). Illegal persecution has strong spatial linkages with land managed for the purpose of grouse shooting (Murgatroyd *et al.* 2019, Ewing *et al.* 2023) and is almost certainly motivated by a desire to reduce actual or perceived predation upon Red Grouse *Lagopus scotica* (Newton 2021), as well as perceived disruption to the predictability of the response of Red Grouse to 'beaters' during driven shooting (Raptor Persecution UK 2023). Hen Harriers do not predate exclusively, or even predominantly, on Red Grouse, although nidifugous chicks (including those of Red Grouse) do form a component of the diet during the breeding season (Redpath *et al.* 2001, Ludwig *et al.* 2018, Nota *et al.* 2019). However, Hen Harrier territories are strongly associated with the habitat types produced by grouse moor management (Redpath *et al.* 1998, Caravaggi *et al.* 2019), creating a conflict between Hen Harrier conservation and grouse moor management.

As a result of this, the contemporary population density of Hen Harriers is extremely low. The English population reached a historic low of just two breeding pairs detected during surveys in 2013, and four in 2016 respectively (Smith & NERF 2016, Wotton *et al.* 2018). This is orders of magnitude lower than an estimated national carrying capacity of 323–340 pairs in England (Fielding *et al.* 2011). Attempts to reduce persecution of Hen Harriers in order to permit the recovery of the English population have been ongoing for many years (Fielding *et al.* 2011) but, until recently, have not resulted in any noteworthy population increase (Wotton *et al.* 2018).

In this context, alternative approaches have been considered that instead aim to reduce the incentive for persecuting Hen Harriers by allowing predation pressure upon Red Grouse to be alleviated legally (Redpath *et al.* 2010). Two of these have been used in England during recent years. The first, diversionary feeding, aims to provide alternative sources of food to breeding Hen Harriers so that they do not need to predate Red Grouse chicks. Evidence for the efficacy of this approach is mixed: whilst Hen Harriers readily take supplementary food and this does result in reduced predation of Red Grouse (Ludwig *et al.* 2018), this has not yet been proven to increase densities of Red Grouse (New *et al.* 2012), limiting its appeal to grouse moor managers (Thompson *et al.* 2009).

The second, brood management, aims to reduce local densities of breeding Hen Harriers by permitting the removal (under licence) of eggs and chicks where multiple nests are present within a small area, exceeding a density of 0.025 nests per km^2 (Elston *et al.* 2014, DEFRA 2016). Removed offspring are reared in captivity and released back into the wild. The project protocols indicate that these birds must be released in the same general area as their natal nest, and that birds taken from nests within Special Protection Areas (SPAs) with breeding Hen Harriers listed as a feature should be released back into the same SPA that they were taken from. Brood management is intended to reduce the numbers of Red Grouse taken by parent Hen Harriers provisioning their broods. This approach is controversial (St John *et al.* 2019) but, in England, has been implemented on a trial basis over a seven-year period (2018–2024), during which the managers of grouse-shooting estates with breeding Hen Harriers have been able to apply for licences to carry out brood management under certain conditions. The trial was envisaged as running for 5–10 years (Holmes 2023), with licences issued by Natural England (NE) initially to cover the period 2018–2022, followed by a review, then a further licence covering 2023–2024. Over the duration of the trial, 15 broods consisting of 59 chicks were collected under licence, and 58 chicks subsequently released, across the five years 2019–2023 (Holmes 2023, Natural England 2023). No nests were brood-managed in either 2018 or 2024 (Bird-Halton 2024).

Set within this context, the number of breeding attempts by Hen Harriers recorded in England has increased almost four-fold during the trial period for brood management, from 14 attempts in 2018 to a peak of 54 attempts in 2023, before decreasing to 34 in 2024 (Natural England 2023). Because 'population size' for the English Hen Harrier population has been measured as the number of observed breeding attempts, it is a function of the total number of breeding-age birds in the population, the proportion of those birds that commence a breeding attempt, and the proportion of those breeding attempts that are detected by surveyors. Despite extensive field survey effort (Kelly *et al*. 2025), it is not possible to conclude that all breeding attempts have been detected in England during the study period, because some attempts that failed at an early stage could have escaped detection (for example, if the breeding attempt commenced and then failed between consecutive survey visits). However, it is likely to represent almost all successful breeding attempts, and an unknown proportion of failures. Additionally, some breeders try again after an initial failed breeding attempt; for example, the 54 breeding attempts recorded in 2023 were considered to have been made by only 50 breeding pairs (Kelly *et al*. 2025). Therefore, the true number of breeding pairs (a more widely-used measure of population size) is likely to be correlated with, but slightly lower than, the reported metric of number of breeding attempts in some years.

Some stakeholders have framed this increase in the number of breeding attempts during the trial period as evidence that brood management is succeeding in its objectives (e.g. Moorland Association 2023), whilst others highlight that illegal persecution has continued during the trial and the reasons for the population increase are unknown (Bjorck 2023). Therefore, there is a need for evidence to understand the drivers of the increase in the English Hen Harrier population. There are several possible mechanisms that could account for a rapid increase in the number of recorded breeding attempts. Each of these mechanisms could arise wholly or in part because of the brood management trial, but they could also operate independently from this. Each mechanism assumes that a particular demographic factor (or factors) is (or has previously been) limiting to Hen Harrier population growth, but none of the mechanisms is exclusive from the others.

The first mechanism is an increase in Hen Harrier productivity. Hand-rearing chicks in captivity could improve their chance of fledging, thus increasing the total number of chicks fledged by the population in each year; this is the conceptual framework underpinning the deployment of headstarting as a conservation tool for threatened populations of some bird species, especially waders (e.g. Loktionov *et al*. 2023, Donaldson *et al*. 2024). Likewise, whilst diversionary feeding is intended to improve the productivity of prey species (Kubasiewicz *et al*. 2016), it is practically similar to supplementary feeding of the relevant predators, which has been demonstrated to increase productivity in a number of raptor species (González *et al*. 2006, Gal *et al*. 2019, McKinnon *et al*. 2024).

Additionally, the availability of diversionary feeding and/or brood management as tools to reduce predation of Red Grouse could reduce the incentive for disturbing or destroying ongoing breeding attempts, leading to an improvement in nest survival rates. Similarly, increased observer effort within Hen Harrier breeding areas in England during the trial period could act as a disincentive for disturbance or destruction of nests in circumstances where breeding attempts might otherwise have been subject to interference. Alternatively, Hen Harrier productivity might have increased during the trial period for unconnected reasons, e.g. if prey availability had been higher (Amar *et al*. 2003), predation rates of Hen Harrier nests lower (Baines & Richardson 2013), or climatic conditions more favourable (Redpath *et al*. 2002a) than in previous years.

The second mechanism is an increase in Hen Harrier survival. The availability of diversionary feeding and/or brood management could reduce the incentive for illegal killing of Hen Harriers both within and outside the breeding season, leading to an increase in the number of adult birds in the population, and in particular an increase in the rate at which immature birds (i.e. juveniles, aged up to one year old, and subadults, aged between one and two years), whose survival is most severely impacted by persecution (Ewing *et al*. 2023), recruit into the breeding population. Alternatively, Hen Harrier survival might have increased during the trial period because of lower natural mortality due to starvation (likely during winter, and therefore unconnected to the availability of diversionary feeding), predation, or inclement weather (Ewing *et al*. 2023) than in previous years.

The third mechanism is an increase in Hen Harrier settlement, or the number of breeding-age birds present in England that initiate recorded breeding attempts. As above, this is a function of the total number of breeding-age birds present in the population, and the proportion of those birds that are known to commence a breeding attempt. It is possible that there are an unknown (potentially large, and potentially changing) number of breeding-age birds present that do not make a breeding attempt in any given year, leading to their exclusion from the estimated population size. If a greater number of these birds commenced breeding attempts over the course of the trial period, this could lead to the observed increase. There are, in turn, several ways in which these scenarios of settlement change could arise.

One is that the pool of breeding-age birds has swelled, including through immigration from other neighbouring populations, including the much larger Scottish population, the Welsh population which is similar in size as of 2023 (Kelly *et al.* 2025), but was much larger at the start of the trial period, and other populations further afield (e.g. Ireland, France). Hen Harriers often breed in close proximity to one another, possibly because while male territories tend to be evenly spaced they can contain multiple active nests, since polygyny can be frequent where there is a female-biased sex ratio (Balfour & Cadbury 1979), and only a proportion of birds in the current British populations are colour-marked and/or tagged (e.g. 34% of adults that were part of a recorded breeding attempt in England in 2024 were individually identifiable), so it is challenging to assess whether there are significant numbers of breeding-age birds present in England that do not ultimately make a breeding attempt, or to quantify the levels of migration between sub-populations within the UK.

Another scenario is that the proportion of breeding-age birds that commence a breeding attempt has increased. Skipping (where annual breeding is facultative, and individual adults may forgo breeding attempts in a given year) has been observed in both male and female Hen Harriers, and can occur at very high rates where food, or nesting opportunities, are limiting. In one population (Orkney), there were breeding attempts made in just 43–51% of territories occupied by breeding-age females between 1998 and 2000 (Amar *et al.* 2003). Indeed, skipping is a potential explanation for the observed decrease from 54 breeding attempts in 2023 to 34 breeding attempts in 2024: at least 32% of females that attempted breeding in 2023 did not make an attempt in 2024 (even without accounting for recruitment of juveniles and subadults). Given that the average survival rate for adult female Hen Harriers in the UK is reported to be 80% (Ewing *et al.* 2023), it is possible that many of these 2023 breeders were still alive in 2024 but skipped breeding. However, 2023 also saw a much higher incidence of reported Hen Harrier persecution events than most previous years (RSPB 2024). It is worth noting that skip rates can also be extremely low, or even zero, in populations where food does not appear to be limiting (Amar *et al.* 2003).

Skipping is relatively well understood in other long-lived species, such as seabirds (e.g. Aebischer & Wanless 1992, Chastel 1995, Nur & Sydeman 1999, Reed *et al.* 2015, Leith *et al.* 2022), and to some extent in waterfowl (Coulson 1984, Reed *et al.* 2004) and raptors (Redpath *et al.* 2002b, Amar *et al.* 2003, Solonen 2005, Karell *et al.* 2009, Passarotto *et al.* 2023). Typically, skipping of breeding is a response either to poor winter/spring weather conditions, which might result in poor adult condition (Reed *et al.* 2004, 2015), or to low food availability in the pre-breeding period (Karell *et al.* 2009). It may also be contributed to by individual-specific constraints (Leith *et al.* 2022), and this has been observed in Hen Harriers (Redpath *et al.* 2002b). An additional factor to consider is that subadult breeding (i.e. breeding attempts made by birds during their second calendar year) is facultatively available to Hen Harriers. The majority of Hen Harriers are assumed to commence breeding at two years old (Picozzi 1984a, Snow & Perrins 1997, Irwin *et al.* 2008), but high frequencies of subadult females commencing breeding at one year old have been reported in Scotland and Wales (Etheridge *et al.* 1997, Whitfield & Fielding 2009). Similar to skipping, subadult breeding in females has been shown to be affected by prey availability, and can fall to almost zero under unfavourable conditions, at least in closely-related species including the congeneric Montagu's *Circus pygargus* (Salamolard *et al.* 2000) and Northern Harriers *Circus hudsonius* (Hamerstrom *et al.* 1985, Simmons *et al.* 1986). Thus, it can be considered that all birds aged one year and older are capable of breeding, but among these, skipping is the rule for subadults, which tend to breed only in favourable conditions (and at low population densities), but is also observed in adults, particularly when conditions are poor.

To our knowledge, there is no documented case in the literature of birds skipping breeding in response to disturbance from human activities, whether direct or indirect. However, human disturbance can directly influence bird breeding distributions at local scales (Haworth & Thompson 1990, Virzi 2010), as well as affecting other metrics of breeding performance, including among birds of prey (Martínez-Abraín *et al.* 2010). It is, therefore, plausible that disturbance could also trigger skipping in a species like Hen Harrier that is prone to disturbance and is known to use skipping as a life-history strategy. It follows that Hen Harrier breeding attempts could historically have been deliberately suppressed in some areas through either direct (targeted at birds) or indirect activities (e.g. large-scale land management activities, such as muirburn (Wilson *et al.* 2022)). Hen Harriers are listed on Schedule 1 of the Wildlife and Countryside Act 1981, and as such it is illegal to intentionally disturb them once they have commenced nest-building, while they have an active nest. Harassment of Hen Harriers at any time of year was explicitly banned in Scotland in 2013 (Scottish Natural Heritage 2014) in response to suspicions that disturbance outside the active nesting period was indeed occurring, but to date no equivalent legislation has been brought forward in England. If disturbance during the pre-breeding phase to prevent settlement (by triggering skipping in adults and/or discouraging subadult breeding) has indeed been historically occurring, the availability of brood management could reduce the incentive for such activities. Alternatively, settlement rates might have increased during the trial period for unconnected reasons, e.g. higher prey availability than in previous years.

This study uses population modelling to project likely trends in the English Hen Harrier population under a range of scenarios with varying productivity, survival, and settlement rates, in order to evaluate the likelihood of each of these mechanisms having contributed to the observed increase in breeding attempts from 14 in 2018 to 54 in 2023. A Population Viability Analysis (PVA)-type approach is used. PVA is a general term for demographic predictive models that forecast the robustness of a population to scenarios of impact compared to an unimpacted baseline (Keedwell 2004, Beissinger *et al.* 2006). We use an established PVA modelling framework (Searle *et al.* 2019) to model scenarios forwards from the 2018 population estimate of 14 breeding pairs, and compare modelled 95% confidence intervals to the observed population increase to assess the plausibility of this increase being driven by impacts on productivity, survival, and settlement respectively.

METHODS

Modelling framework and environment

Natural England has developed a PVA modelling framework (NEPVA; Searle *et al.* 2019) as a front-end, interactive web application user interface allowing users to set up, apply and run their own PVA models, within the parameters of that framework, without the need for access to specific software. Although this application was developed within the context of modelling mortality of seabirds as a consequence of collisions with offshore wind turbines, the modelling tool can be used to assess any type of impact that changes the survival or productivity rates of any avian species (Searle *et al.* 2019). In other words, the generic nature of the tool is such that it can be applied to other groups of birds. The NEPVA tool is available to other users under an Open Government Licence. BTO staff have developed the capacity to use the underpinning tools for the NE web application within the R programming environment (R Core Team 2024) as part of several previous studies (Macgregor *et al.* 2022, Hereward *et al.* 2024). For this study, all analyses were conducted in R v4.4.1 (R Core Team 2024), using the NEPVA R package v4.18 (Searle *et al.* 2019).

Within the NEPVA tool, models are parameterised using a range of (preferably evidence-based) demographic metrics. Some of these are supplied to models as single, fixed population-level values: specifically, maximum brood size and age at first breeding. The remainder are supplied as population means, with an associated variance that represents the amount that the population mean varies between years: productivity (into which we incorporated the effect of skip rate), and survival rates for breeding-age birds (adults) and each age class of juveniles/subadults.

Using the NEPVA tool imposes certain constraints on model setup and parameterisation that are relevant to this study. First, models fitted using the tool always assume a closed population (i.e. no emigration or immigration). This is unlikely to be strictly the case for the English population of Hen Harriers, due to its proximity to the southern Scottish population in particular, but also the possibility of exchange with Welsh, Irish, Manx, and even continental European populations. If more birds immigrate than emigrate in a typical year, models could underestimate the rate of population growth, provided immigrating birds are able to recruit into the English breeding population. Second, the tool does not allow for the specification of multiple age classes of breeding birds (e.g. subadult and adult breeders), but treats all breeding birds as full adults (and vice versa: all adults are treated as breeding birds). A related third constraint is that age at first breeding is treated within models as a fixed value: in species where age at first breeding varies among individuals, this may be a reasonable proxy if it is symmetrically distributed about the mean age, but not if it follows another pattern. The steps taken to explore the consequences of these constraints to model setup are detailed below.

Design of scenarios to model

In order to evaluate the potential contributions of variable productivity, survival and settlement rates (including adult skipping and subadult breeding) to the observed rapid increase in the English Hen Harrier population, we designed a series of scenarios for PVA modelling that individually adjusted the respective variables. The full set of modelled scenarios is described in Table 1.

To assess the potential impact of productivity change, we parameterised models using productivity rates that represented: (i) the observed population during the brood management trial, incorporating known deployment rates of both diversionary feeding and brood management; (ii) a population comprised entirely of nests with no brood management or diversionary feeding; (iii) a population with diversionary feeding deployed at the same rate as during the brood management trial period, but with no brood management; and (iv) a population with brood management deployed at the same rate as during the trial period, but with no diversionary feeding (Table 1, models a–d). These models explicitly consider the possible direct effects of diversionary feeding and brood management on productivity of observed breeding attempts (in other words, the number of additional chicks fledged from intervened nests, compared to if all observed nests had proceeded naturally).

To assess the potential impact of changes in survival, we parameterised models using survival rates that represented: (i) the observed recent survival of satellite-tagged British Hen Harriers during a study period that partially overlapped with the brood management trial in England (Ewing *et al*. 2023); and (ii) the survival of the same population, if it were not subjected to illegal killing (assuming causes of death act additively), as estimated by Ewing *et al*. (2023). In most models, we parameterised all survival rates (juvenile, subadult and adult) according to the same persecution scenario (Table 1, models e–h). However, we additionally explored the possible impacts of age-class-specific persecution by modelling all possible combinations of un-persecuted and persecuted survival rates across the three age classes (Table 1, models i–n).

To assess the potential impact of settlement change (incorporating change in pre-detection nest failure rates), we parameterised models using a wide range of hypothetical skip rates, with an assumption that the age at first breeding is two years (i.e. all adults, and no subadults, breed). There is evidence that skip rates in Hen Harrier can vary widely between populations and between years, but there is no evidence as to what annual skip rates have been within the English population during the brood management trial period. The purpose of this exercise was to understand the range of variation in population growth rates that could arise within the Hen Harrier population if average skip rates were to change, including potentially through reduced pre-breeding disturbance (Table 1, models o–x).

In addition to the scenarios considered in models a–d, it is also possible that population-level productivity could change because of a change in the failure rate of breeding attempts during their very early stages, prior to detection in surveyors. Although, in reality, this would affect productivity (because it influences the average success of all commenced breeding attempts as a whole), within the framework of our modelled scenarios it is much more closely aligned with settlement change. Settlement, here, refers to the rate at which individuals initiate breeding attempts, but breeding attempts are not included in the productivity dataset until the point at which they have been detected by surveyors. Therefore, settlement within our models could actually be considered to represent the initiation of breeding attempts and their subsequent progress until the point of detection. Consequently, models o–x also encompass scenarios where a proportion of breeding attempts fail prior to detection, such that the defined skip rates in each model actually represent the percentage of birds that do not make a recorded breeding attempt.

To explore whether an unusually high level of subadult individuals breeding could help to explain the observed population growth, we also parameterised a model in which age at first breeding was set to one year. It is important to note that this model (when constructed within the NEPVA modelling framework) has two main assumptions that are likely to be violated in reality. First, that 100% of individual females commence breeding as subadults, whereas the highest observed rates of subadult female breeding in established populations of Hen Harriers are around 70% (Etheridge *et al*. 1997, Whitfield & Fielding 2009). It was not possible within the NEPVA modelling framework to specify age-class-specific skip rates to account for this. Second, that the subadult survival rate is equal to adult survival rate, because a single survival rate is supplied for all breeding-age birds. This is not the case currently because subadult birds are more vulnerable to illegal killing (Ewing *et al*. 2023), but might be the case if no illegal killing were to take place. Again, it was not possible within the NEPVA modelling framework to specify different breeding age classes with different survival rates, as the models consider all breeding-age birds to be a single age class. Therefore, we only constructed this model in combination with the ‘no illegal killing’ survival scenario (Table 1, model y), since this scenario does assume subadult and adult survival are equal.

We designed scenarios that apply productivity, survival, and settlement rate change individually, and in some cases in combination, to explore the range of possible resulting population growth trajectories.

Demographic metrics

As above, it was necessary to numerically define productivity (numer of young fledged per breeding pair), maximum brood size, age at first breeding, survival rates for breeding-age birds (adults) and each age class of juveniles, and skip rate. For most parameters, the multi-annual mean and the standard deviation of interannual variation (i.e. the mean and standard deviation of annual mean values) were required for modelling. The exceptions to this were maximum brood size, which is a fixed value in models, and age at first breeding, which is treated during modelling as a fixed value, but effectively represents a population mean, accepting that some individuals may commence breeding earlier or later in their lives than the average.

For this study, parameters relating to productivity were estimated from a dataset of all known Hen Harrier breeding attempts in England during the brood management trial period 2018–2024. Data were mainly collected by NE, RSPB, Northern England Raptor Forum and other local Raptor Study Groups (Kelly *et al.* 2025). As discussed above, this is likely to represent a complete census of all successful breeding attempts made in England during this time period, supplemented by a number of failed breeding attempts. It is especially likely that breeding attempts that failed very early (e.g. within two weeks of commencement) went undetected. Every nest attempt was recorded as either successful or not, along with the number of fledged offspring (zero for unsuccessful attempts). Wherever possible, the clutch size and number of chicks hatched were also recorded. Fields in the dataset indicated which nest attempts were subject to diversionary feeding and brood management. The identities of both parent birds were recorded where possible; even for unmarked individuals, ages of parents were recorded if known.

Maximum brood size

This parameter imposes a fixed upper bound on productivity variability during PVA modelling. The maximum value for clutch size (seven eggs) in the nest record dataset (i.e. the largest number of eggs in any single breeding attempt) was taken as the maximum brood size.

Productivity

Annual productivity rate is simulated from a beta distribution parameterised with a specified mean and standard deviation, bounded by zero and the maximum brood size. Annual means of productivity were directly calculated from the entire nest record dataset (effectively representing the status quo situation, including application of both diversionary feeding and brood management at current levels), and also separately for the subsets of nests that received no intervention, diversionary feeding, and brood management. These annual means represent the average number of chicks fledged per nest attempt that was initiated and subsequently detected by surveyors. The mean and standard deviation of these annual means were calculated for the full dataset and the subset of non-intervened nests, to yield a multiannual mean and interannual standard deviation (s.d.) for the ‘current’ and ‘no intervention’ productivity scenarios. For the two scenarios where only one of the two interventions was applied, we simulated interannual variation in productivity by sampling 54 nest attempts (the number of nests recorded in the peak year of 2023), with replacement, from the nest record dataset, taking nest records from the non-intervened and intervened subsets in proportion with the average annual rate at which each intervention had been applied during the trial period. In this manner we calculated the mean productivity of 10,000 replicate simulated years for each intervention type, and then took the mean and s.d. of these ‘annual’ means to yield an estimate of the multi-year parameters.

It is important to note that the productivity estimates calculated by this method are very likely to be higher than the true population productivity rate, because breeding attempts that were not detected by surveyors are not factored into this calculation of productivity rates. Given the high levels of geographical coverage (including all suitable habitat within both the known range and other probably suitable areas with no recent known breeding attempts) of survey efforts (Kelly *et al.* 2025), undetected breeding attempts are far more likely to have been failures than successes (i.e. attempts in monitored areas that commenced and then failed between consecutive survey visits, as opposed to attempts that went undetected because the area was unmonitored).

Survival

Annual survival rate is simulated from a beta distribution with a specified mean and standard deviation, bounded by zero and one, separately for breeding-age (adult) birds and for each age class of immature birds (juveniles and subadults). Mean annual survival rates were drawn from a recent study of 148 satellite-tagged individuals in Britain (Ewing *et al*. 2023), which provides estimates for juvenile (from fledging to one year old) and subadult (from one to two years old) males and females, and adult females (two years and older), using a recurrent time window of 1 June to 31 May for the boundaries between age classes. In addition to survival rates for all birds, this study also provided estimated survival rates for juvenile and subadult males and females in the absence of any illegal killing, which were qualitatively similar to observed survival rates in the Orkney population that was thought to be unpersecuted at the time of study (Picozzi 1984b). Since population modelling deals with the number of breeding pairs, and in polygynous Hen Harriers this is limited by the number of females, not by the number of males, we exclusively used the estimated survival rates for females throughout this analysis. We assumed that the survival rate for adult females in the absence of illegal killing would be equal to that of subadult females.

Following a similar approach to that applied for productivity, we simulated interannual variation in survival to estimate the variation between years in population-level rates. For this purpose, we required an estimate of female population size per age class to use as a sample size, which we made for the 2023 breeding season (in which 54 nest attempts had been made), assuming productivity across the 54 breeding attempts was in line with the rate in an average year, and assuming an equal sex ratio at fledging (Picozzi 1984b). Thus, we estimated that there were probably around 54 adult females in the population (assuming one adult female per breeding attempt), and 68 juvenile females, of which 21 would survive to become subadult females with illegal killing, or 41 without. The true number of individuals in 2023 may be slightly lower, given that at least some of the 54 breeding attempts were made by subadult females, and a small number of females made two attempts. Alternatively, if there were unrecorded non-breeding individuals present in the population, then the true number may have been higher. Applying these estimates as sample sizes, we estimated the proportion of individuals surviving for one year from a binomial distribution with probability equal to the relevant survival rate, repeating this 10,000 times for each of the six survival rates (three age classes, with and without illegal killing). We calculated the standard deviation of each set of 10,000 estimates to yield estimates of interannual variability in survival rates.

Skip rate

We considered that the habitat and land management contexts of the English population are most likely to be similar that of the Langholm population, in which skipping was never observed and all occupied territories resulted in an active breeding attempt. Therefore, across the majority of models where we were not directly exploring the effects of settlement, we set skip rates to zero. However, to explicitly explore whether an increase in settlement rates in a population that did have occurrences of skipping could explain the observed sudden growth of the English population (in the absence of productivity or survival change), we parameterised a set of models (o–x, Table 1) with skip rates of 5, 10, 15, 20, 40 and 80% respectively.

For practical reasons, skip rate was incorporated into productivity estimation rather than modelled as an independent parameter. Therefore, we again used a simulation approach to estimate interannual variation in population-level productivity rates incorporating specified rates of skipping. As above, we simulated interannual variation in productivity by sampling 54 nest attempts, with replacement, from the nest record dataset; however, we then set the productivity of a given percentage of these nest records, i.e. the proportion assumed to skip breeding, to zero before calculating the sample mean. As before, we then took the mean and s.d. of 10,000 such 'annual' means to yield an estimate of the multiannual mean and interannual s.d. of productivity, factoring in skipping.

Age at first breeding

This parameter determines the number of years for which a young bird must survive before it enters the pool of breeding birds. It interacts with survival, by determining the number of age classes for which survival rates are considered. For the majority of models, this parameter was set to two, with juvenile and subadult survival rates specified in addition to those for adults.

To explore whether an unusually high level of subadult breeding could explain the observed sudden growth of the English population, we also constructed a model in which age at first breeding was set to one. As above, we only constructed this model in combination with the 'no illegal killing' survival scenario, since this scenario assumes subadult and adult survival are equal.

Density-dependence

It was agreed to construct models without density-dependence, because the Hen Harrier population in England is currently recovering from a historic low and almost certainly well below carrying capacity (Fielding *et al.* 2011). Indeed, it is more likely that density dependence is acting positively (c.f. Ferrer & Penteriani 2008) than negatively under the current situation, by increasing opportunities for male polygyny in areas with relatively high densities of females present (Balfour & Cadbury 1979), but it was considered that there was too little evidence to incorporate this possibility into modelling. It is likely that density-dependent suppression of demographic rates will begin to apply to the Hen Harrier population at some point in the future, if it continues to grow. However, this is unlikely to have influenced the recent observed population trend, which is the subject of this study.

Modelling approach

The most recent version of the NEPVA R package (v4.18) was downloaded into a local directory on 19 August 2024 (from https://github.com/naturalengland/Seabird_PVA_Tool); in order to provide maximum reproducibility, this version of the package has been archived alongside the R scripts used for analysis in the BTO's institutional Github repository.

A range of options are available within the NEPVA package to conduct PVAs in different ways. For the purposes of this study, the following options were agreed upon. We used the function 'nepva.simplescenarios()' to run PVA models. Environmental stochasticity was applied (by setting model.envstoch = 'betagamma') in order to allow both survival and productivity rates to vary with a beta distribution; productivity was constrained by maximum brood size (model.prodmax = TRUE). Demographic stochasticity was also applied (model.demostoch = TRUE), allowing the number of birds surviving (of each age class) and the proportion of chicks fledging to be simulated from a binomial distribution. As above, models were constructed without density dependence (model.dd = 'nodd'). An option to include a number of 'burn-in' years to allow age structure within the model to settle was used where possible. Initial trials suggested that a value of two burn-in years was sufficient for age structure to stabilise. However, because the initial population size was very small, in some models the population could go extinct during burn-in, preventing models from being run; in these instances, the number of burn-in years was set to zero and eliminated in order to allow models to run. Each model was run for 10,000 simulations (sim.n = 10000), with a different specified seed set to enable reproducibility.

Demographic parameters were set as appropriate using the arguments 'mbs' (maximum brood size), 'afb' (age at first breeding), 'demobase.prod' (productivity), 'demobase.survadult' and 'demobase.survimmat' (survival of adults and juveniles/subadults respectively). The skip rate argument 'demobase.bskippc' is not implemented for nepva.simplescenarios() so we incorporated skipping into population productivity rates, as described above.

All models were fitted with an initial population size of 14 breeding pairs (which in polygynous Hen Harriers effectively equates to the number of breeding females), the number of observed breeding attempts during the first year of the brood management trial period, 2018. Models were run forward from 2018 until 2035. We ran a separate iteration of the NEPVA function for each scenario, so we did not employ the impacts modelling functionality of the tool; all arguments relating to this were set to arbitrary values in order to allow the function to run, and the resulting outputs discarded. Model outputs were also expressed as the number of breeding pairs.

Using the appropriate rates for productivity, survival, and other parameters (as defined above), we designed a set of 25 models to test the effect of changes in productivity, survival and settlement rates on projected population growth during (and beyond) the trial period (Table 1).

Table 1: full list of modelled scenarios. In column 3, 'DF' signifies diversionary feeding and 'BM' signifies brood management.

Model set	Model label	Productivity scenario	Survival scenario
Productivity	a	DF + BM applied (current situation)	Current survival (all age classes)
	b	DF only applied	Current survival (all age classes)
	c	BM only applied	Current survival (all age classes)
	d	No interventions applied	Current survival (all age classes)
Survival	e	DF + BM applied (current situation)	No persecution (all age classes)
	f	DF only applied	No persecution (all age classes)
	g	BM only applied	No persecution (all age classes)
	h	No interventions applied	No persecution (all age classes)
	i	DF + BM applied (current situation)	Current survival (2nd year and adult) + no persecution (1st year)
	j	DF + BM applied (current situation)	Current survival (1st year and adult) + no persecution (2nd year)
	k	DF + BM applied (current situation)	Current survival (1st year and 2nd year) + no persecution (adult)
	l	DF + BM applied (current situation)	Current survival (adult) + no persecution (1st year and 2nd year)
	m	DF + BM applied (current situation)	Current survival (2nd year) + no persecution (1st year and adult)
	n	DF + BM applied (current situation)	Current survival (1st year) + no persecution (2nd year and adult)
Skipping breeding	o	DF + BM applied + 5% per year skip rate	Current survival (all age classes)
	p	DF + BM applied + 10% per year skip rate	Current survival (all age classes)
	q	DF + BM applied + 15% per year skip rate	Current survival (all age classes)
	r	DF + BM applied + 20% per year skip rate	Current survival (all age classes)

	s	DF + BM applied + 5% per year skip rate	No persecution (all age classes)
	t	DF + BM applied + 10% per year skip rate	No persecution (all age classes)
	u	DF + BM applied + 15% per year skip rate	No persecution (all age classes)
	v	DF + BM applied + 20% per year skip rate	No persecution (all age classes)
	w	DF + BM applied + 40% per year skip rate	No persecution (all age classes)
	x	DF + BM applied + 80% per year skip rate	No persecution (all age classes)
Subadult breeding	y	DF + BM applied + age at first breeding = 1	No persecution (all age classes)

Results

Demographic metrics

Summary of nest record dataset
In total, the supplied dataset contained details of 221 breeding attempts made by Hen Harriers in England during the trial period 2018-2024. In total, 158 of these breeding attempts were successful (71.5%), fledging 1-6 chicks per nest.

Productivity
Across all monitored nests during the seven years of the brood management trial, including those nests subject to diversionary feeding or brood management, 71.5% of nests were successful (i.e. fledged at least one chick). Annual success rates varied between 64–79%. The mean annual productivity across all monitored nests was 2.57 ± s.d. 0.20 (range 2.35–2.93).

Excluding nests that received interventions, 67.2% of nests were successful. Annual success rates varied between 62–75%. The mean annual productivity of nests that proceeded naturally was 2.37 ± 0.21 (range 2.10–2.62).

Thirty-two nests received diversionary feeding, including at least one nest in every year of the trial period. A mean of 13% of nests received diversionary feeding in each year (range 7–20%). Of these nests, 81% were successful, and on average, nests receiving diversionary feeding fledged 2.78 ± 1.84 chicks per nest attempt (range 0–5). We simulated that a population receiving diversionary feeding at 12.6% of nests per year, but not brood management, would have a mean annual productivity of 2.42 ± 0.26.

Fifteen nests received brood management. Nests received brood management in only five out of the seven years of the trial period. A mean of 6% of nests received brood management in each year (range 0–11%). All brood-managed nests were successful, i.e. resulted in the release of at least one chick. On average, nests receiving brood management fledged 3.93 ± 1.39 chicks per nest attempt (range 1–6). We simulated that a population receiving brood management at 6% of nests per year, but not diversionary feeding, would have a mean annual productivity of 2.46 ± 0.26.

Survival
Annual survival rates (for all combinations of sex and age class except adult males) are reported by Ewing *et al.* (2023), which we used to simulate the interannual variation in survival rates for each modelling scenario (Table 2).

Table 2: annual female survival rates from Ewing *et al.* (2023). For each rate, the standard deviation of variation in annual survival rate was estimated through simulation. Ewing *et al.* did not provide a specific estimate of adult female survival rate in the absence of illegal killing, but we presumed it would not be lower than the equivalent subadult rate.

Scenario	Sex	Age	Annual survival rate	95% CI (from Ewing *et al.* 2023)	N birds in study (N yearly survival periods)	Sample size for simulation	Estimated s.d. of annual variation in survival rate
Current situation	Female	Juvenile	0.303	0.218–0.423	83 (83)	68	0.06
		Subadult	0.579	0.395–0.850	19 (19)	21	0.11
		Adult	0.800	0.621–1.000	7 (16)	54	0.05
No illegal killing	Female	Juvenile	0.600	–	–	68	0.06
		Subadult	0.900	–	–	41	0.05
		Adult	(0.900)	–	–	54	0.04

Skip rate

We simulate population-level mean annual productivity incorporating a range of mean annual skip rates for use in modelling (Table 3). Simulated annual skip rates varied widely, and a skip rate of 37% (drawn from the observed decrease from 54 nest attempts in 2023 to 34 in 2024) fell within the ranges simulated by scenarios with mean annual skip rates of 20 and 40% respectively.

Table 3: simulated population-level productivity given specified hypothetical skip rates.

Simulated mean annual skip rate (%)	Range of simulated annual skip rates (%)	Mean ± s.d. of annual productivity, incorporating skipping
5	0.0–20.4	2.41 ± 0.26
10	0.0–25.9	2.29 ± 0.27
15	0.0–35.2	2.16 ± 0.27
20	1.9–42.6	2.03 ± 0.27
40	16.7–66.7	1.53 ± 0.26
80	57.4–98.2	0.51 ± 0.18

Outputs of population modelling

Scenarios of productivity change

Under the baseline scenario (model a, see Table 1), designed to reflect the presumed situation during the brood management trial period based on the best available evidence for productivity and survival rates, the English Hen Harrier population was projected to grow very slightly in the median estimate, but with the 95% confidence interval indicating a decline (of up to 33% by 2024) was possible (Figure 1a). This same pattern held for both scenarios in which only one intervention was applied (b: diversionary feeding only; c: brood management only), while the scenario where neither intervention was applied (model d) forecast stability in the median estimate (Figure 1d). In all four scenarios, the observed population trend falls outside the modelled upper confidence limit in all years from 2020 onwards. Differences between scenarios in terms of projected population by 2023 are negligible (Figure 2a–d).

Scenarios of survival change

Under all four scenarios that modelled a complete cessation of illegal killing, with or without productivity-focussed interventions (models e–h), the population was projected to grow rapidly and exponentially (Figure 1e–h), matching the observed population trend up until 2023 but exceeding it in 2024 (Figure 2e–h).

Projected population growth was considerably lower in all scenarios that modelled age class-specific changes in survival (models i–n) than in the equivalent model where illegal killing of all age classes ceased (model e; Figure 3). Population growth was lowest when persecution of both juveniles and subadults continued (model k), and highest when persecution of adults only continued (model l). Persecution of juveniles alone (model i) had a larger impact on population growth than persecution of either subadults or adults alone (models j and k respectively). Of these models, only models l and m (persecution of adults only and of subadults only, respectively) produced a population estimate for 2023 that was consistent with the observed number of breeding attempts in that year (Figure 4).

Scenarios of settlement change

Across all scenarios, population growth rates decreased as skip rates increased. With current survival rates (models o–r), even a 10% skip rate (model p) was sufficient for decline to be more likely than growth (Figure 5). With no illegal killing (models s–x), an 80% skip rate (model x) was sufficient for decline to be possible, but still less likely than growth. The effect of changes in skip rate between 5 and 20% on projected population size by 2023 was negligible, although a modelled skip rate of 80% with no illegal killing (model x) produced a similar projected population size by 2023 to the models with much lower skip rates but current survival rates (models o). The models with no illegal killing and skip rates between 5–20% (models s–v) were compatible with the observed population in 2023, whilst the model with no illegal killing and a skip rate of 40% (model w) was compatible with the observed population in 2024.

The model in which all subadult females bred, with no illegal killing (model y), projected the fastest population growth of any in this study, and was the only model where the observed population growth was slower than the modelled 95% confidence interval for the full period 2018–2024 (Figure 7).

Figure 1: projected population growth under model scenarios for productivity and survival change. Models a–d project population rates under different productivity scenarios with current survival rates, and models e–h project the same productivity scenarios, but with survival rates adjusted to eliminate the effect of illegal killing (see Table 1 for full details of each model). In all panels, the observed population trend during the brood management trial period is shown in blue with a dotted line. The median and 95% confidence interval of modelled outcomes are shown in black, running forward to the year 2035 or until the modelled population exceeds the current observed population.

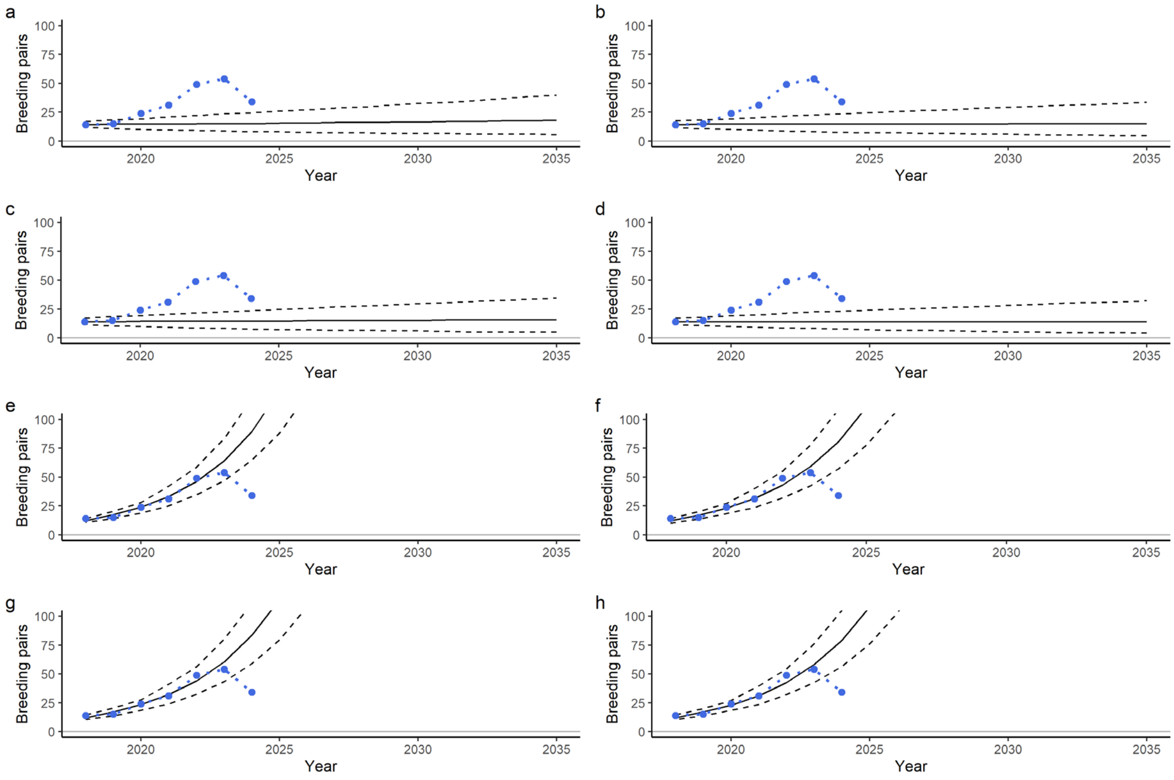


Figure 2: projected population size in 2023–2024 under model scenarios for productivity and survival change. Model scenarios are the same as depicted in Figure 1 (see Table 1 for full details of each model). Points and lines show the median and 95% confidence interval for the projected population in 2023 (orange) and 2024 (blue) respectively. Dashed lines show the observed population in the same years (depicted using the same colours to facilitate comparison).

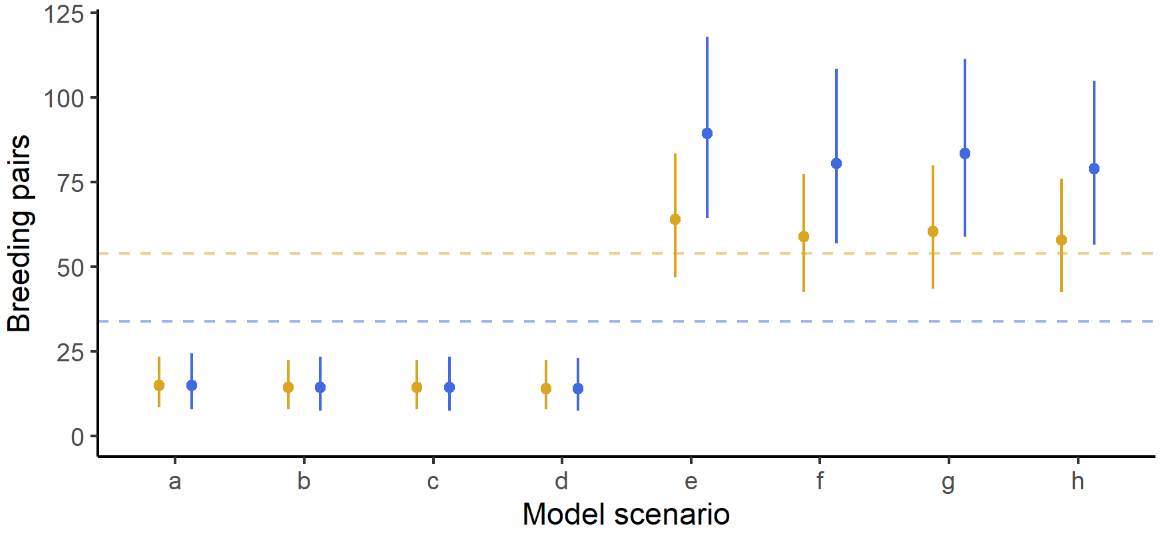


Figure 3: projected population growth under model scenarios for age class-specific survival change. Models i–n project population rates under different combinations of current and adjusted survival rates (see Table 1 for full details of each model). In all panels, the observed population trend during the brood management trial period is shown in blue with a dotted line. The median and 95% confidence interval of modelled outcomes are shown in black, running forward to the year 2035 or until the modelled population exceeds the current observed population.

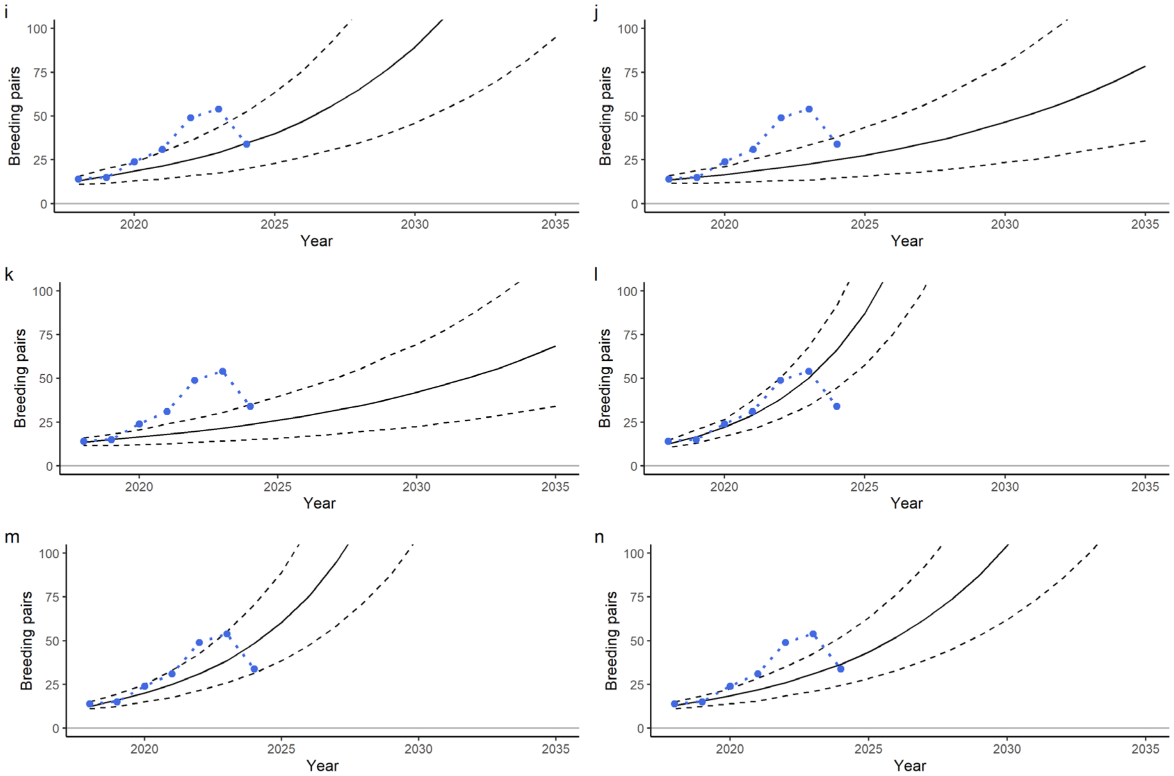


Figure 4: projected population size in 2023–2024 under model scenarios for age class-specific survival change. Model scenarios are the same as depicted in Figure 3 (see Table 1 for full details of each model). Points and lines show the median and 95% confidence interval for the projected population in 2023 (orange) and 2024 (blue) respectively. Dashed lines show the observed population in the same years (depicted using the same colours to facilitate comparison).

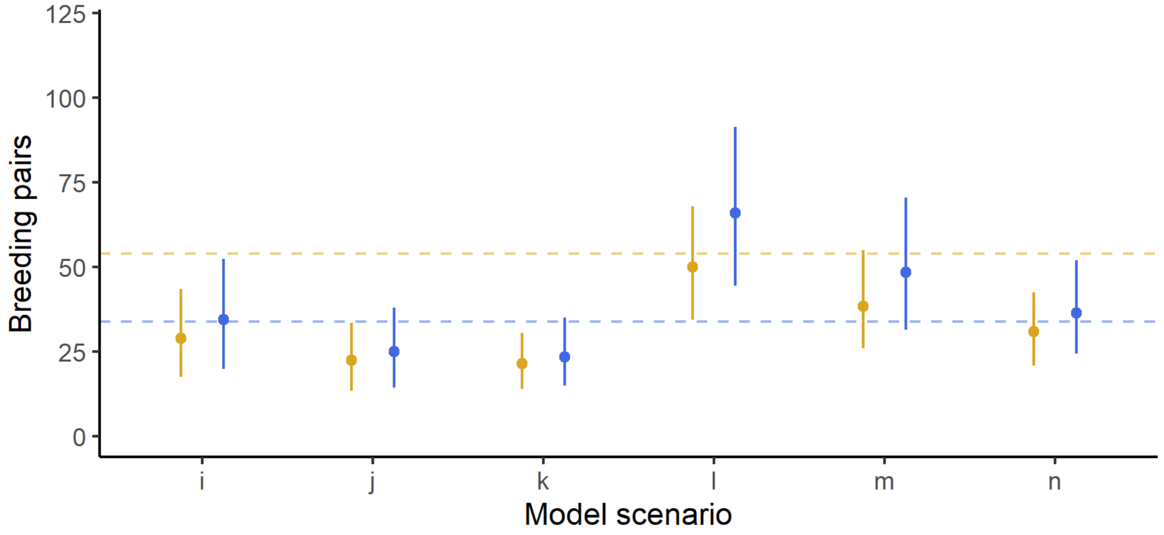


Figure 5: projected population growth under model scenarios for settlement (skip rate) change. Models o–r project population rates under different skip rates with current survival rates, and models s–x project population rates under different skip rates with adjusted survival rates (see Table 1 for full details of each model). In all panels, the observed population trend during the brood management trial period is shown in blue with a dotted line. The median and 95% confidence interval of modelled outcomes are shown in black, running forward to the year 2035 or until the modelled population exceeds the current observed population.

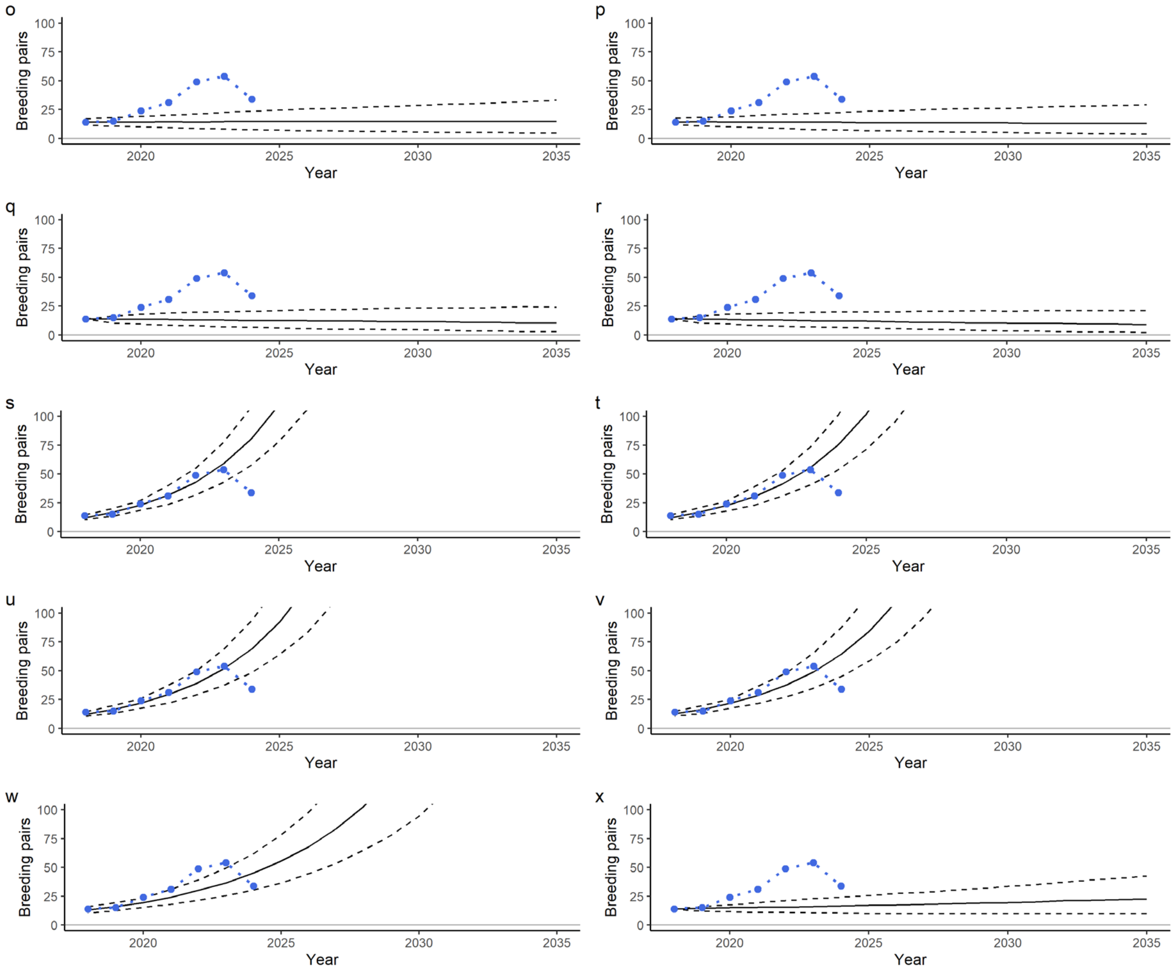


Figure 6: projected population size in 2023–2024 under model scenarios for settlement (skip rate) change. Model scenarios are the same as depicted in Figure 5 (see Table 1 for full details of each model). Points and lines show the median and 95% confidence interval for the projected population in 2023 (orange) and 2024 (blue) respectively. Dashed lines show the observed population in the same years (depicted using the same colours to facilitate comparison).

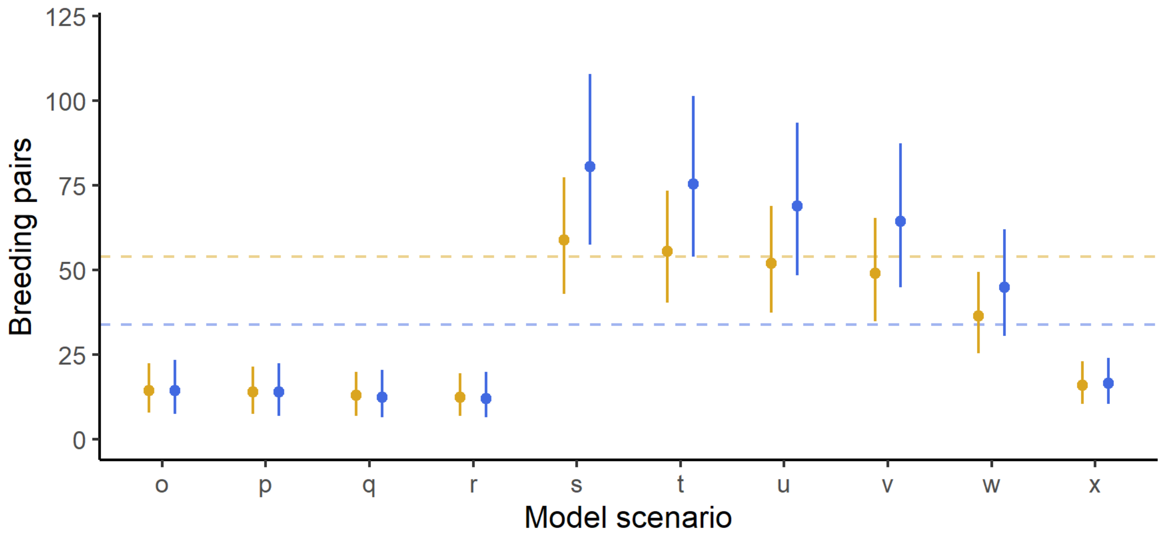
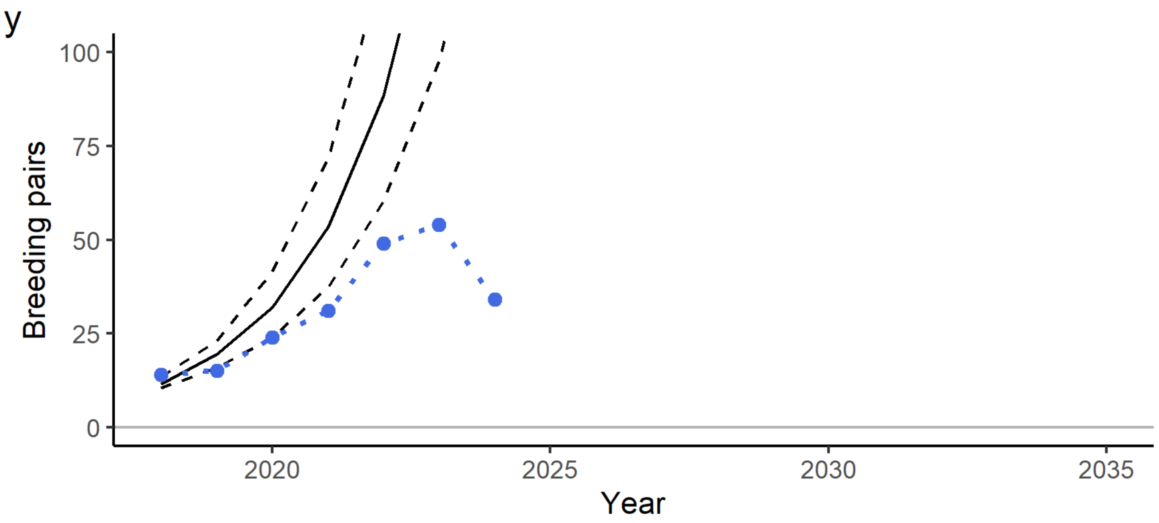


Figure 7: projected population growth under a model scenario for settlement (subadult breeding) change. Model y projects population rates under a scenario where all subadults breed, with adjusted survival rates (see Table 1 for full details of each model). The observed population trend during the brood management trial period is shown in blue with a dotted line. The median and 95% confidence interval of modelled outcomes are shown in black, running forward to the year 2035 or until the modelled population exceeds the current observed population.



Discussion

The Hen Harrier population in England has increased rapidly over the period of the brood management trial, and this study explores the capacity for this increase to have been driven by change in productivity, survival, or settlement of Hen Harriers during (or at the outset of) the trial period.

Productivity change

It is clear that the observed population increase cannot be explained by the productivity uplift at nesting attempts where brood management is carried out (i.e. due to the direct effects of captive rearing), nor even by the effects of brood management combined with the benefits experienced by broods subject to diversionary feeding. The direct benefits of brood management and diversionary feeding to Hen Harrier productivity appear to be minimal: a difference of 0.2 in mean annual productivity rates with and without interventions suggests that an additional one chick should fledge per five breeding attempts in the population as a result of both interventions being applied at current rates. In the peak year of 2023, this would represent an additional 10–11 chicks fledged across England, even though 24 chicks were released from brood managed nests and 14 fledged from nests subject to diversionary feeding in that year. To put this another way, almost three-quarters of chicks fledging from intervened nests would have been expected to fledge anyway in the absence of interventions. Given the low survival of juvenile and subadult birds, this translated to a modelled difference of only a single breeding pair by 2023–2024 (Figure 2), rather than the observed increase of 40 pairs. The lack of significant direct benefits of brood management is unsurprising, since headstarting as a conservation measure is typically considered to be beneficial in species and populations where nest survival rates are very low (Loktionov *et al*. 2023, Donaldson *et al*. 2024), which is not the case for Hen Harriers, whose natural nest success rates in the absence of interference are often above 50% (c.f. Green & Etheridge 1999, Irwin *et al*. 2008).

No outgroup was available with which to test whether any uplift in population-level productivity has occurred as a result of indirect effects of the brood management trial, e.g. through reductions in interference at nests. Productivity at non-intervened nests in England during the trial period was similar to some comparable estimates from previous studies elsewhere, but higher than others, including those in populations thought to be in low-quality habitat or subject to widespread persecution (Etheridge *et al*. 1997, Amar *et al*. 2008, Irwin *et al*. 2008). In particular, the observed productivity at non-intervened nests (2.37 fledged offspring per breeding attempt) was nearly identical to that observed on unmanaged moorland in Scotland (2.4 fledglings per breeding female per year) by Etheridge *et al*. (1997), but far higher than the value of 0.8 observed on managed grouse moors in the same study, whose authors attributed this difference between productivity on managed and unmanaged moorland entirely to human interference (Etheridge *et al*. 1997).

It is important to acknowledge that the productivity estimates made in this study may be biased high, because it is believed that all successful breeding attempts were recorded (Kelly *et al*. 2025), but some breeding attempts that failed early in the season are likely to have been missed (Etheridge *et al*. 1997 report the same caveat). For the same reason, it is possible that a change in population-level productivity could have produced the observed population increase, if it was driven by an increase in the likelihood of a breeding attempt surviving the early part of the breeding season and subsequently being detected by surveyors (rather than by the direct effects of brood management or diversionary feeding). However, as outlined in the Methods above, this possibility is most closely aligned with the models framed around settlement change (discussed below). There have been some cases of destruction of nests reported during the trial period (RSPB 2023) so it seems unlikely that interference at nests has ceased entirely.

Survival change

It is possible, but not likely, that changes in survival alone can explain the observed population growth. The modelled scenarios with no illegal killing projected population growth similar to that which has occurred. However, there is abundant evidence that illegal killing of Hen Harriers in England has not yet ceased; indeed, there were more confirmed and suspected occurrences of persecution of Hen Harriers in the UK during 2023 than in any previous year (RSPB 2023, 2024), so these scenarios cannot be considered an accurate reflection of the real situation. The question of whether illegal killing has reduced to some extent, and survival rates accordingly improved by comparison to those reported by Ewing *et al*. (2023), cannot be addressed through a population modelling approach. Survival analysis for individuals tracked during the trial period may shed light on this, although some evidence suggests that satellite-tagging may discourage the persecution of individual tagged birds without discouraging persecution of untagged Hen Harriers more generally (Thomson 2024), such that survival rates of tagged birds may not be representative of the population as a whole.

Nonetheless, projected population growth under scenarios of no illegal killing was substantially faster than that under the productivity uplift scenarios (Figure 1). These findings are comparable with previous individual-based modelling on Hen Harrier populations, which found the greatest elasticity of population change to be in juvenile male survival rates (Heinonen *et al*. 2014). Our age-class-specific models also suggest that persecution of juveniles has had the biggest impact on population growth rates (Figure 3), probably because it is estimated that juvenile survival rates in the absence of persecution should be at least twice those observed in the current population (Ewing *et al*. 2023). Persecution of subadults also has a large impact on population trends, because subadult survival should be similar to adult survival, but at present a much larger proportion of subadults fall victim to persecution than adults (Ewing *et al*. 2023). This may be because adults tend to remain in established territories in areas where they have previously avoided persecution, whereas subadults may attempt to form territories in both safe and unsafe areas, and be exposed to persecution in the latter. Therefore, the higher level of adult survival could even be argued to be an example of survivorship bias; birds that reach adulthood (and subsequently have high survival) are those which established territories in unpersecuted areas when subadults. Future research might reveal whether territory-forming by subadults in safe or unsafe areas is random, or linked to factors such as place of origin or behavioural patterns. Of the age-class-specific models, every model that included persecution of juveniles produced population estimates for 2023 that were lower than the observed population growth, as did the model that included persecution of both subadults and adults (but not juveniles).

Therefore, it is possible that improved survival, especially in areas where persecution occurred prior to the trial period, may have contributed to the observed population increase, but probably in combination with other factors, given our scenarios of no illegal killing do not appear to reflect the current situation (RSPB 2024).

Settlement change

Compared to productivity and survival change, it is much harder to provide a clear interpretation of the possibility of an increase in apparent settlement rates in Hen Harrier, which might actually comprise, partly or entirely, an increase in the survival of nest attempts through the early stages, and their subsequent detection by surveyors. This is partly because of a lack of evidence around the presence (and frequency) of non-breeding, skipping, adults in the English population, especially given that skipping is known to occur in Hen Harriers, but at highly variable rates depending on local conditions (Amar *et al*. 2003). There is similarly a lack of quantitative data on rates of nest failure during the first days after initiation, which would be very difficult to overcome at population scale, because daily surveys across all suitable habitat in the entire breeding range would be required to be confident of detecting every breeding attempt upon initiation. Nonetheless, model x demonstrates that it would be theoretically possible for very high skip rates and/or early failure rates (well above those observed to occur naturally in Hen Harriers, but plausible in a hypothetical scenario of high levels of targeted disturbance during, and immediately prior to, the breeding season) to have suppressed population growth almost to zero, even in the absence of illegal killing. Halting or reducing this disturbance could release the population and contribute to population growth. Given that population size for Hen Harriers in England is measured as the number of breeding attempts, this apparent growth could occur extremely quickly if a substantial pool of non-breeding individuals with very low settlement rates was present (or available through immigration) at the start of the trial period.

Other factors may also contribute to high population growth rates if opportunities to settle in previously unoccupied areas of suitable habitat become available. High rates of subadult breeding could substantially increase population growth rates (model y), and may be especially likely to do so in good-quality habitat with abundant food resources. Although it is not possible to determine the exact rate of subadult breeding within the English population during the trial period, subadults (including both males and females) were recorded as the parent birds of a substantial number of nest attempts in the nest record dataset.

A sudden increase in the rate of immigration into the English population could likewise increase the number of breeding-age birds present, and therefore the potential for nest attempts, if it exceeds emigration. Juvenile Hen Harriers disperse extremely widely (Picozzi 1978, Morollón *et al*. 2024) before recruiting into areas with high densities of prey species, particularly Field Vole *Microtus agrestis* and Meadow Pipit *Anthus pratensis* (New *et al.* 2011). Therefore, rates of immigration into England could have increased if: a) neighbouring populations, or others further afield, produce larger numbers of juveniles that disperse through England in search of suitable habitat (however, there have been no similar increases in the immediately neighbouring populations of Wales and Scotland's Southern Uplands that would be suggestive of this mechanism; Kelly *et al.* 2025); (b) prey availability in suitable habitat in England has increased; or c) other impediments to recruitment (e.g. disturbance, as above) have been alleviated.

Therefore, it is plausible that increased settlement rates, perhaps linked to reduced disturbance during the pre-breeding phase, could have contributed to the observed population increase. However, given that models a–h all assume a skip rate of 0% (i.e. all breeding-age birds settle), it is evident that this would still require some improvement in survival rates, as well as the pre-existence (or development during the trial period) of a pool of non-breeding birds and/or supplementation by subadult breeding or immigration, in order to be sufficient explanation for the sudden and rapid increase in the number of Hen Harrier breeding attempts in England. The lack of a shared response between neighbouring populations in England, Wales and southern Scotland further suggests that the rapid increase in numbers in England is unlikely to be driven by weather or other large-scale natural phenomena.

Caveats to interpretation

There are a number of important caveats to consider when interpreting the outcomes of the population scenarios modelled in this study. Chief among them is a lack of direct information quantifying the rates of survival, adult skipping and subadult breeding in the English population during the brood management trial and how these, and the productivity rate, compared to the pre-trial period. This knowledge gap necessarily requires a more speculative approach to be taken when comparing the modelled outcomes to the observed population increase, especially with regard to what level of persecution (of different types, including disturbance during the pre-breeding phase) may have been applied prior to the trial period, and whether this might have changed during the trial.

Care also needs to be taken to ensure that interpretation accounts for the substantial decrease in the number of breeding attempts between 2023 and 2024. The observed population size in 2024 falls outside the 95% confidence intervals of several modelled scenarios with which the 2018–2023 observed population is consistent, most notably for models e–h. In these cases, the models do not allow for the possibility of skipping, so the decline in 2024 could be attributable to a high skip rate after several years of very little skipping. In further support of this, the 2023 observed population is compatible with models that include a combination of no illegal killing and an average annual skip rate of 5–20% (Figure 6, models s–v), whereas the 2024 observed population is only compatible with the equivalent model that applies a 40% average annual skip rate (model w).

Density-dependence has been excluded from our modelling entirely. On the one hand, it is at least possible that positive density-dependence (Ferrer & Penteriani 2008) may be in effect in the population, because of male polygyny allowing for multiple females to make successful nest attempts in close proximity to one another even in the absence of an equivalent number of males. With this possibility excluded from our models, actual population growth could have been faster than was simulated by our models. On the other hand, negative density-dependence is likely to begin to apply to the Hen Harrier population at some point in the future if the population continues to grow rapidly. Given there are large areas of suitable habitat in the English landscape that remain unoccupied, it is impossible to say with any certainty at what population size this will begin to apply (and, indeed, it may apply locally in some areas where higher densities are reached before others), although carrying capacity of the English population has been estimated at 323–340 pairs (Fielding *et al.* 2011). Since this is far in excess of the current population size, it is very unlikely that negative density-dependence is currently affecting the English population, and so excluding it from our models is not likely to have impacted our ability to compare models with the recent observed trend. It does, however, mean that models forecasting exponential growth into the future will sooner or later diverge from reality. Brood management, too, may effectively have density-dependent impacts on future population growth that are not accounted for in our modelled projections beyond 2024. Our models assume that brood management would continue to be applied at current levels (in terms of proportion of nests) into the future, which may become unrealistic as Hen Harrier densities increase and a larger proportion of nests meet the criteria for potential brood management. However, as the population grows and population density in some areas increases accordingly, it is likely that a greater proportion of nests would meet the criteria to be eligible for brood management, and that this could in turn increase the cumulative effect of brood management on population productivity.

Conclusions

Viewed in the round, the population models presented in this study do not support productivity uplift from the direct effects of brood management (c.f. headstarting) as the sole explanation for the sudden, rapid growth in the English population of Hen Harriers during the brood management trial period 2018–24. Instead, the most parsimonious explanations for the population increase require improvements in one or both of survival rate and settlement rate. Whilst either of these rates could respond positively to environmental drivers (e.g. high prey availability), equivalent increases have not occurred in the neighbouring populations of Wales or southern Scotland (Kelly *et al.* 2025), and it is also plausible that both rates have responded positively to a reduction in killing and/or nest interference coincident with the availability of brood management as a tool to alleviate conflict between Hen Harriers and grouse moor management. Nonetheless, whilst it is evident that illegal killing has continued at some level throughout the trial period (RSPB 2023, 2024), it is not possible to conclude from this study whether Hen Harrier survival has actually increased in England during the trial period, or if so, to what extent. The substantial decline in the number of breeding attempts between 2023 and 2024, likely attributable to a high skip rate, highlights that adverse conditions (whether natural or linked to persecution) still have the capacity to slow or reverse the ongoing recovery of the Hen Harrier population in England.

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Assessment of recent Hen Harrier population trends in England through population modelling. Natural England Commissioned Report

This study uses a population modelling approach to explore the effects of changes in rates of productivity, survival, and settlement on population growth in the English population of Hen Harriers. Model outcomes are compared to the observed population trend to assess the plausibility of a range of candidate mechanisms to explain the population increase, including productivity uplift from nest-level interventions including brood management and diversionary feeding, increased survival, and increased settlement rate.

Viewed in the round, the population models presented in this study do not support productivity uplift from the direct effects of brood management (c.f. headstarting) as the sole explanation for the sudden, rapid growth in the English population of Hen Harriers during the brood management trial period 2018–24. Instead, the most parsimonious explanations for the population increase require improvements in one or both of survival rate and settlement rate.

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