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Intensive supplementary feeding improves the performance of wild bird seed plots in provisioning farmland birds throughout the winter: a case study in lowland England

Short title: Supplementary feeding of farmland birds in winter

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Abstract

Capsule

Sown bird-food plots with intensive (daily) supplementary feeding throughout the winter attracted substantially greater numbers of seed-eating farmland birds than control plots without additional feeding, whose planted seed resource was exhausted by midwinter.

Aims

We studied the performance of cultivated agri-environment scheme (AES) plots, predominantly growing winter bird seed (WBS), in addressing the 'hungry gap' of food scarcity for seed-eating farmland birds over the winter period. We assessed whether intensive supplementary feeding can improve AES-WBS plot performance to support greater numbers of birds over a longer period throughout the winter.

Methods

Five monthly bird counts were conducted from November to March on AES-WBS plots on three farms during three winters, alongside assessment of standing seed availability on the plants. Daily supplementary feeding of 8-25 kg of mixed seeds was scattered directly onto each treatment plot, with additional seed provided in hanging birdfeeders. The density of target farmland birds, and the depletion of the standing seed resource on plants, was compared between treatment plots and controls over the winter, using generalised linear models.

Results

Cultivated AES-WBS plots contained only c. 25% of their potential full capacity of seed availability at the beginning of winter, and this was exhausted by midwinter (January). Supplementary feeding attracted significantly greater numbers of farmland birds to AES-WBS plots than unfed controls, with up to 421 birds per plot, dominated by Common Chaffinches *Fringilla coelebs*, Yellowhammers *Emberiza citronella* and Common Linnets

Linaria cannabina. Bird densities on fed plots peaked in the late winter (February) 'hungry gap', but the magnitude of peak densities varied between years and farms.

Conclusion

Intensive supplementary feeding can substantially improve poor performance of AES-WBS plots in supporting farmland birds throughout the winter, particularly during the late winter 'hungry gap' when seed availability on AES-WBS plots is otherwise exhausted.

Introduction

The substantial decline of European farmland birds since the mid 20th Century is well documented (Benton et al. 2002, Donald et al. 2006). In the UK, abundance of specialist farmland birds declined by 75% between 1970 and 2018, and has continued to fall (Defra 2019), as part of the general decline in farmland biodiversity (Macdonald & Feber 2015). The introduction of the Environmental Stewardship agri-environment scheme (AES) in England in 1995, and its successors and parallel AES elsewhere in the UK, has yet to reverse this negative trend (Colhoun et al. 2017, Walker et al. 2018, Dadam & Siriwardena 2019, Daskalova et al. 2019, Defra 2019).

The collapse in UK bird populations, in particular, has been attributed to intensification of farming methods, including loss of semi-natural habitats, greater efficiency of harvesting and increased use and efficacy of pesticides (Chamberlain et al. 2000, Donald et al. 2006, Kleijn et al. 2011). This intensification has resulted in a loss of plant diversity in arable landscapes, and therefore fewer insects and seeds to support farmland birds (Robinson & Sutherland 2002, Marshall et al. 2003, Newton 2018).

The AESs designed to improve the UK's overall farmland biodiversity can be moderately successful for some taxa, such as small mammals and invertebrates (e.g. Broughton et al. 2014, Carvell et al. 2015). However, basic entry-level schemes (ELS), including provision of semi-natural field margins and relaxed hedgerow management, have had little widespread impact on farmland bird abundance, probably due to limited participation by farmers in arable options that could improve winter food availability (Davey et al. 2010, Baker et al. 2013). Comparisons of different levels of environmental enhancement showed increasing biodiversity benefits from basic ELS measures through to higher-level scheme (HLS, providing a wider range of AES options), or to organic farming, which delivered most improvements for biodiversity (Hinsley et al. 2010a, Hardman et al. 2016). For farmland birds, abundance appears to correlate closely with measures of food and habitat availability, and less intensive agricultural methods (Ponce et al. 2014, Newton 2017, Zellweger-Fischer et al. 2018).

In England, cultivated wild bird seed (WBS) plots were added to AES options in 2002 to address winter food scarcity for farmland birds (Stoate et al. 2004). WBS plots are typically small (< 1 ha) areas sown with a mix of seed-producing plants to produce food for seed-eating birds in autumn and winter, aimed at increasing winter survival and local breeding populations. However, assessments of farmland containing WBS plots have shown mixed results, with higher winter and breeding abundance for some species compared to controls, but also continued population declines, though to a lesser extent than areas without WBS plots (Siriwardena et al. 2010, Baker et al. 2012, Redhead et al. 2018, Walker et al. 2018, MacDonald et al. 2019).

As with AES in general, the reasons for a lack of greater success of WBS plots in reversing national farmland bird declines is probably due to poor uptake and implementation of the options, and insufficient delivery of food resources at landscape scales (Field et al. 2011, Daskalova et al. 2019, Walker et al. 2018). A potential limitation of WBS plots is insufficient food provision during the crucial ‘hungry gap’ for farmland birds, which occurs in late winter and early spring (February-April) when seed resources have typically become exhausted (Siriwardena et al. 2008, Field et al. 2011). To address this, supplementary ground feeding was added to AES options in England in 2011.

Several early versions of the supplementary winter feeding option were offered in England, and by 2020 the option required farmers to scatter 25 kg of mixed cereal and small oil-rich seeds once per week at each of two feeding areas on a participating farm, from December to April (Henderson et al. 2014, Rural Payments Agency & Natural England 2020). This feeding targeted seed-eating species of conservation priority, namely Yellowhammers *Emberiza citrinella*, Corn Buntings *Emberiza calandra*, Common Linnets *Linaria cannabina*, Tree Sparrows *Passer montanus* and Grey Partridges *Perdix perdix*.

Nevertheless, the efficacy of differing models of supplementary feeding are poorly tested, as few studies have investigated its specific contribution, and these have typically involved the weekly feeding option. Siriwardena et al. (2007) found that supplementary winter feeding alone improved local population trends for Yellowhammers on English farmland, but not Corn Buntings or Tree Sparrows. Higher volumes of supplementary food usage were associated with less steep local declines of Yellowhammer, Reed Bunting *Emberiza schoeniclus*, House Sparrow *Passer domesticus*, Dunnock *Prunella modularis* and Common Chaffinch *Fringilla coelebs*, with peak activity occurring during the late winter 'hungry gap', from February onwards (Siriwardena et al. 2007, 2008).

In the wider landscape, in areas where weekly supplementary food was delivered alongside WBS plots, Redhead et al. (2018) found higher winter abundance of Yellowhammers, Reed Buntings and Common Linnets, when compared to control sites, but individual effects were not separated. However, Aebischer et al. (2016) found that supplementary feeding of cereal grain was negatively associated with local abundance of farmland birds, but the seed mix and delivery was not a close match to the English AES option.

Siriwardena et al. (2006) reported that supplementary feeding sites with weekly replenishment showed a quadratic pattern of bird usage. Few birds utilised the food in the day following replenishment, rising to a peak after 3-4 days before falling again towards the end of the week as the food became depleted again. This suggests that the current AES option of weekly feeding may not be ideal as a reliable food source, with regular food depletion forcing the birds to disperse repeatedly to forage elsewhere, or risk starvation if food is not replenished soon enough. In the widest assessment, Henderson et al. (2014) found that the weekly feeding model was often poorly deployed and delivered inconsistent results, but could attract target priority species during the 'hungry gap'. However, Henderson et al. (2014) concluded that improvements were required to the supplementary feeding option and its delivery before its success could be definitively judged.

In this study, we provide new evidence of the role of supplementary feeding and AES (primarily WBS) plots in supporting priority farmland birds throughout the winter, by trialling the provision of more intensive feeding than prescribed under the English AES option. We compare bird counts over three winters on multiple WBS or proxy plots on three arable and mixed farms in lowland central England. We tested the daily supplementary feeding of birds on one set of plots on each farm against a set of unfed controls, and compared the densities of birds using each set. Uniquely, we also assessed the monthly availability of the seed resource on the plants on the AES-WBS plots over the course of multiple winters to determine if and when they became exhausted, and whether this pattern was consistent between years.

The results provide a useful case study of AES performance in feeding farmland birds throughout the winter, and the potential contribution of supplementary feeding. The results contribute to other studies highlighting the limitations of current AES options, and can inform further trials as a basis for AES refinements.

Methods

Site description

The study took place over three winter periods between 2016 and 2019 on three farms in Oxfordshire, southern England. Over Norton Park (ON: 51°57′13"N 001°31′52"W) and Walk Farm (WF: 51°57′44"N 001°30′15"W) are 1.6 km apart, and Honeydale Farm (HD: 51°52'12"N 001°34'51"W) is a further 9 km south-west from ON. The farm soils are largely of moderate quality agricultural land with a high limestone rock fraction (‘Cotswold brash’), and some heavier clay on parts of each.

WF and ON were under single management and have been in the English HLS or subsequent Countryside Stewardship scheme since 1998. ON lies on a suburban fringe and is a mixture of permanent pasture, arable, mature hedges, scrub and woodland, broadly unchanged for over 100 years, while WF is mainly arable with 20 ha reversion to flower rich meadows, mature hedges and some scrub. HD changed ownership in 2013 after several decades of continuously cropped barley and hay, with mature boundary hedgerows. In the two years prior to the study, HD shifted to mixed farming and environmental delivery (www.farm-ed.co.uk), including addition of arable rotations, additional hedge plantings, water capture and shelterbelts. No predator control or gamebird release occurs at the farms.

AES plots

The ON and WF farms have had WBS plots since 2006 as part of HLS, and the HD farm had them since 2015. During the study period, eight or nine plots were surveyed annually across all farms: ON had three WBS plots per year (1.0-1.75 ha each, total 3.25 ha) and HD had two or three such plots (0.05-0.8 ha each, totalling up to 1.0 ha). WF had three plots (0.1-3.0 ha, total 3.25 ha), but two of these were originally sown as AES annually cultivated margins (measuring 0.1-0.24 ha) containing a mixture of seed-bearing arable annual wildflowers and colonising wild plants. Due to similarities with WBS plots in providing a range of seeding plants, and to increase sample sizes, these two margins were used as proxies for WBS plots and pooled with the others for analysis (see below).

The seed mixture sown on WBS plots varied slightly across sites and years. Each sowing was a multi-species mix of one cereal (wheat, barley or triticale *X triticosecale* 25%) and varying proportions of five or more of Fodder Radish *Raphanus sativus*, Brown Mustard *Brassica juncea*, Quinoa *Chenopodium quinoa*, Common Millet *Panicum miliaceum*, Common Buckwheat *Fagopyrum esculentum*, linseed *Linum* spp. and Common Sunflower *Helianthus annus*. Crimson Clover *Trifolium incarnatum*, Lacy Phacelia *Phacelia tenacetifolia* and Annual Ryegrass *Lolium westerwoldicum* together were sometimes added to a maximum of 7% to increase diversity.

Most plots were renewed annually in late spring and the single remainder, containing kale *Brassica oleracea,* was a biennial crop. Plot locations were rotated as required, with fertiliser applied sparingly but no herbicides or insecticides were used. Establishment and coverage of the sown seed-bearing species was variable between plots, with extensive colonisation by wild species that also produce seed palatable to farmland birds, including White Goosefoot (or Fat Hen) *Chenopodium album*, Mugwort *Atemisia vulgaris*, Creeping Thistle *Cirsium arvense*, Oxeye Daisy *Leucanthemum vulgare*, Common Knapweed *Centaurea nigra*, campions *Salene* spp., hawkbits *Leontodon* spp. and grasses.

The two annually cultivated margins at WF contained a sown mixture of seed-bearing Corn Marigold *Glebionis segetum*, Cornflower *Centaurea segetum,* Corn Chamomile *Anthemis austriaca* and Common Poppy *Papaver rhoeas*. However, as with the WBS plots, they were extensively colonised by a similar broad group of wild seed-bearing plants, providing an abundant variety of seeds available to birds. Due to this overlap of seed resource, all plots were grouped in the study, hereafter referred to as AES-WBS plots. The nearest distance between plots on each farm ranged between 5 m and 760 m (mean 220 m), reflecting the patterns of farm management. All plots were located adjacent to one or more hedgerows.

Seed resource surveys

The coverage and standing seed resource on AES-WBS plots was assessed for cultivated and unsown (wild/feral) seed-bearing plants at monthly intervals between November and March, using established methods (Heard et al. 2012, Staley et al. 2018). On the initial annual survey (November), the percentage ground cover of plant species was estimated by eye for those greater than 1%. Seed availability on these plants was estimated on each monthly survey by assessing (by visual inspection) the proportion of seed remaining on standing seed heads. This was judged by examining a selection of seed heads while walking through the plot, inspecting those that were full, partially depleted or empty/damaged, and then deriving an overall estimate of remaining seed as a proportion (estimated in increments of 0.1 between 0 and 1) of the total for that species, compared to when all seed heads would have been full (i.e. representing no seed depletion).

Supplementary feeding

AES-WBS plots were selected to receive a treatment of supplementary feeding or to act as controls, comprising five controls and four treatment plots in winter 2016/17, six controls and three treatments in 2017/18, and five controls and three treatments in 2018/19. Each farm contained a mix of treatment (fed) and control plots (unfed), where each plot type mostly had the alternate as its closest neighbour. The two cultivated margins pooled with the WBS plots were split between a treatment and control.

Supplementary feeding took place within or directly alongside a treatment plot. Feeding was initiated approximately weekly in mid November, increasing to daily feeding by December as food became more rapidly depleted. The daily feeding regimen was aimed to be ad libitum, ensuring that food was constantly available, based on the plot area and amount of remaining seed the following day, ranging from 8-25 kg per plot of loose mixed seeds (approximately 15-30 kg per ha per day). The feed was manually scattered each morning, using a hand-held scooping tool, and distributed thinly over the plot and/or an adjacent track. Daily feeding lasted 130 days, until mid April, before tapering in frequency and amount to cease in mid May. This provided between 1.3 t and 3.3 t of scattered seed at each farm during winter.

The supplementary seed mixes differed between sites, but provided a combination of cereal and oil-rich seeds attractive to seed-eating farmland passerines. At HD the mix was a commercially produced wild bird seed, containing cereals, Common Sunflower (in husks, 37.5%) and kernels only (10%), Canary Grass *Phalaris canariensis* (15%), Common Millet and linseed (12.5% each). Supplementary food for ON and WF was produced on the farm and contained crushed barley & wheat (75%), Common Millet (8%), Rapeseed *Brassica napus* (8%), whole wheat (5%) and linseed (4%).

In addition to scattered supplementary feed, between two and four hanging bird-feeders (commercial bird-feeders designed for garden birds, minimum capacity 0.5 kg each) were also provided at each supplementary feeding plot. These feeders dispensed millet only, targeted primarily at Tree Sparrows and Reed Buntings, and were suspended approximately 1.5 m above the ground in adjacent hedges, or fixed on poles, bordering the plot. The feeders were replenished daily to provide a constant supply of millet seed throughout the winter period.

Bird surveys

Birds on each plot were surveyed once monthly between November and March, in the morning and during good weather (light wind, no rain), using established methods (Hinsley et al. 2010a). Timing between counts was three to five weeks apart, in the middle part of the month. All birds associated with each plot were counted to species on each survey, first by observing from a distance to assess overall numbers and composition in the plot and the associated hedgerows within 10 m (or less if plot were nearer). Plots were then walked through slowly to flush hidden birds for counting. Care was taken to avoid double counting of the same birds moving between plots, by noting the number and direction of birds leaving or arriving. Mobile birds were included in counts of only the first plot on which they were encountered, and simultaneous counts of neighbouring plots where made where possible, by two observers.

Analyses were limited to 12 species, consisting of priority farmland songbirds of conservation concern and/or species considered likely to benefit from provision of cultivated AES-WBS or supplementary feeding: Common Chaffinch, Brambling *Fringilla montifringilla*, European Greenfinch *Chloris chloris*, Common Linnet, European Goldfinch *Carduelis carduelis*, Eurasian Bullfinch *Pyrrhula pyrrhula*, Yellowhammer, Reed Bunting, Tree Sparrow, House Sparrow, Dunnock and Song Thrush *Turdus philomelos*. Records of potentially undesirable species were also noted, including Woodpigeon *Columba palumbus*, Common Pheasant *Phasianus colchicus*, Rook *Corvus frugilegus* and Carrion Crow *Corvus corone*.

Statistical analysis

Seed availability on the standing plants was assessed using an index calculated for each AES-WBS plot, derived by multiplying the percentage ground cover of each seed-bearing plant species by the estimated proportion of remaining seed on the seed heads. For example, if Quinoa covered 25% of a plot but only half of the seed remained on the heads, this would give 25 x 0.5 = 12.5 index of remaining seed. The individual indices for each plant were then summed to give an overall seed resource index for each plot, where complete coverage of seed bearing plants with full seed-heads would give an overall seed index of 100. The progressive seed depletion on each plot over the winter was therefore reflected in a declining index in each monthly survey.

Seed index on the plots was modelled over the winter periods using a generalised linear model (GLM) with a binomial error family and log link function. The monthly seed availability index per plot, expressed as a proportion (index value/100), was the response variable, and the predictor variables were survey month (November to March), site (farm), year (treated as a factor) and treatment (supplementary feeding or unfed control). We also tested for an interaction between treatment and year, and treatment and site.

Usage of the AES-WBS plots over the winter by the priority farmland birds was assessed using a GLM with Gamma error family and inverse link function. The response variable was total bird density per 0.1 ha of each AES-WBS plot. This density was calculated by dividing the monthly count of all target bird species by the plot area, which controlled for variation in plot size. The predictor variables were survey month, site, year (treated as a factor) and treatment. We included interactions between treatment and year, and treatment and site, to test for effects between farms and different winters. Initial data exploration indicated distinct peaks in the bird data over the winter duration, and so a quadratic effect of month was included in the model. Site and year were treated as fixed variables as we lacked a sufficient number of factor levels to include them as random terms (Harrison et al. 2018).

Results

Seed availability on the plots

Modelled seed availability on plants sown on AES-WBS plots was strongly related to the monthly progress of winter, with no significant effect of site, year or treatment (Fig. 1 and

Table 1, McFadden's Pseudo R-squared: 0.29). At the beginning of winter (November), typical seed availability on plots was only a quarter (~25%) of the potential full capacity, and then declined rapidly over subsequent months. By January, seed availability on the plots was typically exhausted, with negligible seed remaining on the plants and therefore offering little or no food available to birds for the rest of the winter. Indeed, from January onwards no plot had a seed availability index greater than 7%, and most were zero (Supplementary Table S1).

The cover of cultivated plants on all plots averaged 50-58% per year, with consecutive annual ranges of 0-100%, 14-96% and 10-100% for individual plots. The remaining area of each plot was occupied by self-sown plants, including means of 71% (range: 62-90%) and 90% (range: 86-94%) for the two annually cultivated margins, comparable with the other WBS margins.

Bird usage of the plots

Overall, priority farmland bird density was substantially greater on plots with supplementary feeding compared to unfed controls; bird densities varied over the progression of the winter months and showed a significant site effect, and also a significant interaction between treatment and year (Fig. 2 and Table 2, adjusted R-squared: 0.82). Bird densities on control plots were typically low from the beginning of winter (November) and declined over subsequent months, with negligible birds using these plots by midwinter and thereafter. Model estimates of bird densities on these control plots were generally fewer than 10 birds per 0.1 ha throughout the winter (see also Supplementary Figure S1).

However, on treatment plots with supplementary feeding, bird densities on two sites (WF and HD) showed a quadratic trend over time (Fig. 2). Densities typically began the winter similar to the controls (when supplementary feeding was just beginning) before increasing to peak at substantially greater densities in late winter (February), with modelled estimates of up to approximately 77-90 birds per 0.1 ha, before then declining again in March.

This pattern of bird densities was similar in all years, although the magnitude of peak densities on the treatment plots varied between winters (Fig. 2). The third farm (ON) had consistently and significantly lower densities on treatment plots than the other farms, largely accounting for the site effect, although these values were generally still greater than on the controls. Lower bird densities at ON apparently reflected the relatively large size of the supplementary feeding plots on this site (1.0-1.75 ha) compared to the others (0.1-0.8 ha). Maximum annual winter counts of birds using individual supplementary feeding plots were typically in the hundreds at all three farms (Supplementary Table S2), with peak counts on each farm of 250, 411 and 421 individuals on a single plot of 0.1 to 1.7 ha in size. This compared to peak farm counts of only 33, 53 and 202 birds for control plots. The bird species using the supplementary feeding plots were dominated by Common Chaffinch, Yellowhammer and Common Linnet (Table 3), with other species occurring in low densities (e.g. Reed Bunting) or being more sporadic in occurrence (e.g. Brambling).

House Sparrows and Tree Sparrows were not recorded on any plots, despite the former at least being present on at least two of the farms. Similarly, single Corn Buntings *Emberiza calandra* were recorded at feeding plots only twice, despite a population being present adjacent to one site. Common Linnets were recorded in sporadic flocks of up to 200 and 300 individuals on a single plot, and the variation in this species was likely to be a contributing factor in the significant annual effect of bird density (Table 3, Supplementary Table S2).

Most birds were observed feeding on the scattered seeds in the open or among the plot vegetation, and frequently moved between a plot and adjacent hedgerows or trees. The birdfeeders located at each plot were particularly used by Reed Buntings.

Potentially undesirable species (for some land managers) were recorded in low average numbers on the 3-4 annual supplementary feeding plots across all winters, with mean (and maximum) counts per plot of 2.7 (90) Woodpigeons, 1.2 (60) Rooks, 0.8 (22) Carrion Crows and 0.7 (9) Common Pheasants.

Discussion

The results indicate a poor performance of AES-WBS plots in supporting farmland birds on the study farms throughout the winter, with sown birdfood patches holding limited seed that quickly depleted by midwinter. The number of birds using plots, and their period of use over the winter, was greatly enhanced by intensive supplementary feeding, which supported substantially greater numbers of birds to the end of the winter period. These results demonstrate in detail that plots sown with seed-bearing plants, and aimed at supporting seed-eating farmland birds, largely fail to provide food throughout the full winter period.

In particular, we found that the cultivated AES-WBS plots already had typically low levels of seed availability on the standing seed-heads by the beginning of winter, at only about a quarter of their potential full capacity. This was partly due to poor plant establishment, with an average of only approximately half of a plot area being occupied by cultivated plants intended to produce seed for birds. The remainder of plot areas was covered with self-sown arable plants that also produced seed, particularly White Goosefoot, Oxeye Daisy, Common Knapweed, Mugwort and thistles. Some late flowering of plants (too late in the year to develop seed) and seed having already been exploited by birds during autumn (pers. obs.) also reduced the plots' capacity to provide seed throughout winter. This is despite conscientious plot management from the highly motivated farm managers, and may reflect vagaries of poor weather, differing cultivation requirements, plant competition and pests such as Rabbits *Oryctolagus cuniculus* during establishment.

The seed on the seed-heads of cultivated and self-sown plants was essentially exhausted by midwinter, which was consistent between years, and so the AES-WBS would be unable to support granivorous birds into the late winter period when food is likely to be most limiting for survival (Siriwardena et al. 2008). The negligible numbers of birds present on the control plots from midwinter indicate that seeds were genuinely scarce, and had not simply fallen from the seed-heads to continue to be available to birds foraging on the ground. Bright et al. (2014) showed that fallen seeds were actually scarce on the ground in WBS plots, presumably because they are consumed before or just after they fall. Meanwhile, birds on the treatment plots in our study were able to forage seeds on the ground that were regularly replenished by supplementary feeding.

There are several other direct assessments of seed availability on AES/WBS plots over the winter. Bright et al. (2014) and Staley et al. (2018) surveyed English cultivated ELS and/or HLS WBS patches, where the seed resource was shown to become heavily depleted or exhausted by late winter (January-March). The study by Staley et al. (2018) also showed that initial seed availability was already low when winter began, with a mean of just 40% remaining on sown plants in October-December. Field et al. (2011) found a similar pattern of low seed availability on cultivated WBS plots in England, although both of these studies also showed that extensive cover of wild plants on the plots contributed seeds for target bird species, as in our study.

Also similar to our results, Hinsley et al. (2010b) and Heard et al. (2012) showed that depletion of the seed resource on WBS patches was exponential, with an initial ~10% depletion in October falling to 50% by late November and more than 90% by January.

Our results, alongside these previous studies, indicate that recent AES options for cultivating seed-bearing plants to support farmland birds appear to seriously underperform in delivering food resources throughout the winter, at least in England. In particular, this supports the recognition that cultivated WBS plots appear to fail to deliver sufficient food resources during the crucial ‘hungry gap’ in late winter (Henderson et al. 2014). As such, expanding provision of WBS plots alone as a major component of AES appears unlikely to enhance winter survival of farmland birds enough to reverse their population declines (Walker et al. 2018). The limitations of WBS plots in providing sufficient food resources throughout the winter have been acknowledged for more than a decade (Siriwardena et al. 2008, Hinsley et al. 2010a, Field et al. 2011). The additional AES option of supplementary feeding, introduced in England in addition to WBS plots to support farmland birds, appears to have some potential benefits (Henderson et al. 2014). However, the prescribed delivery of supplementary feeding in AES options, of 25 kg provided weekly, is likely to result in food being depleted before replenishment, and this is reflected in birds dispersing from the site (Siriwardena et al.

2007). This factor may largely underpin the inconsistent performance of AES supplementary feeding options in delivering the required objectives for farmland birds (Henderson et al. 2014).

If farming policy shifts towards subsidies dependent on providing ‘public goods’, such as maintaining populations of farmland birds, as is expected in the UK (Bateman & Balmford 2018), then the existing AES options appear to provide broadly inadequate outcomes. Under any policy of ‘payment by results’ for farming subsidies (Herzon et al. 2018, Chaplin et al. 2019), positive results of feeding birds through the hungry gap may be difficult to verify. Chaplin et al. (2019) showed that wild bird seed plots had moderately greater establishment of cultivated plants when management was shifted to a results-based approach. However, as our result indicate, more plants may not necessarily translate into substantially greater seed availability that lasts through the winter. Assessing results more directly, by measuring bird abundance at plots or supplementary feeding sites, could be challenging due to temporary or permanent depletion of food resources under current prescriptions.

The results of our study indicate that increasing the frequency and quantity of supplementary feeding can consistently attract large numbers of seed-eating birds through the entire winter period including priority Yellowhammers and Common Linnets, and particularly during the ‘hungry gap’ of January to March. This pattern was similar to that reported by Siriwardena et al. (2008) for late winter peak counts of Yellowhammers, Common Chaffinches, Reed Buntings and Dunnocks at supplementary feeding stations. However, our results appear to be the first to directly compare the effect of supplementary feeding in relation to WBS plots and their seed availability.

Our study of three relatively nearby farms indicated some significant variation in the number or density of birds attracted to plots on different sites, which may reflect populations of e.g. Yellowhammers in the local landscape (Siriwardena & Stevens 2004). Annual variation was likely driven by influxes of species that were somewhat sporadic in occurrence, such as Bramblings and Common Linnets, which may be influenced by migratory behaviour at larger scales (Browne & Mead 2003, Swann et al. 2014).

The general annual pattern of bird numbers was a gradual build-up from early winter, before peaking in late winter when food is presumed to be most limiting in the landscape. As such, the large aggregations at our supplementary feeding sites probably reflected wider food scarcity and increasing numbers of birds being attracted to a relatively good food source as others became depleted (Siriwardena et al. 2008). The annual decline of birds in March was presumably due to dispersal prior to breeding.

Despite the significant effect of supplementary feeding, our study has important limitations and caveats. The small sample of three study farms is not necessarily representative of arable or mixed farming in England, although they share many features of arable cropping and livestock pasture that are common in the central region of the country. The HD site was somewhat atypical of a conventional farm in its transition to trialling of sustainable low inputs and environmental enhancements, but it was still essentially a mixed arable and livestock farm. The proximity of the three farms may limit their independence, although being at least 1.6 km distant they were far enough apart to host different flocks of birds (Siriwardena 2010). However, the plots and treatments were not in a randomised study design, but reflected the existing constraints and patterns of farm management. This may also have reduced their independence due to specific plot effects of surrounding landscape and trees etc., or the influence of nearby plots.

To minimise these limitations as much as possible, care was taken to distinguish birds using individual plots that were close together, and it seemed unlikely that nearby plots could influence each other's seed availability. Nevertheless, flocks of birds and much greater abundance of food on treatment plots could potentially have attracted birds away from control plots. However, there may have instead been a conservative effect of supplementary feeding, with counts possibly inflated on a control plot due to exploring birds spilling over from a nearby feeding plot, rather than the other way around.

Pooling of the two annually cultivated margins with the WBS plots was not considered to have undermined assessment of the latter, as these margins were largely covered by similar wild seed-bearing plants as much of the average WBS plot. Additionally, the two margins were split between supplementary feeding and a control, to prevent undue influence on either plot treatment.

Despite the limitations, the overall results are an informative case study, if not a definitive trial. Nevertheless, we suggest it could act as a proof of concept for a larger scale trial of enhanced supplementary feeding based on the regimen used at our study farms. The costs and practicality of adopting daily supplementary feeding, and to produce and distribute perhaps in excess of 3.3 t of mixed seeds per farm per winter, may be challenging and possibly prohibitive for intensive commercial agriculture.

The ON/WF farm manager's conservative 'best estimate' of the seed production on the annual WBS plots was approximately 0.5 t per ha in August/September (typical 'harvest time' for standard crops), based on experience (pers. obs.). If valid, this would be approximately half the weight of direct supplementary feeding received per ha over the winter. Under such circumstances, direct feeding onto arable stubbles may seem more economical than growing plots of mixed seed-bearing plants. However, AES-WBS plots can supply other valuable services for biodiversity that are more difficult to quantify, such as habitat resources for pollinators, mammals and nesting birds (including gamebirds), and the habitat itself could be a visual cue to attract wintering farmland birds to search for food within them. Such potential factors make the costing of AES-WBS plots difficult to assess.

Regular feeding in the same places throughout the winter will potentially carry an increased risk of disease transmission and predation for farmland birds, although this would be minimised by multiple feeding sites and broadcasting seed widely within plots. Automated feeding stations could reduce the time input required to distribute food, but this would come with additional cleaning costs to minimise disease, and also increase the concentration of birds around feeders (while reducing access for competing individuals), and so a wider broadcast of seed within plots seems more beneficial.

Such considerations of cost and practicality are important, but our results add to the existing literature that indicates the scarcity of natural food for birds in modern farmed landscapes, and also the relative failure of current AES options in adequately addressing this to reverse farmland bid declines (Baker et al. 2013). A potential incentive for adopting more intensive supplementary feeding could be the more consistent numbers of feeding birds throughout the winter, acting as a verifiable benefit under a subsidy regime of ‘public goods’ and ‘payment by results’ (Bateman & Balmford 2018, Chaplin et al. 2019).

In summary, our small study detected a significant positive effect on several species of priority farmland bird by providing daily supplementary feeding onto WBS plots. This feeding substantially increased the performance of WBS plots in supporting seed-eating farmland birds throughout the winter, and during the crucial ‘hungry gap’ period of late winter. WBS plots on their own were shown to perform poorly in providing over-winter seed resources for birds, delivering below-capacity levels of seed that quickly depleted, which further supports the limited evidence from other studies. Expanding the study to a wider trial of supplementary feeding, including a set of more isolated control locations, would be useful in helping to identify and design practical enhancements to AES aimed at reversing farmland bird declines. Future studies should also assess the most effective spatial distribution of feeding sites, and volume of food supplied, to achieve maximum benefits at minimum public and commercial costs.

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Tables

Table 1. Estimated regression parameters, standard errors, Z values and P values for the binomial GLM exploring natural seed availability on plots cultivated to provide wild bird seed. McFadden's Pseudo R-squared: 0.29.

	Estimate	Standard error	*Z* value	*P* value
Intercept	0.144	0.756	0.190	0.849
Month	-1.516	0.564	-2.687	0.007

Table 2. Estimated regression parameters, standard errors, *T* values and *P* values for the Gamma GLM exploring bird density. Adjusted R-squared: 0.82.

	Estimate	Standard error	*T* value	*P* value
Intercept[a]	0.136	0.034	4.002	<0.001
poly(Month, 2) (1)	0.935	0.397	2.354	0.020
poly(Month, 2) (2)	0.251	0.283	0.888	0.376
Treatment (Fed)	-0.109	0.035	-3.132	0.002
Year (2016/17)	0.165	0.067	2.449	0.016
Year (2017/18)	0.189	0.080	2.357	0.020
Site (ON)	0.084	0.027	3.112	0.002
Site (WF)	-0.002	0.005	-0.324	0.747
poly(Month, 2) (1):Treatment (Fed)	-1.062	0.403	-2.634	0.010
poly(Month, 2) (2):Treatment (Fed)	-0.115	0.290	-0.398	0.692
Treatment (Fed):Year (2017)	-0.172	0.068	-2.538	0.012
Treatment (Fed):Year (2018)	-0.183	0.081	-2.262	0.026

Single-term deletions (Chi-sq test):				
	Δ Degrees of freedom	Δ Deviance	Δ AIC	P value
Site	2	30.87	18.32	<0.001
poly(Month,2):Treatment interaction[b]	2	11.82	10.68	0.014
poly(Month,2):Treatment interaction[c]	2	16.05	7.6	0.003
Treatment:Year interaction	2	18.06	9.06	0.001

[a] For Intercept continuous terms (Month) are set to a value of zero, and categorical terms (Treatment, Year, and Site) are set to their reference levels of 'Control,' '2016/17' and 'HD' respectively.

[b] Compared to a model where 'poly(Month, 2)' (quadratic curve) is replaced with 'poly(Month, 1)' (linear relationship) throughout the model.

[c] Compared to model without interaction.

Table 3. Mean and minimum-maximum range of counts of birds on control and treatment (SF: supplementary feeding) plots grouped across three farms in three winter periods (2016/17 to 2018/19).

Species	2016/17				2017/18				2018/19			
	Control (n = 5)		SF (n = 4)		Control (n = 6)		SF (n = 3)		Control (n = 5)		SF (n = 3)	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Common Chaffinch	2.6	0-30	24.1	0-60	4.2	0-100	46.9	0-100	7.5	0-100	44.1	0-130
Yellowhammer	8.3	0-60	18.4	0-50	1.2	0-15	30.4	0-130	1.0	0-8	29.3	0-100
Common Linnet	2.0	0-30	5.4	0-55	1.8	0-30	54.2	0-120	5.5	0-80	79.5	0-300
European Goldfinch	0.6	0-6	1.8	0-15	0.3	0-6	0.9	0-5	1.2	0-20	0.5	0-4
Dunnock	0.7	0-3	1.8	0-7	0.3	0-3	1.4	0-5	0.5	0-3	1.1	0-2
Song Thrush	1.3	0-9	1.1	0-8	0.3	0-5	0.2	0-1	0.6	0-4	0.0	0-0
Brambling	0.0	0-0	0.3	0-2	3.0	0-80	7.8	0-40	0.0	0-1	0.1	0-1
Reed Bunting	0.3	0-5	0.3	0-3	0.3	0-6	5.0	0-26	0.2	0-2	3.1	0-15
Eurasian Bullfinch	0.1	0-2	0.1	0-1	0.0	0-0	0.1	0-1	0.0	0-0	0.0	0-0
House Sparrow	0.0	0-0	0.0	0-0	0.0	0-0	0.0	0-0	0.0	0-0	0.0	0-0
Tree Sparrow	0.0	0-0	0.0	0-0	0.0	0-0	0.0	0-0	0.0	0-0	0.0	0-0

European Greenfinch	0.0	0-0	0.0	0-0	0.0	0-0	0.1	0-1	0.0	0-1	1.7	0-21
All species	15.8	0-93	53.1	0-131	11.4	0-202	146.9	5-411	16.5	0-167	159.4	3-421

Figures

Figure 1. Decline in monthly natural seed availability (on seed heads of cultivated or wild plants) over winter on cultivated wild bird seed plots, summarised over three winter periods. Fitted line represents model predicted natural seed availability, and error bars represent standard error. Points represent raw data of seed availability on plots with supplementary feeding (shaded black, n = 10) or unfed controls (grey, n = 16), although there was no significant difference between these treatments in the GLM, hence we fitted a single line.. Data were combined from monthly plot surveys in 2016/17, 2017/18 and 2018/19 (respective annual sample sizes: supplementary feeding = 4, 3 and 3 plots; controls = 5, 6 and 5 plots).

Figure 2. Change in winter monthly bird density per 0.1 ha year on wild bird seed plots divided into supplementary fed (black) and control unfed (grey) plots. Fitted lines represent model predicted bird density, and error bars represent standard error. Fitted lines are shown for the three study sites: HD (solid line), ON (dashed), and WF (long-dashed). Points represent raw bird density recordings on the three study sites: HD (circles), ON (triangles), and WF (squares). Panels represent the three winters of the study: 2016/17, 2017/18 and 2018/19. Respective annual sample sizes for the number of supplementary fed plots were: 2, 1 and 1 (ON); and 1 each in all three years (HD and WF). For controls the respective sample sizes were: 1, 2 and 2 (ON); 2, 2 and 1 (HD); and 2 in all years (WF). For more detail of the control data and fitted lines, see Supplementary Figure S1.

Supplementary Material

Supplementary Table S1. Monthly survey counts of seed availability on plots, recorded on three farm sites in three winter periods. For calculation of seed index, see Methods.

Supplementary Figure S1. Change in bird density per 0.1 ha between November and March on control (unfed) plots. Fitted lines represent model predicted bird density, and error bars represent standard error. Fitted lines are shown for the three study sites; HD (solid line), ON (dashed), and WF (long-dashed). Points represent raw bird density recordings on the three study sites; HD (circles), ON (triangles), and WF (squares). Panels represent the three seasons of the study, starting in winter 2015/16 and finishing in winter 2017/18.

Supplementary Table S2. Monthly survey counts of priority farmland birds on plots, which received supplementary feeding or were controls, recorded on three farm sites in three winter periods.