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Review

Monitoring wader breeding productivity

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A robust understanding of the mechanisms driving demographic change in wild animal populations is fundamental to the delivery of effective conservation interventions. Demographic change can be driven by variation in adult survival, recruitment of juveniles into the breeding population or breeding productivity – the number of fledglings produced per breeding pair. Across Europe, low breeding productivity in wader populations has been a significant driver of population decline, increasing the importance of gathering accurate data on breeding productivity. Monitoring wader breeding productivity is challenging because finding nests can be time-consuming and requires experienced fieldworkers; wader chicks are nidifugous and difficult to count due to their cryptic behaviour; and waders often have high re-laying rates following nest failure, meaning that hatching or fledging can be highly asynchronous. This paper reviews approaches to estimating breeding productivity where fieldworkers either record the agitation or alarm-calling behaviour of adults with dependent young, make direct observations of broods on survey visits, or both. Using a systematic literature search (restricted to Europe where most of these studies have taken place) we identified 38 peer-reviewed papers which used this approach. The productivity metrics produced can be divided into the following categories: (i) 'Hatching Success' (HS), (ii) 'Fledging Success' (FS) and (iii) 'Young Fledged Per Pair' (YFP), from the coarsest to the most precise. The first two metrics are most often used when direct observations of broods are not possible due to the behaviour of broods or vegetation structure; YFP is preferred if brood counts are possible. Design of an appropriate metric depends on (i) whether accurate brood counts are possible; (ii) whether adults exhibit diagnostic agitation behaviour when young are present; (iii) whether individual breeding territories are separable; (iv) whether re-nesting rates are assumed to be high; and (v) the availability of experienced surveyors (particularly where behavioural observations are required). Globally there are many wader species for which the methods described here could provide valuable information and we hope this review encourages further development or adoption of these methods.

Keywords: breeding success, chick survival, fledging rate, meadow bird, productivity, shorebird, territory success.

A robust understanding of the mechanisms driving demographic change in wild animal populations is fundamental to the delivery of effective conservation management interventions (Sutherland *et al.* 2004). Identifying which part of a species' life cycle is most prominent in causing decline is a key part of this process (Schuster *et al.* 2019). In wild bird populations, this can mean estimating between-year survival of adults (Robinson *et al.* 2020, Weiser *et al.* 2020), the

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recruitment of juveniles into the breeding population (Beale *et al.* 2006, Pakanen *et al.* 2021) or fledglings produced per breeding pair – breeding productivity (Plard *et al.* 2020).

Bird population monitoring programmes involving extensive, long-term recording of breeding birds are well established in many countries (e.g. Lehikoinen *et al.* 2014, Harris *et al.* 2021, Smith & Edwards 2021). These schemes have informed habitat management and protected status decisions (O'Brien & Bainbridge 2002, Gaston *et al.* 2008) and have identified those species where declines warrant further investigation or intervention. However, for long-lived, low-fecundity species, declines in site occupancy may only provide evidence in support of conservation intervention many years after the need arises, because populations will appear stable for many years after breeding productivity has fallen below the rate required to maintain population stability (Kuussaari *et al.* 2009, O'Donoghue *et al.* 2019). Although occupancy data can be used to infer correlates of decline (Wilson *et al.* 2014, Franks *et al.* 2017), where low productivity is a causal factor, occupancy data provide an incomplete picture due to this time lag. Moreover, population buffer effects – where sites with poorer quality habitat are vacated first in a declining population – can result in the incorrect inference that habitat quality is driving declines even when changes in habitat quality or availability are not a driver of decline (Brown 1969, Gill *et al.* 2001, Gunnarsson *et al.* 2005).

WADERS

Many wader species are globally threatened (Roodbergen *et al.* 2012, Pearce-Higgins *et al.* 2017, McMahon *et al.* 2020), with populations declining across much of the northern hemisphere (Zöckler *et al.* 2003, Smith *et al.* 2020). Most species nest on the ground in open habitats and so have relatively high rates of nest failure, with productivity fluctuating between years and sites (MacDonald & Bolton 2008, Roodbergen *et al.* 2012, Kentie *et al.* 2015), and are relatively long-lived, low-fecundity species in avian terms (Sandercock 2003). In Europe, low breeding productivity has been identified as the primary demographic cause of population decline for various wader species – for example Eurasian Curlew *Numenius arquata* (Grant *et al.* 1999), Northern Lapwing *Vanellus vanellus* (Peach *et al.* 1994) and Black-tailed Godwit *Limosa limosa* (Kruk *et al.* 1997). The causes of low productivity are often interactive factors such as agricultural intensification (Berg *et al.* 2002), afforestation (Hancock *et al.* 2009, Wilson *et al.* 2014), climate change (Wauchope *et al.* 2017) and high predation rates (MacDonald & Bolton 2008, Fletcher *et al.* 2010, McMahon *et al.* 2020). Because these interactive factors can be difficult to disentangle using site occupancy data, direct monitoring of productivity provides more robust evidence on the causes of decline and the effectiveness of interventions, as well as a more robust understanding of wader population dynamics (Teunissen *et al.* 2008, Fletcher *et al.* 2010, Malpas *et al.* 2013, Douglas *et al.* 2014).

MONITORING WADER BREEDING OUTCOMES

Outcomes from wader nests can be monitored by periodic nest visits, deploying cameras overlooking nests or placing temperature data loggers in nests (Teunissen *et al.* 2008), with some metric of nest survival usually produced using some variation of the Mayfield method (Mayfield 1961). These approaches have provided a wealth of insight into wader nesting ecology (Groen & Hemerik 2002, Meyer *et al.* 2020), drivers of variation in hatching success (Rickenbach *et al.* 2011, Laidlaw *et al.* 2015, Machin *et al.* 2019) and the relative significance of different nest predators (Teunissen *et al.* 2008, Calladine *et al.* 2017). Combining nest monitoring with radio-tracking chicks can add further information on fledging success (Ratcliffe *et al.* 2005, Hönisch *et al.* 2008, Mason *et al.* 2018), brood foraging behaviour (Schekkerman *et al.* 2009), predation rates of chicks and identification of chick predators (Teunissen *et al.* 2008, Mason *et al.* 2018).

Breeding productivity data can also be estimated by counting the proportion of juveniles in wintering flocks (Minton *et al.* 2012), which can provide information at a flyway scale or even at a local or regional scale if the counts are carried out immediately after breeding (Blomqvist & Johansson 1991). However, it would be challenging to produce information on the relative productivity of different breeding populations using this method due to local differences in habitat or post-breeding behaviour making directly comparable counts difficult to obtain. The colour-marking of juveniles facilitates monitoring the recruitment of marked birds into the breeding population (Blomqvist & Johansson 1991, Nol *et al.* 2010) but recruitment is also influenced by conditions on wintering and staging areas, and the mortality of first-winter birds is significant for waders (Kersten & Brenninkmeijer 1995).

All the methods described above are very labour- and resource-intensive to implement. For example, to locate and monitor sufficient nests to produce statistically robust inferences on the causes of low breeding productivity or the relative impact of different nest predators requires a large amount of equipment and experienced fieldworkers (although see Teunissen *et al.* 2008, Laidlaw *et al.* 2015). As such, a broad suite of methods have been developed to monitor wader breeding productivity which do not require fieldworkers to find and monitor individual nests, and which can therefore be deployed at larger geographical scales. These methods are the focus of the remainder of this paper.

VISIT-BASED PRODUCTIVITY MONITORING

'Visit-based productivity monitoring' describes a suite of survey approaches where appropriately timed visits during the breeding season are carried out to infer either nesting or fledging success from behavioural observations of adults, or assess fledglings produced per pair by making direct observations of broods (Table 1). Most wader species are vocal and conspicuous in establishing their territories early in the breeding season (Cramp & Simmons 1983), enabling surveyors to record a significant proportion of territorial pairs (Kålås & Byrkjedal 1984, Meltofte 2001, Calladine *et al.* 2009), though there are specific challenges for some species – European Golden Plover *Pluvialis apricaria*, for example, can be difficult to detect once incubation begins (Pearce-Higgins & Yalden 2005). Later in the breeding season, when pairs have dependent young, many species will alarm call persistently, show a reluctance to leave the area, and may fly aggressively towards an intruder or circle above them (Cramp & Simmons 1983). In contrast, failed breeders are unlikely to show any of these behaviours and will, in many instances (although this varies with habitat and species), leave the breeding grounds altogether (Carneiro *et al.* 2022). Because chick mortality appears to decline significantly beyond 7 and 10 days (Grant *et al.* 1999, Machin *et al.* 2019), there is a relatively large window beyond this period during which the presence of a brood is likely to indicate a successful breeding attempt, particularly for species with longer fledging periods, for example: Northern Lapwing 35–40 days, European Golden Plover 25–33 days, Eurasian Curlew 32–38 days, Black-tailed Godwit 25–30 days (Cramp & Simmons 1983). However, the propensity of waders to re-nest after nest failure (Pakanen *et al.* 2014) means that pairs recorded as active late in the breeding season may in fact be engaging in second or third incubation attempts, making it necessary for a fieldworker to be able accurately to distinguish adult brood-rearing behaviours from incubation behaviours (if the broods are not visible). Additionally, brood movements following hatching may reduce the chances of re-finding a particular brood, or broods may move into or out of the study area, thus reducing the accuracy of productivity estimates.

In response to interspecific variation in wader ecology and breeding habitats, a suite of different approaches to visit-based productivity monitoring has emerged (Table 1). These methods can be divided into three categories based on the type of breeding productivity metric they produce. The coarsest metric – 'Hatching Success' (HS, Table 1) – estimates the proportion of pairs which successfully hatch broods (Grant *et al.* 2000). The next approach – 'Fledging Success' (FS, Table 1) – estimates the proportion of pairs successfully to have fledged any number of young (Yalden & Yalden 1990). Both these approaches (HS and FS) can be used to make comparisons between sites and years to investigate correlates of breeding productivity, but cannot be used to model population change unless FS is supplemented with a subset of brood size estimates (e.g. Baines *et al.* 2023). The final metric – 'Young Fledged per Pair' (YFP, Table 1) – produces estimates of the number of fledged young produced per breeding pair, which has the additional benefit that it can also be used to model population change. HS has been used regularly for Eurasian Curlew (Grant *et al.* 2000), and FS has been used for many species including European Golden Plover (Finney *et al.* 2005), Black-tailed Godwit (Gunnarsson *et al.* 2005), Eurasian Whimbrel *Numenius phaeopus* (Grant 1991) and Common Redshank *Tringa totanus* (Nijland 2007). YFP has usually been used for species with visible, countable broods such as

Table 1. Summary of metrics produced by survey-based wader breeding productivity monitoring methods.

Metric	Uses of resulting metric	Early-season survey visits	Late-season survey visits	Age/period of presence at which fledging can be assumed	Do individual pairs need to be separable?	Do broods need to be counted/ observed?	Do adults with broods need to demonstrate agitated brood-rearing behaviour?	Exemplar species
Hatching Success (HS): the proportion of pairs estimated to have successfully hatched clutches based on adult alarm-calling behaviour after hatching	Comparison of hatching success between sites and between years. Likely to be the least accurate proxy for actual breeding output	Multiple (e.g. 3) early visits to obtain a maximum estimate of breeding pairs	Multiple (e.g. 3) visits to obtain a maximum estimate of alarm-calling or agitated pairs	N/A	No	No	Yes	Eurasian Curlew: overlapping territories, difficult to observe young in rough grassland or moorland habitats, diagnostic alarm-calling behaviour when broods present. Although in lower density populations and where sward structure allows, FS and YFP also possible
Fledging Success (FS): the proportion of breeding pairs estimated to have successfully fledged young based on alarm- calling pairs for a period consistent with likely fledging	Comparison of fledging success between sites and between years. Can be used to model population change if a subset of brood size estimates are obtained	Multiple (e.g. 3) visits to obtain a maximum estimate of breeding pairs and record the approximate nest location/ breeding territory	Regular (e.g. weekly) visits to re-find pairs after clutches hatch to record the presence and alarm-calling behaviour of each pair for a period consistent with a high likelihood of fledging	Brood-rearing behaviour recorded for 3/4 weekly visits consistent with high probability of fledging for European Golden Plover (fledging period of 28–33 days)	Yes	No	Yes	European Golden Plover: separable territories and individuals, diagnostic agitation response with broods, but very difficult to observe or count broods

(continued)

Table 1. (continued)

Metric	Uses of resulting metric	Early-season survey visits	Late-season survey visits	Age/period of presence at which fledging can be assumed	Do individual pairs need to be separable?	Do broods need to be counted/ observed?	Do adults with broods need to demonstrate agitated brood-rearing behaviour?	Exemplar species
Young Fledged per Pair (YFP): the number of fledged young divided by the total number of breeding pairs. Based on observations of fledged young	Actual breeding productivity per pair – data can be used to model population change, as well as make comparison between sites and years	Visit(s) early in the season to estimate number of breeding pairs and (sometimes) record the approximate nest location/ breeding territory	Either: (i) visit(s) to re-find pairs timed to the pre-fledging period to each breeding pair to count young or (ii) periodic visits to breeding areas to count well-grown young	Visits to count well-grown young every 3 weeks for Lapwing (fledging period of 35–40 days)	No – for species breeding at high densities a peak count of adults suffices	Yes	No	Northern Lapwing: nest colonially so not possible to separate territories. Broods visible and easy to count. High propensity to re-lay means fledging can occur across a wide time period, making periodic repeat visits useful. However, where sward structure makes brood observations difficult, FS or HS also appropriate

Details for studies producing Hatching Success (HS), Fledging Success (FS) and Young Fledged per Pair (YFP) are described in Tables 2–4. Early-season visits refers to visits in the territory establishment, laying and early incubation periods and late-season visits refers to visits from approximate hatching date to approximate fledging date. Although there is much variation in laying dates across Europe for wader species, in most European contexts, early-season visits will take place between March and May, and late-season visits will probably be from May to July.

Northern Lapwing (Bolton *et al.* 2011), Pied Avocet *Recurvirostra avosetta* (Lengyel 2006) and Eurasian Oystercatcher *Haematopus ostralegus* (Heppleston 1972).

As researchers and policy-makers have become more aware of declining productivity of breeding waders in Europe (MacDonald & Bolton 2008, McMahon *et al.* 2020), visit-based productivity monitoring methods are being used more frequently (see Fig. 1). Despite this, there is no comprehensive review of these methods. Here we review published applications of visit-based wader productivity monitoring in Europe to (i) identify widely adopted approaches for individual species; (ii) summarize factors which affect the suitability of different metrics; and (iii) provide guidance on how to select an appropriate productivity metric for a given species and context.

METHODS

To collate published applications of visit-based wader productivity monitoring in Europe, we searched the Web of Science (http://apps.webofknowledge.com) using combinations of keywords and Boolean logic operators: Species: 'shorebird' OR 'wader' OR 'meadow bird' OR 'Scolopax' OR 'Vanellus' OR 'Gallinago' OR 'Philomachus' OR 'Calidris' OR 'Limosa' OR 'Charadrius' OR 'Pluvialis' OR 'Numenius' OR 'Burhinus' OR 'Tringa' OR 'Recurvirostra' OR 'Himantopus' OR 'Actitis' OR 'Haematopus' OR 'Arenaria' OR 'Lymnocryptes' OR 'Phalaropus' OR 'Limnodromus' OR 'Actophilornis', and Topic: 'breeding success' OR 'breeding productivity' OR 'fledging success' OR 'chick survival' OR 'fledgling survival' OR 'productivity' OR 'territory success' OR 'territorial success'.

Abstracts (and methods sections if necessary) were then screened to identify whether the study used a method which produced a metric of breeding productivity as described in Table 1. For those studies which matched the criteria, we extracted the following key information: study species, metric produced, study aim, location, habitat, frequency and timing of survey visits, how breeding

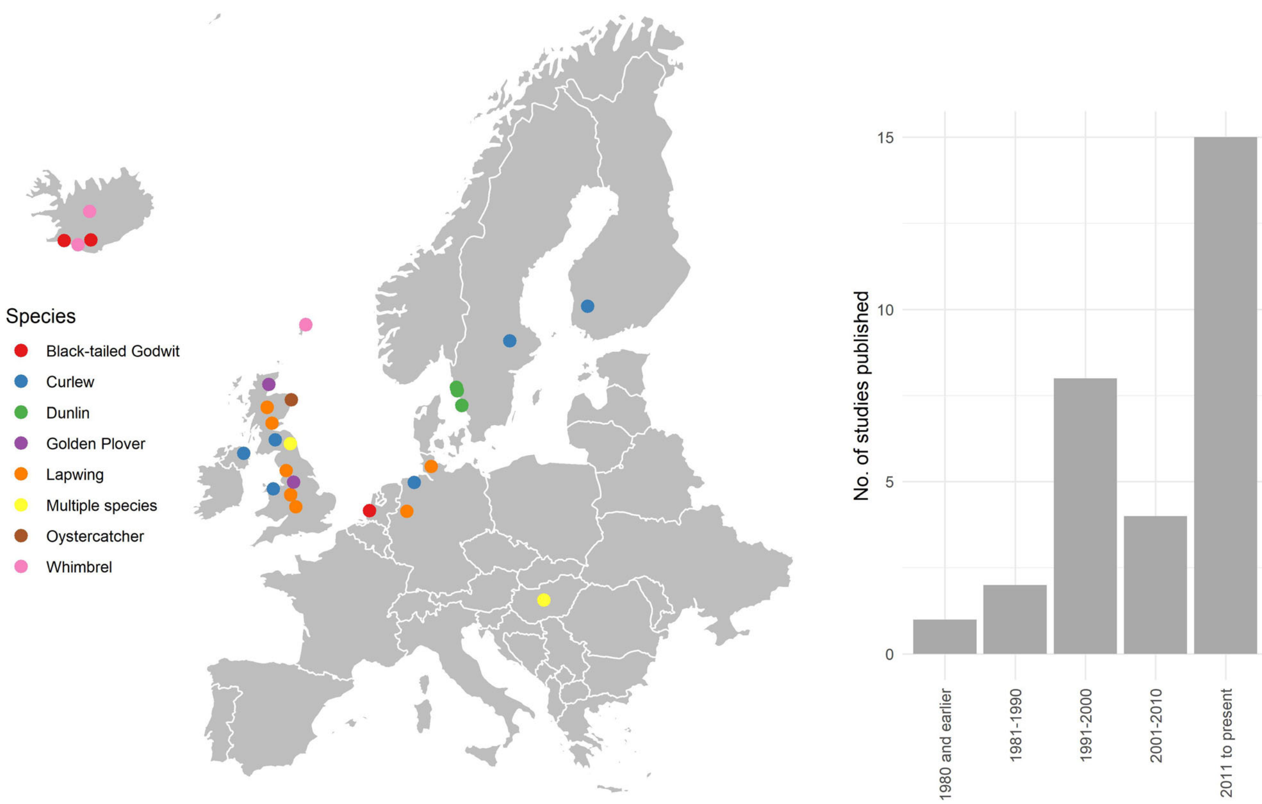

Figure 1. Location of the 38 studies included in this review (taken either from coordinates provided in the paper or the estimated centrepoint of the reported study sites) and summary of their timing of publication.

success was inferred, and any supporting field data gathered to validate the approach. For each study identified, we reviewed each paper, subsequently referencing this study for further papers which we might have missed in the initial search (though this did not identify any further papers for inclusion). We omitted studies where the method used was not clear or no metric of productivity was reported, or where the study was reporting on the survival of nests or radiotagged broods.

RESULTS AND DISCUSSION

Summary of literature search

The Web of Science search returned 1016 studies. Screening titles and abstracts reduced this to 38 studies that used methods that matched our description of 'visit-based productivity methods' (Table 1). Almost half (18) of these studies were published in the last decade (Fig. 1).

The species most frequently monitored using these methods were Northern Lapwing (9 studies), Eurasian Curlew (8), European Golden Plover (4), Black-tailed Godwit (3) and Eurasian Whimbrel (3). Geographically, study sites were concentrated in the UK, Ireland, Iceland, western Europe and Fenno-Scandia (Fig. 1). Of the 38 studies, 20 (Tables 2–4) described novel methods and the remaining 18 studies adopted an existing method. While many studies gathered large datasets to compare different treatments, the statistical power of the study was often unclear because of a failure to account for sources of uncertainty arising from field methods (see Bolton *et al.* 2011). However, in two studies the methods used to estimate breeding productivity were validated against productivity estimates from intensive monitoring – HS for Curlew (Grant *et al.* 2000) and YFP for Lapwing (Bolton *et al.* 2011). The extra assurance produced by this validation means that these approaches have been widely adopted (with both approaches used in at least four subsequent studies).

Other studies reported on the likelihood of observing broods when broods were assumed to be present based on behaviour (Gunnarsson *et al.* 2005, Fletcher *et al.* 2010) or on the likelihood of overlooking a territorial pair on any individual survey visit (Yalden & Yalden 1990, Pearce-Higgins & Yalden 2005). These data are valuable in informing decisions regarding the frequency of survey visits. In 13 studies, some or all of the study population was colour-marked, which allowed researchers to follow the fate of individual pairs with more certainty.

With the exception of Dunlin *Calidris alpina*, the species for which these methods have been deployed have relatively long fledging periods for waders, allowing a longer time window to record well-grown chicks or adult agitation behaviour when chicks are older and have a higher daily survival probability (Galbraith 1988, Grant 1991, Pearce-Higgins & Yalden 2005). These species are also larger-bodied (again, with the exception of Dunlin), have higher detectability (Cramp & Simmons 1983), exhibit characteristic wader territorial display behaviours early in the season and show agitation behaviour when they have dependent broods and are approached by fieldworkers. Two of the studies (Hegyi 1996, Fletcher *et al.* 2010) generated productivity indices for multiple species. These methods have not been deployed in the high Arctic (Fig. 1) where high densities of waders breed but where these methods would be limited by two factors: firstly the practical challenge of accessing breeding grounds in the territory establishment phase when there may be large accumulations of snowmelt; and secondly, at higher latitudes the breeding season is more compressed (Meltofte 2001), affording researchers a smaller early survey window to assess numbers before incubation begins and detectability declines.

For the remainder of the paper, we describe each breeding productivity metric, then summarize factors a researcher must consider when designing a metric, before presenting a schematic to assist researchers in the process of selecting an appropriate metric.

Productivity metrics

Hatching success (HS)

A hatching success metric has only been used for Eurasian Curlew (in five studies – Table 2). Monitoring Eurasian Curlew breeding productivity is particularly challenging, especially in high-density areas (Grant *et al.* 2000). Curlews will exhibit territorial behaviour over a far larger area than the immediate nesting site (Bowgen *et al.* 2022) but pairs can nest in close proximity, making separating individuals or pairs very difficult. This can be a challenge for monitoring the productivity of many wader species (although for European Golden

Plover, individuals can often be identified by plumage variation). For Curlew, it can also be challenging to observe broods, and difficult to determine the stage of a particular breeding attempt without more intensive observation (Douglas *et al.* 2014). These factors rule out using an FS or YFP metric in high-density breeding areas. As such the widely adopted method for Curlew breeding productivity (Grant *et al.* 2000) estimates 'Hatching Success' by using three survey visits during the chick-rearing period and taking the maximum count of alarm-calling territorial pairs across these three visits (three visits are used because Curlews can renest following nest failure, meaning fledging can be asynchronous). Studies have also produced FS and YFP metrics for Curlew (Tables 3 and 4), but these studies were with smaller, lower density (e.g. 1.6 pairs/km^2 in Valkama & Currie 1999) populations and were carried out in cultivated areas, meaning researchers were able to revisit pairs regularly to follow broods, and broods were likely to be easier to observe than in upland study sites (Fletcher *et al.* 2010).

Fledging success (FS)

FS has been estimated for multiple species, most notably for European Golden Plover (Table 3). The approach is based on surveyors re-visiting the approximate nest location when clutches are expected to have hatched, and then re-visiting the location that pairs were last observed to record the presence of adult agitation behaviours across a period consistent with successfully fledging a brood. Studies of Golden Plover have used different periods of chick presence – between 21 and 30 days – as being indicative of successful breeding (Yalden & Yalden 1990, Finney *et al.* 2005, Douglas & Pearce-Higgins 2014). This approach is dependent on frequent repeat visits, with all studies using this approach, revisiting pairs at least on a weekly basis (Table 3) to produce the estimate of chick presence. The approach is ideal for Golden Plover because after clutches hatch, adults will alarm call persistently at intruders, territories used by broods are often small and territories are less likely to overlap than territories of many other wader species (Parr 1980), and Golden Plover plumage characteristics can also be used to separate individuals (Byrkjedal & Thompson 1998). Broods are very difficult to observe or count, so no study has produced a YFP metric for Golden Plover. A key challenge when attempting to produce any breeding productivity metric for Golden Plover is that they can be relatively cryptic early in the breeding season and during the incubation period with relatively low detectability, meaning that obtaining an accurate count of total breeding attempts early in the season can be challenging (Pearce-Higgins & Yalden 2005), though this can be mitigated by regular repeat visits.

FS has also been estimated for both Eurasian Whimbrel and Black-tailed Godwit, and YFP has also been estimated for both these species in different contexts. In Iceland, where Black-tailed Godwit breed in riverine willow scrub and blanket bog, FS was used, with a mean of the two highest counts of alarm-calling pairs considered to be the number of pairs successfully fledging young (Gunnarsson *et al.* 2005). One study used just a single field visit timed to the late chick-rearing period to produce annual estimates of productive pairs, an approach that needs a large sample size to be effective (Gunnarsson *et al.* 2017). FS has also been used for Eurasian Curlew, with an adapted version of the widely used HS method (Grant *et al.* 2000) where rather than use a peak count of alarm-calling birds from the three later visits, the continuous presence of alarm-calling on the three later visits is assumed to indicate fledging success (Fletcher *et al.* 2010). The age at which broods can be considered to have fledged is an important decision (see Table 3 for the ranges used in the reviewed studies). While it is generally assumed that mortality declines with age, this may not always be the case, and different predators or sources of mortality at different sites may mean that the form of age-dependent chick mortality is site-specific (Grant *et al.* 1999).

Young fledged per pair (YFP)

'Young Fledged per Pair' has been estimated in studies on species of breeding wader that nest in short or bare vegetation – Northern Lapwing (Bolton *et al.* 2011), Eurasian Oystercatcher (Heppleston 1972), Eurasian Stone-curlew *Burhinus oedicnemus* (Bealey *et al.* 1999) and Pied Avocet (Lengyel 2006). Broods of all these species are usually visible and relatively easy to count in their typical nesting habitats (Table 4), although this will vary with sward structure. Northern Lapwings are semi-colonial and can nest at high densities, making it difficult to follow the outcomes of specific territories in the absence of colour-marking. However, when disturbed pre-laying or during the

Table 2. Hatching Success (HS). Each row of the table represents a study or a group of studies using a different methodological design.

Paper(s)	Species	Breeding density	Description of habitat	Frequency of survey visits	Time of day	How is abundance estimated?	How is hatching success confirmed?	Additional field data used
Grant *et al.* (2000); Douglas *et al.* (2014); Johnstone *et al.* (2017); O'Donoghue *et al.* (2019); Douglas *et al.* (2023)	Eurasian Curlew	Low, medium & high across all sites included in studies	All studies were carried out in upland areas of moorland/ grassland	Five survey visits across the breeding season: 14–25 April, 6–22 May, 26 May– 10 June, 16–30 June and 1–13 July	One of the first three visits within 3 h of either dawn or dusk, and the other two between 09:00 and 17:00 h	Survey to within 100 m of all areas to count apparently paired individuals, displaying birds, nests or broods on three early visits	Maximum count of agitated or alarm-calling pairs on any of the three later visits assumed to be no. of pairs that hatched nests	–

Papers that report using the same methodology as a previous study are listed in the first column after the paper describing the original methods. The 'breeding density' column is an approximate qualitative assessment relative to other studies of similar species based on information in each paper.

incubation period, all adults typically take flight over the breeding area, making it possible to obtain an accurate count of adults. As such, in the most widely adopted method, half the maximum number of adults observed in a breeding area is used as an estimate of total territories (Bolton *et al.* 2011). Because Lapwings have an extended breeding season (relative to other waders) driven by relatively early first laying dates and high rates of renesting (Cramp & Simmons 1983), total counts of well-grown young at 3-week intervals are used to estimate the number of fledged birds. This method has been deployed successfully in multiple studies (Malpas *et al.* 2013, Smart *et al.* 2013, Kamp *et al.* 2014, Bell & Calladine 2017) and the efficacy of this approach has been demonstrated by simulation (Bolton *et al.* 2011).

YFP also works well for Eurasian Oystercatcher because broods are relatively easy to observe, large brood movements are infrequent, and revisiting territories during the fledging period to count broods works effectively. There have been few recent studies on Oystercatchers in Europe (Heppleston 1972) but similar methods have been used for Black Oystercatcher *Haematopus bachmani* (Morse *et al.* 2006) and African Oystercatcher *Haematopus moquini* (Calf & Underhill 2002). In previous studies, counts of broods occurred approximately every 3–6 days (Heppleston 1972, Calf & Underhill 2002, Jodice *et al.* 2014). The only mention of challenges counting broods was due to seasonal crop growth (Heppleston 1972).

The Dunlin studies which produce a productivity index use colour ringing of broods or adults to allow fieldworkers to re-find breeding pairs to confirm the status of a breeding attempt (e.g. Blomqvist & Johansson 1991). Dunlin fledglings surviving for more than 14 days has been taken as evidence of a successful breeding attempt (Pakanen *et al.* 2021). These studies are in coastal meadows, where re-finding breeding pairs is likely to be more feasible than in upland habitats. It would be difficult to apply these methods on an unmarked population because it is difficult to observe or count Dunlin broods in the field, as adults do not exhibit a diagnostic alarm-calling behaviour when they have young, and at 19–21 days the fledging period for Dunlin is relatively short (Cramp & Simmons 1983).

YFP was also used for Eurasian Whimbrel in Iceland (Katrínardóttir *et al.* 2015), although another study in Shetland found that counting or observing broods was very challenging (Grant 1991), though agitated responses of Whimbrel are considered sufficient to indicate the presence of chicks. While in Iceland FS has been used with Black-tailed Godwit, in Dutch agricultural landscapes brood counts have been carried out to

Table 3. Fledging Success (FS). Each row of the table represents a study or a group of studies using a different methodological design.

Paper(s)	Species	Breeding density	Description of habitat	Frequency of survey visits	Time of day	How is abundance estimated?	How is fledging success confirmed?	Additional field data used
Yalden and Yalden (1990)	European Golden Plover	High	Blanket bog	Visits every 7 days from early April to late July	Not described	Sites surveyed on same route each visit, recording all Golden Plover seen, clusters across visits assumed to be territories	Fledging success inferred from the presence of alarm-calling adults for a minimum of 4 weeks	Plumage characteristics recorded to aid the re-finding of specific pairs
Finney *et al.* (2005)	European Golden Plover	High	Blanket bog	Visits every 2–8 days from May to July	Between 09:00 and 18:00 h	Approached all areas of a study site to within 200 m, only included birds observed at least once with chicks in assessment of reproductive success	Pairs observed alarm-calling for 30 days or more considered successful. Pairs alarm-calling for >22 days considered failed. Remaining pairs omitted from analysis	Plumage characteristics recorded to aid the re-finding of specific pairs
Douglas and Pearce-Higgins (2014); Sansom *et al.* (2016)	European Golden Plover	Medium	Blanket bog	Four visits to estimate abundance and weekly visits during the chick-rearing period (all surveys between early April and mid-July)	Between 08:30 and 18:00 h	Transects spaced 200 m apart. Abundance per square was the maximum count of pairs across the four visits	Fledging success inferred from the presence of alarm-calling adults for a minimum of 3 weeks	Plumage characteristics recorded to aid the re-finding of specific pairs
Gunnarsson *et al.* (2005)	Black-tailed Godwit	High	Dwarf birch bog and marsh	Every 3–4 days from mid-April to 'late summer'	Not described	Number of pairs considered to be the mean of the three maximum counts between late May to mid-June	Mean of two highest counts of alarm-calling pairs considered to be number of successful pairs	Some colour-marked broods used to confirm observations
Gunnarsson *et al.* (2017)	Black-tailed Godwit	High	Surveys carried out from roads (198 km), so different habitat types covered	Single visit during the chick-rearing period in last 10 days of June	Not described	*No estimate of abundance*	Slow drive through all sites. Conspicuous alarm-calling behaviour considered to indicate pairs with young	–

(continued)

Table 3. (continued)

Paper(s)	Species	Breeding density	Description of habitat	Frequency of survey visits	Time of day	How is abundance estimated?	How is fledging success confirmed?	Additional field data used
Valkama and Currie (1999)	Eurasian Curlew	Low	Agricultural areas of spring cereals, hay meadows and fallow fields	Each territory revisited every 2–3 days (start and end of survey period not reported)	Not described	Nest searches of suitable habitat	Agitated or alarm-calling adults when chick age estimated at 25–30 days	Sample of brood sizes used to produce estimate of young fledged per pair (YFP)
Baines *et al.* (2023)	Eurasian Curlew	High	Upland study sites	Five survey visits across the breeding season: 14–25 April, 6–22 May, 26 May–10 June, 16–30 June and 1–13 July	One visit started at dawn or terminated at dusk, with remaining visits conducted at 09:00–17:00 h	Survey to within 100 m of all areas to count apparently paired individuals, displaying birds, nests or broods on three early visits	Presence of alarm-calling in an area on visits 3–5 considered evidence of fledging success	Sample of brood sizes used to produce estimate of young fledged per pair (YFP)
Carneiro *et al.* (2021)	Eurasian Whimbrel	High	Lowland grasslands	Territories regularly visited (start and end of survey period not reported)	Not described	Broods were regularly monitored until fledging age (27 days)	Fledging success recorded as fledged young or not based on adult behaviour at fledging date	Colour-marked adults
Fletcher *et al.* (2010)	European Golden Plover, Eurasian Curlew, Northern Lapwing	Low to medium	Moorland and marginal farmland with mosaics of heather, grassland and rushes	Two early-season visits (mid-April to early June), and weekly visits during the chick-rearing period (from early May)	Early season visits at 04:15–08:00 h or 16:00–20:00 h	Two early visits across all areas of the study site approached to within 100 m to locate individual territories	Fledging success inferred from the presence of alarm-calling adults for a minimum of 3 weeks	–
Hegyi (1996)	Black-tailed Godwit, Common Redshank, Northern Lapwing	High	Abandoned fish ponds	Sites visited every 3–4 days (start and end of survey period not reported)	Not described	Study sites scanned from vehicle/hide	Presence of adults tending young 25–30 days after estimated hatching dates	–

(continued)

Table 3. (continued)

Paper(s)	Species	Breeding density	Description of habitat	Frequency of survey visits	Time of day	How is abundance estimated?	How is fledging success confirmed?	Additional field data used
Nijland (2007); Oosterveld *et al.* (2011)	Black-tailed Godwit, Eurasian Curlew, Northern Lapwing, Common Redshank	Medium to high	Agricultural grasslands	5–6 survey visits across the breeding season from April to June	Not described	Territorial behaviour mapped in study plots	Successful breeding inferred from alarm-calling behaviour in 2-week period around the time that first chicks fledge	–

Papers that report using the same methodology as a previous study are listed in the first column after the paper describing the original methods. The ‘breeding density’ column is an approximate qualitative assessment relative to other studies of similar species based on information in each paper.

produce YFP metrics (Table 4), often aided by colour ringing or radiotagging of adults.

Considerations when designing or selecting a productivity metric

Habitat and brood detectability

To produce a YFP metric, surveyors must be able to count broods accurately. How feasible this is will be influenced by the species’ behaviour and the availability of vantage points, but in practice the sward structure during the pre-fledging period is likely to be the key consideration. Where vegetation is short and good vantage points are available (within vehicles or from higher ground), it is often possible to count broods, whereas in longer, denser vegetation it is likely to be very challenging. YFP has been produced in cultivated or well-grazed landscapes for Black-tailed Godwit, Eurasian Curlew, Northern Lapwing, Eurasian Oystercatcher, Pied Avocet and Eurasian Stone-curlew (Heppleston 1972, Berg 1992, Kruk *et al.* 1997, Bealey *et al.* 1999, Lengyel 2006, Bolton *et al.* 2011, Katrínardóttir *et al.* 2015; see Table 4). However, in areas of blanket bog, rough grassland, moorland or willow scrub, where vegetation is longer and observing broods is harder, HS or FS has been used, for example with Black-tailed Godwit, Eurasian Curlew and European Golden Plover (Yalden & Yalden 1990, Grant *et al.* 2000, Gunnarsson *et al.* 2005; Tables 2 and 3). The fact that the same species (particularly Black-tailed Godwit and Eurasian Curlew) have often been monitored with different metrics due to habitat structure elucidates the point that habitat is often the key consideration in selecting a metric. Even when it is difficult to observe broods in the nesting habitat, if young birds are likely to forage in more open habitat they could be counted in these areas (Blomqvist & Johansson 1991).

Territoriality and brood movements

The extent to which pairs remain in the same location once they have mobile chicks will influence the design of an appropriate metric, and the scale at which productivity can be assessed. Large movements of pairs with broods from nest-sites, or between survey visits, could make it difficult for fieldworkers to re-find specific pairs, thus causing the incorrect inference that a breeding attempt has failed, when actually the brood has been moved to a new area. Where broods are likely to remain in

Table 4. Young Fledged per Pair (YFP). Each row of the table represents a study or a group of studies using a different methodological design.

Paper(s)	Species	Breeding density	Description of habitat	Frequency of survey visits	Time of day	How is abundance estimated?	When are young confirmed as fledged?	Additional field data used
Galbraith (1988)	Northern Lapwing	Low to high	Cultivated land with cereals, silage and permanent pasture, and unimproved hill farm with low intensity grazing	Every 2–3 days (start and end of survey period not reported)	Not described	Not described	Broods checked every 2–3 days. Young seen in flight considered fledged	Hatching dates estimated from mean egg weight. Adults colour-marked
Blomqvist and Johansson (1995)	Northern Lapwing	No information	Coastal pastures and arable fields	Visits every 1–7 days (start and end of survey period not reported)	06:00–21:00 h	Nests counted by scanning for incubating birds from a distance	Young thought to be 35 days or older based on estimated hatching date considered to be fledged	Adults and broods colour-marked
Bolton *et al.* (2011); Bell and Calladine (2017); Kamp *et al.* (2014); Malpas *et al.* (2013); Smart *et al.* (2013)	Northern Lapwing	Low to high	Lowland wet grassland, upland grassland and arable habitats	Visits at 3-week intervals from late March to early July	Between dawn and 12:00 h	Scans of suitable habitat for adult birds – no. of pairs considered to be half the max. number of adults recorded between mid-April and end of May	Chicks estimated to be 35 days or older counted as fledged, summed across visits	–
Plard *et al.* (2020)	Northern Lapwing	Medium	Floodplain/marsh	Visits every 5 days from March to July	Not described	Not described	Young known to be present for 21 days or more considered fledged	Adult (and near fledged) birds colour-marked
Berg (1992)	Eurasian Curlew	Low	Mixed farmland sites with cereals and cattle pasture	Visits every 7 days (start and end of survey period not reported)	Not described	Field protocol not described. Minimum criterion for a territory was observation of a pair or two birds observed within 1 km	Fledglings counted at 35 days. If a brood not found, 3 more searches carried out	–

(continued)

Table 4. (continued)

Paper(s)	Species	Breeding density	Description of habitat	Frequency of survey visits	Time of day	How is abundance estimated?	When are young confirmed as fledged?	Additional field data used
Kruk *et al.* (1997)	Black-tailed Godwit	Medium	Grassland areas cut for silage or hay, or grazed with cattle	Daily visits from May to June	Not described	Searches of suitable habitat	Maximum and minimum count of fledged birds produced for each site. Maximum = peak count of young older than 16 days old; minimum = peak count of young older than 25 days old	Colour-marked adults
Roodbergen and Klok (2008)	Black-tailed Godwit	Medium	Grassland areas cut for silage or hay or grazed with cattle	Three early-season visits (April–June), and two visits per week during brood-rearing (survey period not reported)	Not described	Territory mapping on three early visits	Chicks known to survive to at least 25 days old were assumed to have fledged	Colour-marked adults
Pauliny *et al.* (2008); Pakanen *et al.* (2021); Blomqvist and Johansson (1991)	Dunlin	Low to medium	Coastal grasslands	Visits every 2–5 days from April to late June	Not described	Searches of suitable habitat for nesting pairs	Chicks known to be at least 14 days old assumed to have fledged. Chicks considered dead if they disappeared before 14 days and adults showed no parental behaviour on two visits	Colour-marked adults and broods. Searches for colour-marked fledglings also carried out on nearby mudflats post-fledging
Katrínardóttir *et al.* (2015)	Eurasian Whimbrel	High	Riverplain sites with rush/willow/crowberry cover and grassland sites	Every 7 days from June to late July	Afternoon or early evening	Walked through study site and recorded Whimbrel exhibiting territorial behaviour. Single territorial birds or two birds together assumed to be a pair	Minimum brood sizes counted within 7 days of assumed fledging date	Colour-marked adults and broods, hatching dates estimated from floating eggs

(continued)

Table 4. (continued)

Paper(s)	Species	Breeding density	Description of habitat	Frequency of survey visits	Time of day	How is abundance estimated?	When are young confirmed as fledged?	Additional field data used
Grant (1991)	Eurasian Whimbrel	High	Heathland and blanket bog	Every 3–6 days (start and end of survey period not reported)	Not described	Approached all areas of study site to within 100 m recording breeding territories	Territories re-visited 28–30 days after estimated hatching date –alarm-calling behaviour considered evidence of fledging	Colour-marked adults and broods, hatching dates estimated from floating eggs
Heppleston (1972)	Eurasian Oystercatcher	Low to medium	Inland farmland and coastal dunes	Every 5 days or less from March to July	Not described	A transect was followed and observations made at set vantage points to identify territorial birds	Not described	Colour-marked adults
Hötker and Segebade (2000)	Pied Avocet	Nesting colonies	Coastal nesting colonies on islands, tidal saltmarsh or coastal grasslands	Two visits per week from April to July	Not described	Nests found by searching breeding colonies	Chicks observed to have reached 30 days counted as fledged	–
Lengyel (2006)	Pied Avocet	Nesting colonies	Lakes, fishponds and wetlands	Visits every 2–3 days from March to July	Not described	Nests found by searching breeding colonies	Chicks observed to have reached 35 days counted as fledged	–
Bealey *et al.* (1999)	Eurasian Stone-curlew	Low	Chalk grassland	Visits every 1–2 weeks from April to August	Not described	Parents observed from vantage points to locate nests	Young were considered to have fledged if they were observed or their parents were showing behaviour consistent with having young beyond the age of 35 days	–

Papers that reported using the same methodology as a previous study are listed in the first column after the paper describing the original methods. The 'breeding density' column is an approximate qualitative assessment relative to other studies of similar species based on information in each paper.

the same field, productivity could be assessed at a small spatial scale, whereas if large movements are considered likely, productivity should only be assessed at a larger scale.

For waders breeding in agricultural systems, the movements of broods will often be driven by the timing of mowing or cutting of agricultural fields and the availability of different sward heights (Schekkerman & Beintema 2007). Consideration should be given to factors likely to influence brood movements when delineating a study area so that predictable brood movements take place within the study site rather than across the borders of the study site, which could bias a productivity index.

Local landscape configuration will influence the frequency and distance of brood movement and there is relatively limited data on brood movements for some wader species. However, there is some evidence to suggest that Eurasian Whimbrel, Northern Lapwing and European Golden Plover do not regularly make move long distances (> 400 m) from nest-sites (Parr 1980, Grant 1991, Blomqvist & Johansson 1995, Machín *et al.* 2017), although Black-tailed Godwit can regularly do so in agricultural systems (Schekkerman & Beintema 2007) and large movements (> 1 km) of European Golden Plover have been documented (Pearce-Higgins & Yalden 2004).

Renesting rates

High rates of renesting following nest failure within a wader population will influence the appropriate design of a productivity index. If renesting rates are low, a single peak count from a late-season visit of alarm-calling birds may approximate hatching or fledging success. However, when there are high rates of renesting, then hatching and fledging will be asynchronous and periodic counts of young at the fledging stage or periodic visits to count adults exhibiting brood-rearing behaviour are required. For example, for Northern Lapwing, which has high renesting rates, the most widely method adopted to produce a YFP metric uses visits at 3-week intervals with counts of well-grown young on each visit (Bolton *et al.* 2011).

Renesting rates will vary between species, with latitude and with the time during the incubation period that the clutch is lost, with nests lost early in incubation more likely to be replaced (Berg 1992, Gates *et al.* 2013). One study compared renesting rates between different wader species at the same study site (Hegyi 1996), providing support for Northern Lapwing (65%) having higher renesting rates than Common Redshank (52%) and Black-tailed Godwit (40%).

Timing and scheduling of survey visits

The frequency of survey visits will be partially determined by available resources and the number of sites being covered. When determining how many visits to make to a site, researchers must consider the benefits that accrue from gathering data from more sites compared with the benefits of more accurate data from each site. For all productivity indices, the detectability of territorial pairs early in the season will influence the number of early visits that are needed. In practice, of all the metrics reviewed here (Tables 2–4), none use more than three or four visits to estimate the number of territorial pairs. The most widely adopted HS metric (Grant *et al.* 2000) depends on obtaining accurate counts of displaying birds early in the season, and peak counts of pairs showing brood-rearing behaviours later in the season. If at least one early visit is during the pre-laying and territory establishment period, and one is within approximately 1 week of the peak of hatching, then these visits are likely to have the highest and most representative counts and the metric is likely to produce accurate estimates. When using an FS metric (Table 3), the propensity of adults to move broods later in the season and the synchronicity of hatching and fledging (driven by renesting rates) will also influence the required frequency of later visits. The benefit of more regular visits is that the locations of pairs can be followed more accurately. When using a YFP metric the survey schedule should be designed such that young are unlikely to fledge and leave the breeding grounds between visits without being recorded as well-grown young. Again, if brood movements are likely, then repeat visits in between the periodic counts of well-grown young may increase the accuracy of the metric.

There is much variation both in the diel timing of survey visits and the reporting of diel timing – and many studies did not report at all on the timing of survey visits (Tables 2–4). Broadly speaking, because early survey visits are intended to produce an estimate of displaying pairs, and for most species display activity varies significantly across the diel cycle with a peak in the early morning followed by a decline in activity during the day before a second evening peak, the diel timing of early visits is important. On later visits or revisits to known territories, where the detection of pairs is often dependent on agitation responses to a surveyor, the diel timing of visits is likely to be less important because there is limited evidence to suggest that adult brood-rearing vigilance varies diurnally. Because diel timing is more likely to influence data for early than late visits, specifying that 'five survey visits were carried out, with at least one visit to each site at dawn' may produce biased data if the distribution of the dawn visits between sites is not taken into account.

Choosing a metric

Figure 2 summarizes key considerations when deciding what type of productivity metric to use. The availability of experienced surveyors with knowledge of study species behaviour will also be important, and perhaps more so if producing an HS or FS metric where the surveyor must assess brood-rearing behaviours. Beyond this, the key questions to consider are: (i) can broods be accurately counted; (ii) do adults exhibit diagnostic agitation behaviour when they have young; (iii) can territories be separated, based on the territorial behaviour of the species, plumage characteristics or because the population is colour-marked; and (iv) renesting rates. We would suggest that these questions be considered in the order shown in Figure 2 to select or design a breeding productivity metric.

CONCLUSIONS

Long-term wader productivity monitoring embedded in national schemes which monitor numbers of breeding pairs or site occupancy could provide valuable information on landscape-scale determinants of demographic change, and early warnings on threats to wader populations and species. In the Dutch Breeding Bird Monitoring Program, for example, surveyors have been asked to record the presence of alarm-calling adult waders – 'Project Alarm' – during a specified 2-week period for each species, timed to coincide with the fledging period (Nijland 2007). Additionally, the UK BTO/RSPB/

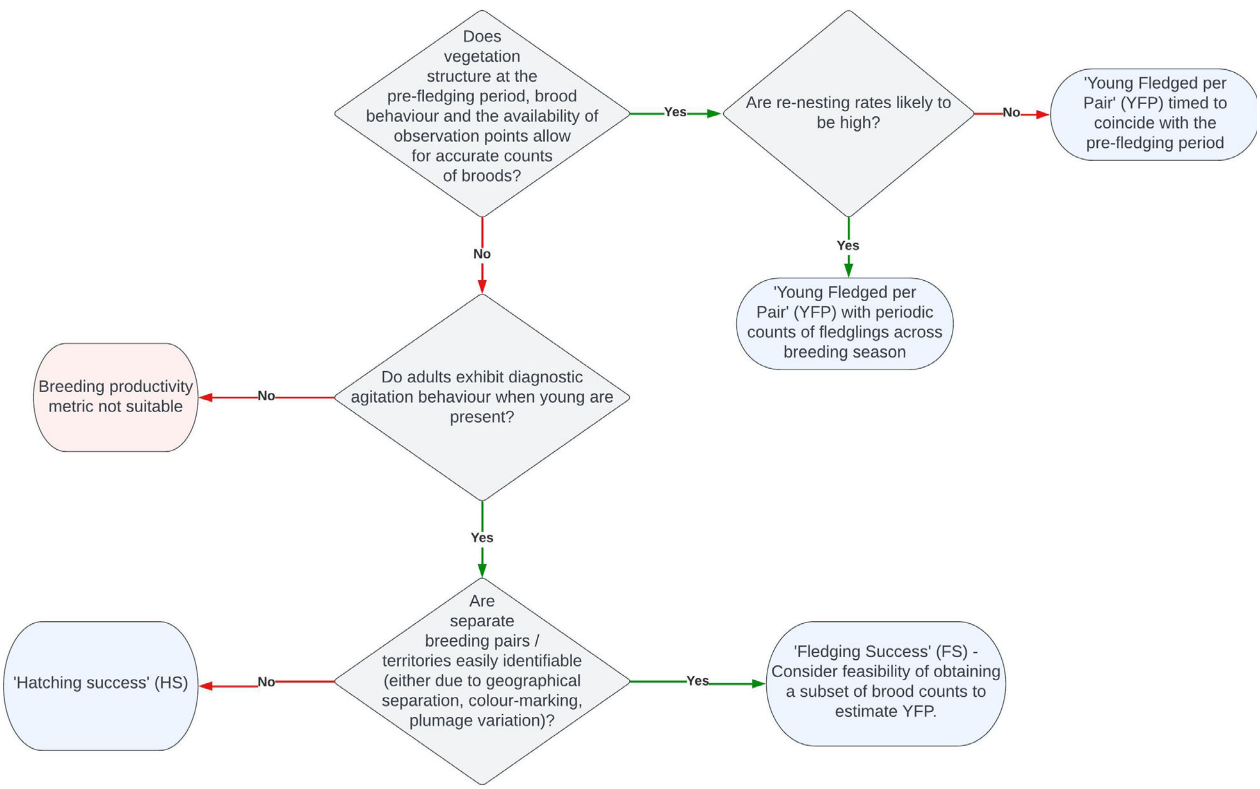

Figure 2. Questions to consider and decision-making process when selecting a breeding productivity metric for a wader species.

JNCC Breeding Bird Survey (Harris *et al.* 2021) is trialling additional visits to surveyed squares to record the presence of alarm-calling waders to obtain an index of productivity (M. Wilson pers. comm.). Robust evaluation of the effectiveness of survey-based productivity monitoring has been carried out for Eurasian Curlew and Northern Lapwing (Grant *et al.* 2000, Bolton *et al.* 2011) and similar evaluation for other species may facilitate wider adoption of these methods. Projects involving either adult or brood tracking may provide opportunities to ground-truth assumptions made during survey visits (Bowgen *et al.* 2022). Finally, we would suggest that globally there are many wader species for which the approaches described here would provide valuable information and be broadly suited and we hope this review encourages further development or adoption of these methods.

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AUTHOR CONTRIBUTIONS

David Jarrett: Conceptualization; writing – original draft; writing – review and editing; formal analysis; methodology. **Aleksi Lehikoinen:** Writing – review and editing. **Steve Willis:** Writing – review and editing; supervision.

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest.

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None.

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