



Habitat selection of the threatened northern lapwing (*Vanellus vanellus*) breeding in an intensive agroecosystem

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Abstract

Land use changes induced by agricultural intensification and wetland reclamation are negatively impacting farmland biodiversity. In this context, information on habitat selection of wildlife can be fundamental to developing effective conservation actions targeting biodiversity conservation, shedding light on fine-scale species-habitat relationships. We studied nesting and foraging habitat selection in a declining shorebird, the northern lapwing (*Vanellus vanellus*), in the intensive agroecosystem of the Po Plain, Italy. Out of 67 nests we found, 94% were in wetlands and summer crops, wetlands being the only habitat actively selected. The likelihood that a pair of lapwings nested in a cropland patch was inversely proportional to plant height and ground cover, which likely explains why summer crops were more favourable than winter and hay crops to the species nest settlement. Tracking data showed that GPS tagged lapwings ($n=14$) stayed close (207 ± 153 m) to their nests throughout the entire breeding period, and they selected the same habitat types for foraging as for nesting. Home ranges averaged 56 ha (range=3–161 ha), and were on average larger than previously reported from elsewhere, probably because the overall low quality of the habitat in the Po Plain. Home ranges of lapwings breeding in croplands were larger and significantly more cohesive than those of birds breeding in wetlands, suggesting a need to explore larger areas to find suitable foraging patches. The dual nesting and feeding strategy highlighted the crucial importance of both wetlands and, unexpectedly, summer crops for this species of conservation concern. To provide suitable habitat for breeding lapwings, restored wetlands must be well managed and attention should be given to intrafield heterogeneity, possibly increasing bare ground patches.

Keywords *Vanellus vanellus* · Italy · Reproduction · Animal movement ecology · GPS · Wetlands

Introduction

Land use change, mostly in the form of rapid expansion, intensive management, and direct exploitation, has been the leading cause of global biodiversity loss in recent decades, ranking as the top driver of changes in species populations, community composition, ecosystem structure, and function (Blavanera et al. 2019; Jaureguiberry et al. 2022). Two of the primary drivers of such effects in both the past and the current century are the ongoing reclamation and degradation of inland wetlands, with an estimated 75% decline in their extent (Reis et al. 2017), and agricultural intensification, which, globally, poses the second greatest threat to red-listed species after overexploitation. Indeed, the expansion and intensification of agricultural activity and land use change are a threat to >5,000 species, accounting for 62% of all those at risk of extinction (Maxwell et

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al. 2016). Moreover, human land use and land reclamation have strongly reduced the extent and worsened the ecological conditions of wetlands in most agricultural landscapes (Gardner et al. 2015). At present, the long-term history of wetland drainage and degradation has been partially offset by restoration and wetland creation in rural areas (Murray 2023), but the existing efforts might still be insufficient to prevent ongoing biodiversity loss (Strayer and Dudgeon 2010) and preserve a range of ecosystem types (Tilman et al. 2001).

In this context, improved information on animal movements and habitat use can help understand the long-term consequences of habitat loss and degradation in highly disturbed landscapes, such as agroecosystems and wetlands, by providing valuable insights into individual behavior and population spatial dynamics (Bowler and Benton 2005). Birds are recognized as particularly useful environmental indicators and are considered a surrogate of wider farmland biodiversity (Butler et al. 2010; Gregory and Strien 2010). Birds are also scale-sensitive to stressors, and their distributions are shaped by land use gradients and human disturbance (Jones 2001; Benítez-López et al. 2017). Therefore, studying their habitat selection can shed light on how population dynamics are shaped by individual-level selection of higher-quality foraging or breeding patches in degraded and restored habitats (Petit and Petit 1996; Jourdan et al. 2021). This can be crucial for the near future, as more than 1,700 bird species are expected to become endangered by 2070 due to land use change alone (Powers and Jetz 2019). Among these, farmland and wetland-dwelling species are particularly at stake, as they need to cope with the challenge of finding resources in habitats regulated by both natural cycles and intensive anthropogenic activities.

In this study, we studied the northern lapwing (*Vanellus vanellus*), a medium-sized migratory shorebird that breeds in open habitats with short vegetation (Klomp 1954; Galbraith 1989), such as wetlands, farmlands, and pastures (Cramp and Simmons 1993; Larsen et al. 2003). In recent decades, changes in agri-environmental management policies in Europe have led to lower reproductive success rates in northern lapwings, leading to a marked decline in this iconic species throughout Europe. As a consequence, the species was listed by the IUCN as Threatened with Extinction (BirdLife International 2015). Indeed, intensification and changes in agricultural practices, especially grassland drainage (Taylor and Grant 2004), the use of inorganic fertilizers (Dauwe et al. 2009), reseeding (Báldi et al. 2005), the increased expansion of winter crops (Eggers et al. 2011), and the loss of wetlands, field margins, and semi-natural habitats (BirdLife International 2024) are severe threats to lapwings. Regardless, the species remains hunted in six European countries (Sibille et al. 2020).

Our study aimed to assess northern lapwing nest site and foraging habitat selection in one of the most intensive agroecosystems in Europe, the Po Plain in Italy (Severini et al. 2022; Assandri et al. 2023), which is characterized by the coexistence of intensive farming and recently established marshland habitats on arable land to promote biodiversity. The overarching goal is to highlight the ecological and conservation needs of the species in disturbed environmental matrixes. We investigated the behaviour of GPS-tagged birds breeding in farmlands and wetlands to assess the relative importance of the two habitats and we defined how animals that reside in structurally different habitats included in the same agroecosystem matrix select habitats. According to previous studies conducted in different contexts (Devereux et al. 2004; Smith 2006; Eggers et al. 2011; Schmidt et al. 2017), we expected that nest site and foraging habitat selection are correlated with specific land cover features (e.g., low plant height, sparse vegetation, and proximity to wetlands). Additionally, we expected that foraging individuals select a mixture of habitats, including summer crops, pasturelands, and wetlands (Cramp and Simmons 1993; Wilson et al. 2004; Kubelka et al. 2012).

Materials and methods

Study area

Our study was conducted in the central-eastern Po Plain in Italy, at the crossroads of the Alps, the Northern Apennines, and the Adriatic Sea. The landscape of the area is characterized by pervasive human disturbance, mainly in the form of intensive agriculture. Agricultural expansion and intensification have played key roles in determining dramatic landscape changes over the past several centuries, particularly the consistent expansion and intensification of maize cultivation for silage production (Bava et al. 2014; Tabacco et al. 2018). However, beginning at the end of the 1990s, the application of EU agri-environmental measures aimed at creating and managing environments for wild fauna and flora on set-aside arable land brought numerous farms to restore thousands of hectares of wetlands, grasslands, shrubs, and hedgerows (Regione Emilia-Romagna 2019). The application of these biodiversity conservation actions in the central-eastern Po Plain helped create low-water wetlands with plenty of mudflats, which are now becoming usual nesting sites for birds, including Northern lapwings (Marchesi and Tinarelli 2007). Within this area, we investigated seven different localities representative of the typical Po Plain landscape, including two protected wetlands, Ostellato (province of Ferrara, delta plain) and Selva malvezzi (province of Bologna, alluvial plain), and five

agricultural areas, Viadana (province of Mantova, alluvial plain), Cervia (province of Ravenna, coastal plain), Buda, Budrio, and Sesto Imolese (province of Bologna, alluvial plain; Supplemental Material Fig. S1).

Nest surveys

Starting from the beginning of April 2022 to the middle of May 2022 and then from the beginning of April 2023 to the middle of June 2023, each study site was inspected for the presence of nesting northern lapwing pairs. A total of 27 survey days (44 person-days) were performed in 2022, and 43 survey days (61 person-days) in 2023. A longer survey was necessary in 2023 due to an extreme flooding event that occurred in May. Direct visual observations were made from a distance with the aid of telescopes in areas that had been previously identified based on the detection of vocalizing pairs. Active nests were quickly reached (to cause the least possible disturbance to the breeding pair), and we recorded the number and incubation stage of the eggs (Päässeen et al. 1984) and the exact location of the nest (averaged GPS coordinates), with a precision of approximately 3 m.

GPS tracking

Lapwings were equipped with GPS devices at each of the seven study sites during the breeding seasons of 2022 and 2023. Once an easily accessible incubating northern lapwing nest had been located, a spring trap was placed on the nest (Supplemental Material Fig. S2). After being flushed to place the trap, individuals rapidly returned to the nest (range: 2–19 min). Trapped individuals were ringed (with both metal and darvic rings), weighed, photographed to determine sex after release (Meissner et al. 2013; Blasco-Zumeta and Heinze 2018), and equipped with a GPS device using leg-loop teflon harnesses (Supplemental Material Fig. S3). We used Lotek PinPoint Cell Solar 2G GPS-GSM devices in 2022 and Interrex/Druid Mini solar-powered 2G GPS-GSM devices in 2023, weighing 6.3 ± 0.4 g. Both units were the same with respect to their design and performance. We optimized the schedule to preserve the battery life by setting the interval at which the device recorded the locations at once every 2 h. GPS deployment was performed only if the overall weight of the device and the teflon harness represented $<3.5\%$ of the body mass. Handling and tagging lasted approximately 20 min. In 2022 only, a wildlife camera (set to take a picture every 2 h) was placed to aim at each nest to record the nest's fate and hatching date.

GPS data were filtered with the *R* package *SDL filter* (Shimada et al. 2016) to remove spatial and temporal duplicates and unrealistic fixes based on speed, considering a conservative threshold of 60 km/h. To make the number of

fixes comparable between individuals and years and reduce spatial autocorrelation, we subsampled our tracks, keeping one fix every six hours with a 15-minute time tolerance with the *R* package *amt* (Signer et al. 2019). In 2022, data related to the breeding period were obtained based on the average length of the lapwing breeding season in Italy (i.e., 25 days of incubation followed by 35–40 days to raise the young; Brichetti and Fracasso 2018–2022). If the hatching date was known, we considered the period from hatching to the following 30 days; if not, we used the day after deployment plus 30 days. By doing so, we could be sure that our data would fall within the fledging date. Since we had evidence that camera traps were a source of stress for the birds, in 2023 we refrained from using them. Therefore, we assessed each breeding phase through direct field observations and kept only the locations falling between the day after deployment and the fledging date (37 days on average, deemed comparable to the data from 2022). We excluded individuals who failed reproduction because they were no longer tied to the nest site and started wandering, sometimes at considerable distances from the study area. We also excluded three individuals (one in 2022 and two in 2023) due to GPS malfunctioning, resulting in seven individuals in both years. The details of the 14 individuals included in the foraging habitat selection investigated by means of GPS tracking are available in Supplemental Material Table S3.

Landcover survey

To describe the landscape composition surrounding each lapwing nest, we created a 500-m buffer around each nest (Fig. 1). Similar studies on habitat use in breeding northern lapwings have used a comparable nest buffer size (Horvat and Denac 2019; Sakseide and Dale 2023), and GPS tracking confirmed the goodness of fit of this threshold, with $80.0 \pm 17.3\%$ (mean \pm SD) of all fixes falling inside the nest buffer zone of the matching individual. Environmental surveys to characterize land cover parcels were then carried out within this buffer. Several new nests were discovered during the land cover mapping and were included in the subsequent analysis. A comprehensive land cover map for the study area was obtained through photointerpretation followed by field validation. An orthophoto with a mapping scale below 1:10,000 was printed for every study site. Then, each discernible parcel captured in the photograph and included in the buffer underwent physical inspection to ascertain its precise boundaries and dimensions, thereby delineating distinct landscape parcels. Each parcel was attributed to a land cover type (Supplemental Material Fig. S4). A total of 24 land cover types were identified (Supplemental Material Table S1, Fig. S5) and subsequently merged into nine habitat categories. Land cover types included in the analysis

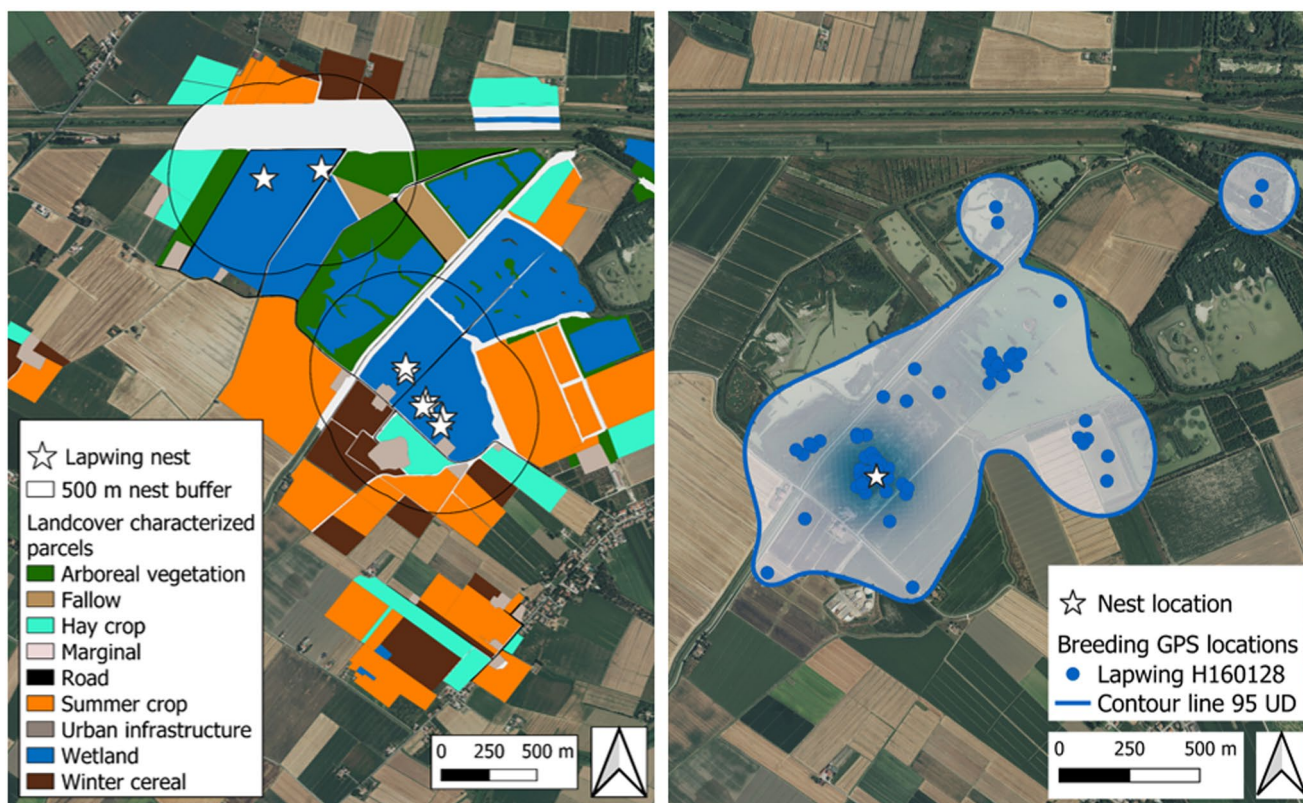


Fig. 1 Left panel: an example of one of the study sites (Selva malvezzi, province of Bologna) showing the landscape-characterized parcels with the 500-m buffers around nest locations of GPS-tagged lapwings.

Right panel: the home range extension of one of the wetland-dwelling tagged lapwings (*Vanellus vanellus*; H160132, FF) as defined by a 95% UD kernel

were arboreal vegetation, marginal areas (i.e., field edges, canals, and ditches), wetlands (i.e., restored wetlands or salt pans), roads, urban areas and infrastructures, and crops. The crop categories were merged according to phenological criteria (Supplemental Material Table S1) as follows: hay crops (i.e., fields from which fodder to feed cattle is produced, cultivated in rotation for a minimum of 3–4 years with annual crops); summer crops; winter crops; and fallows. The summer crops included annual crops sown in spring and harvested in autumn; commonly, grains such as maize and sorghum; herbs such as sunflower and coriander; and legumes such as soybean. However, maize, among summer crops, represented the predominant land cover in our study area (26.6%). Winter crops included annual crops sown in autumn and harvested in summer, namely, cereals such as wheat and barley, and oilseeds such as rapeseed. For each parcel of each crop category, we additionally assessed the mean plant height (based on three different measurements in representative areas of the field) and mean plant ground cover (based on the percentage of soil covered by green vegetation, estimated visually from the centre of the field's edge, according to the thresholds 0, 1–15%, 16–30%, 31–50%, 51–75%, 76–90%, and 91–100%). The wetness of the field was not considered, as in this intensive

agroecosystem matrix the landscape is mostly dry, with no naturally occurring stagnant water or in-field wet features.

Nest site habitat selection

Nest site habitat selection was conducted according to a use-availability design (Manly et al. 2002; Montgomery and Roloff 2013). Availability was defined as the overall amount of habitat inside each of the 500-meter buffers described above (overlapping buffers, in the case of close nests, were merged). Use was defined as the habitat in which each nest was found. For each habitat category, a selection ratio was computed as a metric of selection strength (Manly et al. 2002). Selection ratios are particularly suited for categorical variables, are easy to compute and interpret and are shown to be a unifying metric in habitat selection (Assandri et al. 2022). Following (Manly et al. 2002), the selection ratio for a given habitat j was identified as presented in Eq. 1:

$$SR_j = \frac{N_{uj}/N_u}{N_{aj}/N_a} \quad (1)$$

where N_{uj} is the number of nesting sites used in habitat j ; N_u is the overall number of nesting sites used; N_{aj} is the

proportional cover of available habitat j within the 500 m nest buffer; and N_a is the overall available area within the 500 m nest buffer. Selection ratios were calculated using the R package *asbio* function *ci.prat* (Aho 2022), and 95% confidence intervals were estimated according to the Koopman method (Aho and Bowyer 2015) with Bonferroni correction (Armstrong 2014). $SR > 1$ denotes positive selection, $SR < 1$ denotes avoidance, and $SR \approx 1$ indicates habitat used in proportion to availability (Manly et al. 2002).

We used generalized linear mixed models (GLMMs) with a binomial error distribution and a logit link function, package *glmmTMB* (Brooks et al. 2017), to assess the effect of plant height and plant ground cover on the probability that a field was selected by the lapwing to nest. We considered occupied all the parcels with a nest, and not occupied all the other parcels occurring within the nest buffer. We built two separate models, one for each covariate, as they were inter-correlated ($r=0.53$). The year was included as a random intercept in our model. Predictor significance was assessed by Wald's χ^2 tests (package *car*; Fox and Weisberg 2019). Model validation was performed with the *DHARMA* package (Hartig 2022) by checking scaled residuals simulated from the fitted model, performing simulation-based non-parametric dispersion tests, and testing for zero inflation.

Home range computation and analysis of foraging habitat selection

Based on subsampled GPS locations, individual breeding home ranges were estimated for each bird as the 95% Utilization Distribution through fixed kernel density estimation with reference bandwidth (href) using the R package *adehabitatHR* (Calenge 2006). To avoid overrepresentation of the nesting site, all fixes within a 5-m radius of the nest position were excluded from this computation. This threshold was determined based on the precision of the GPS, defined as the average distance between fixes around a stable point before deployment (5.48 ± 2.13 m, mean \pm sd). Kernels obtained at these foraging positions represented the area within which breeding northern lapwings foraged during the breeding period.

To determine if there were any significant differences in home range size based on wider nest habitat typology (wetland vs. farmland), we ran a generalized linear model (GLM) with a gamma distribution. We used a generalized Poisson distribution GLM model to determine whether the number of polygons comprising each kernel (a proxy of habitat disjointedness) significantly differed between lapwings based on habitat typology. This model better fit the data than did a GLM with a Poisson distribution, which showed moderate underdispersion. We validated the models using the *DHARMA* package (Hartig 2022) as described

above. Predictor significance was assessed by Wald's χ^2 test, package *car* (Fox and Weisberg 2019).

We then explored third-level foraging habitat selection (Johnson 1980), which refers to the use of various habitat components within the home range of an individual. In this context, we conducted separate analyses of birds nesting in wetlands and birds nesting in croplands. The reason for this is that the two ecosystems were fundamentally distinct from both geographical and phenological points of view and hence could not be combined into a single analysis. Furthermore, wetland-dwelling and cropland-dwelling birds in our study were sampled in two different years (2022 and 2023, respectively), which further justified a separate analyses of each group. Availability was defined as the proportional area covered by each habitat within the individual home range (based on the landcover survey described in Sect. "Landcover survey"), while use was defined as the intersection between the GPS fixes (i.e., the foraging locations during the breeding period) and the specific characterized land cover parcel within the individual home range where each fix fell. Selection ratios were computed as previously described above.

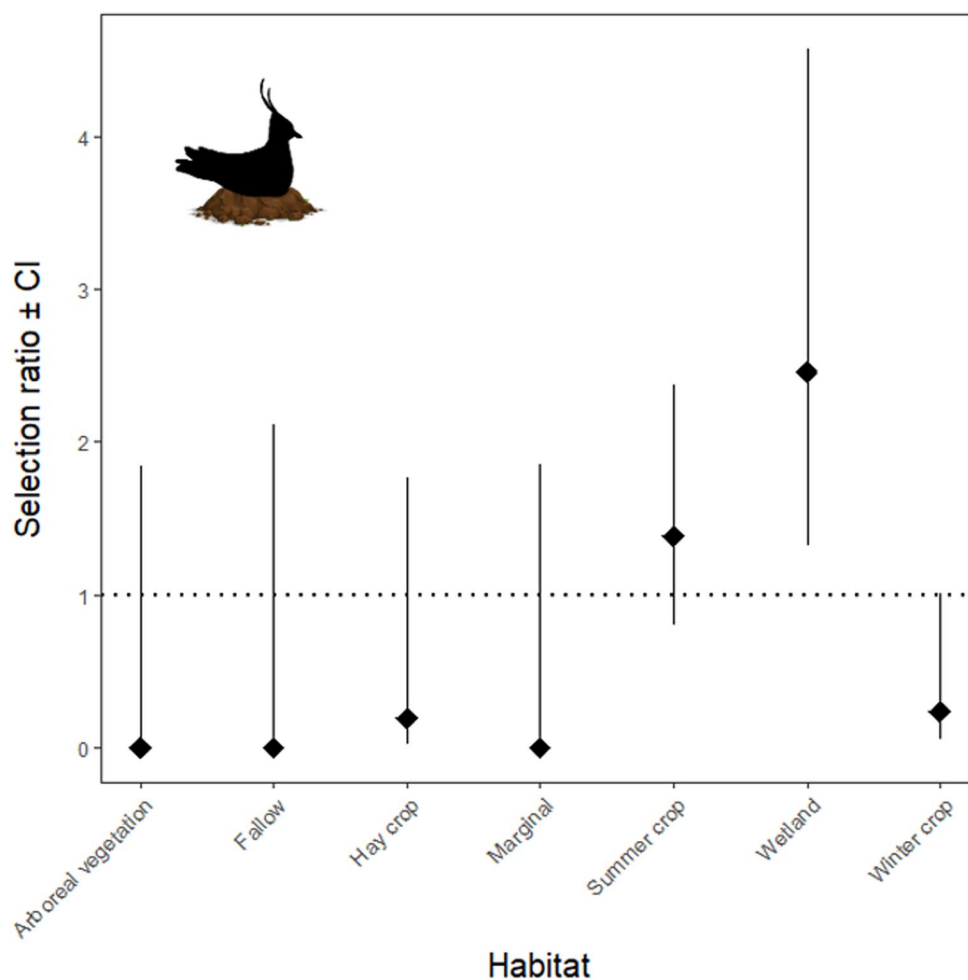
Results

Northern lapwing nest site selection

Overall, we found 67 northern lapwing nests (42 in 2022, 25 in 2023) in 10 habitat categories (Supplemental Material Table S2). However, when merged according to the phenological classification, only five habitat categories were used, the majority of nests being in summer crops (38 nests, 57%) and wetlands (25 nests, 37%). Accordingly, we found a positive and statistically supported selection for wetlands; summer crops were also positively selected, but the selection was not fully statistically supported; winter crops and hay crops were avoided (i.e., used less frequently than expected based on their availability; negative selection, although not fully statistically supported); and no nests were found in other habitat types (Fig. 2).

We found negative effects of plant height ($\beta = -0.024 \pm 0.008$; $\chi^2 = 9.9$, $df = 1$, $P < 0.002$) and ground cover ($\beta = -0.023 \pm 0.006$; $\chi^2 = 13.4$, $df = 1$, $P < 0.001$) on nesting probability. This implied that as the cropland patch plant height or ground cover increases, the likelihood of nesting in that patch decreases (Fig. 3a, b). When comparing plant height and plant ground cover for crops of different phenologies, we found that winter crops and hay crops (which were negatively selected by lapwings) had both a median plant cover of 100% and a median plant height of 83 cm and 60 cm, respectively. In contrast, summer crops

Fig. 2 Nest site habitat selection by northern lapwings (*Vanellus vanellus*) in Italy. $SR > 1$ (falling above the dotted line) denotes positive selection, $SR < 1$ (falling below the dotted line) denotes avoidance, and $SR \approx 1$ indicates habitat use in proportion to availability (Manly et al. 2002)



(which were positively selected) had a 30% median plant cover and 25 cm median plant height (Fig. 3c, d).

Foraging habitat selection during breeding

We relied on GPS data from 14 individuals, seven nesting each in wetlands and croplands (Supplemental Material Table S3). The mean duration of GPS tracking considered for each individual was 34 ± 12 days (mean \pm SD). As shown by the individual 95% KDE, the nesting northern lapwings in our study had home ranges that spanned 73.2 ± 54.3 ha (mean \pm SD; range: 2.8–161.3 ha), with a median of 56 ha. Our sample was strongly biased toward females, so a statistical comparison between the sexes' home range size was not feasible; however, the two males included in the sample had a home range comparable in size to that of females (Supplemental Material Table S4). Tagged lapwings stayed 206.7 ± 152.8 m (mean \pm SD; range of average distance for each individual: 43–521 m) from their nest during the whole breeding period.

Home ranges in croplands were not significantly larger than those in wetlands ($\beta = 0.010 \pm 0.007$; $\chi^2 = 2.3$, $df = 1$,

$P = 0.126$; Fig. 4; Supplemental Material Fig. S6). Individual 95% KDE showed some level of disjointedness (Supplemental Material Fig. S7), with wetland home ranges being significantly more disjointed than cropland ones ($\beta = 0.4895 \pm 0.218$; $\chi^2 = 5.1$, $df = 1$, $P = 0.025$; Fig. 4; Supplemental Material Fig. S6). Lapwings breeding in wetlands significantly and positively selected wetlands as foraging habitats ($SR > 1$), while all other habitat typologies were avoided ($SR < 1$), although this negative selection was not fully statistically supported for fallows. Lapwings breeding in croplands significantly and positively selected summer crops as foraging habitats ($SR > 1$) and used wetlands according to their availability ($SR \sim 1$), while all other habitat typologies were avoided ($SR < 1$), although this negative selection was not fully statistically supported for marginal areas (Fig. 5; Supplemental Material Fig. S8).

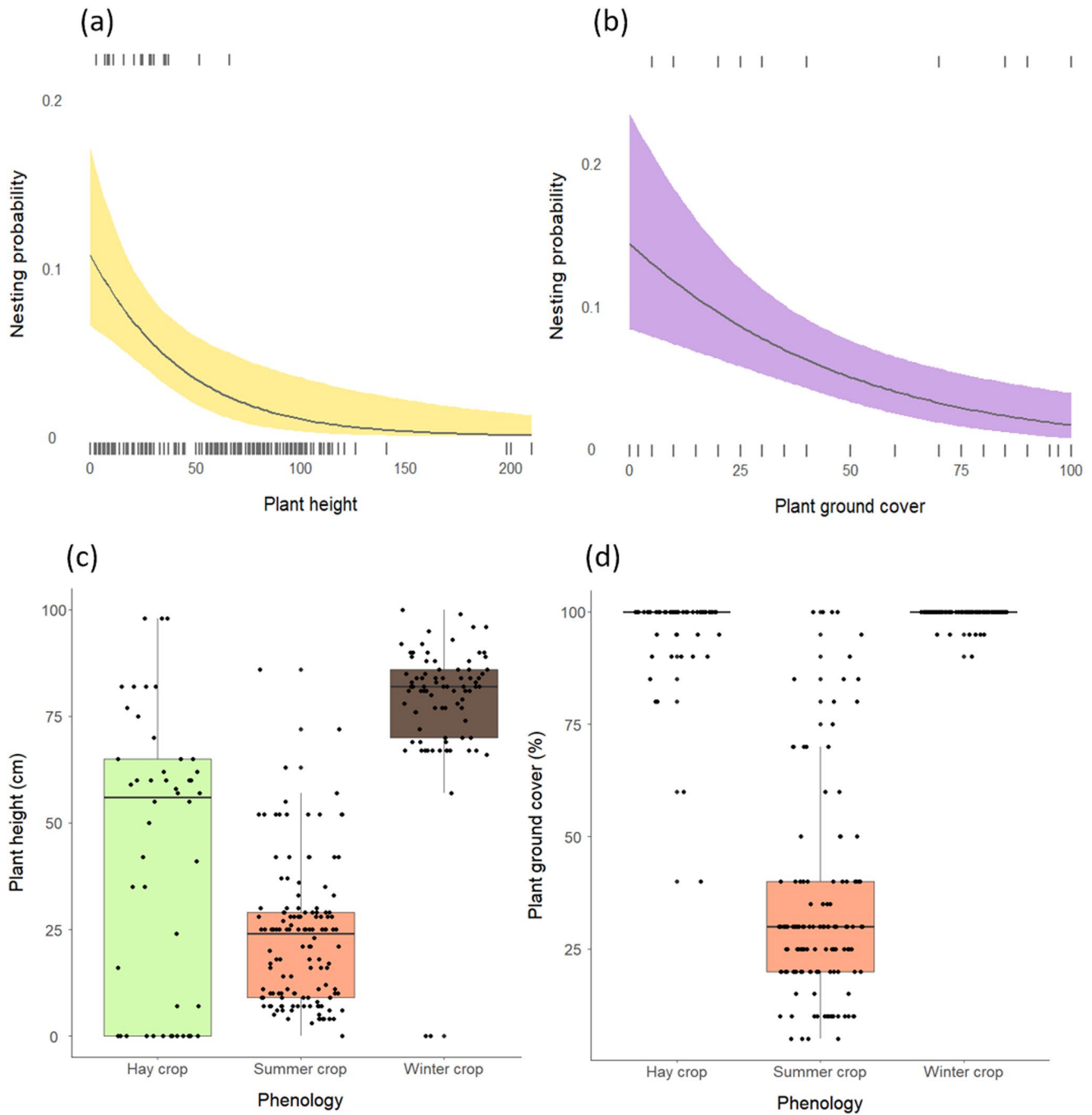


Fig. 3 Effect of plant height (a) and ground cover (b) on the nesting probability of the northern lapwing (*Vanellus vanellus*) in the central-eastern Po Plain of Italy as predicted by GLMMs. Plant height and ground cover were included as predictors, one for each model. Regression lines and confidence intervals (95% CIs) derived from binomial GLMMs are shown in shaded color ($n=67$ nests). We distinguished between occupied and nonoccupied parcels. As a response, we used

the effect of plant height (a, $P=0.002$) and plant ground cover (b, $P=0.0002$) of each identified landscape parcel on nest occupancy. Plant height (c) and plant ground cover (d) distributions for the three crop typologies considered in the nest site habitat selection analysis. Dots represent observed values; a small amount of jittering was applied to reduce dot overlap

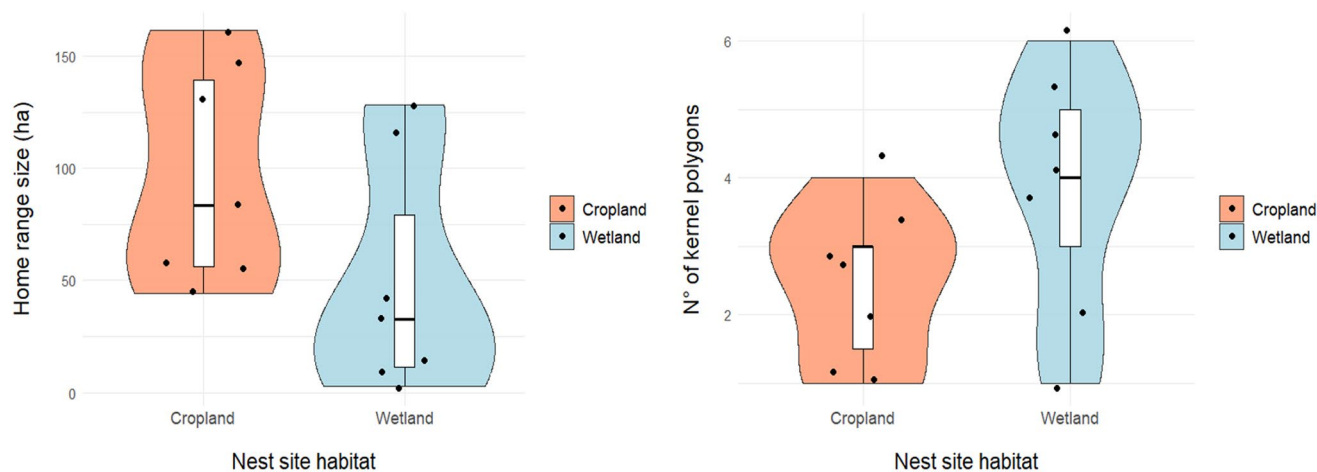


Fig. 4 Left panel: Violin plots showing the home range size in hectares for northern lapwings (*Vanellus vanellus*) breeding in croplands (left) and in wetlands (right) ($P=0.126$) in Italy. Right panel: number of

polygons in each 95%UD kernel for lapwings breeding in croplands (left) and in wetlands (right) ($P=0.025$). Violin plots represent the raw data and are not the values predicted by the GLM

Discussion

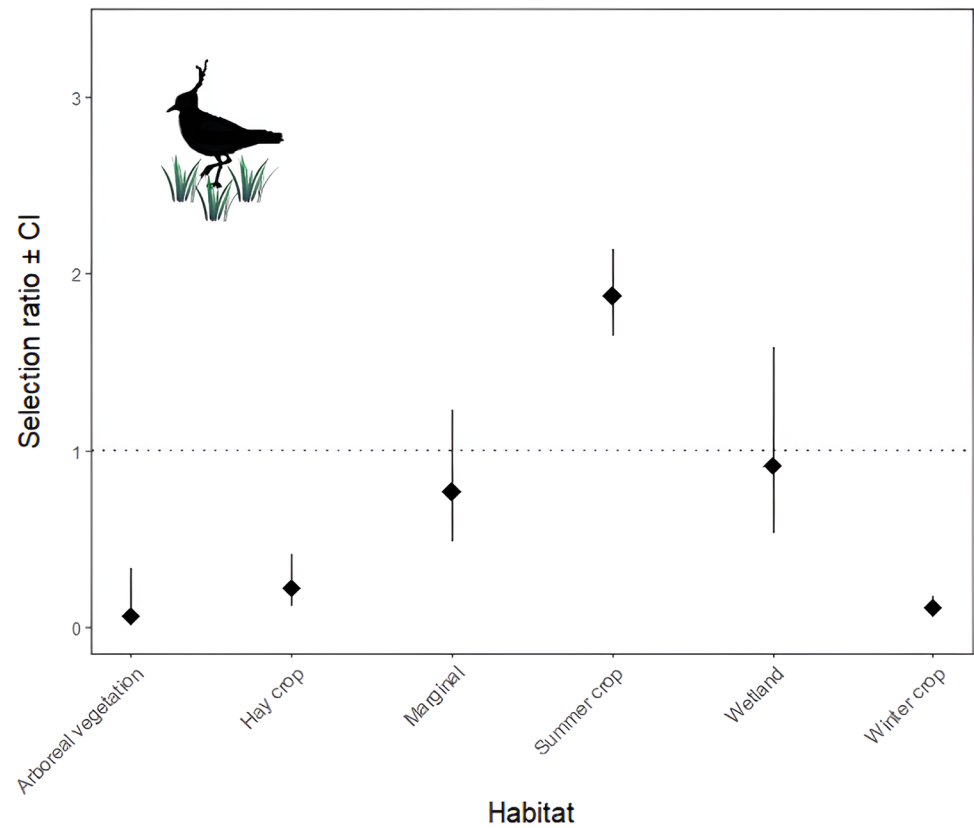
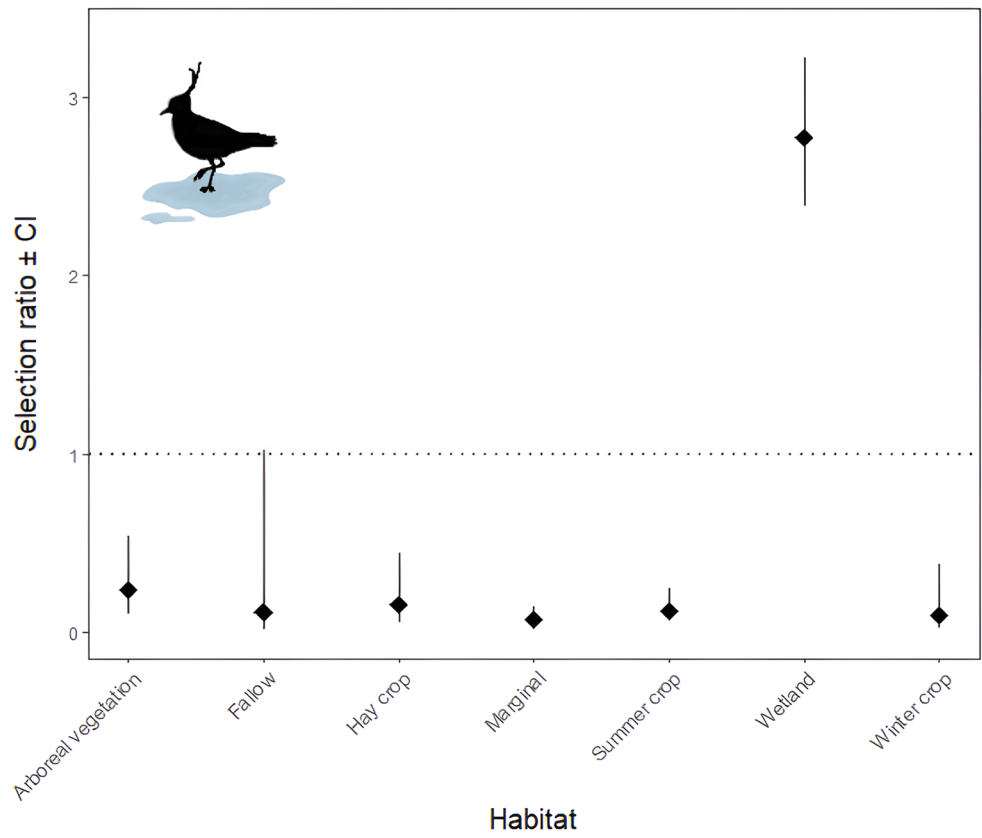
The 67 lapwing nests found in our study indicated that northern lapwings adopted a dual nesting strategy in the Po Plain, breeding in both wetlands and summer crops, with these two habitats having comparable importance in the agroecosystem matrix. Winter and hay crops, on the other hand, were avoided. In cropland, as expected, lapwings selected nesting sites characterized by low plant height and cover. GPS tracking revealed that breeding northern lapwings stayed close to their nest for the whole breeding period (206.7 ± 152.8 m) and that home ranges in the two habitat types did not differ in size, but those in wetlands were more disjoined than the ones in cropland. Birds breeding in wetlands selected only wetlands for foraging and avoided all other habitat types. Lapwings breeding in cropland selected summer crops and used wetlands according to their relative availability. The median home range extension (56 ha) was greater than that reported by Cramp and Simmons (1993; range: 0–36 ha). Even if without much information available on the exact home range size of breeding northern lapwings, we might speculate that the reason for greater home ranges in our study is related to the overall low quality of the intensive agroecosystem of the Po Plain, which is unsuitable for fulfilling breeding lapwings' foraging requirements and leading breeders to move further away to find more foraging opportunities.

Wetlands of varying typologies, including restored marshes and salt pans, were positively selected as nesting sites. Twenty-five out of the 67 lapwings monitored nested there. Unfortunately, due to high vegetation heterogeneity, we could not statistically assess whether the species selected specific conditions of plant height or plant ground cover in the wetlands. Interestingly, GPS tracking revealed

that individuals nesting in wetlands clearly preferred to forage in wetlands, actively avoiding cropland and other habitat types. Wetland-dwelling lapwings had slightly smaller and significantly more fragmented home ranges than did cropland-dwelling lapwings, suggesting an overall good foraging quality in specific patches within the wetland. The nesting habitat type may determine home range size and disunity since resource availability significantly controls movement patterns in breeding individuals (Rolando 2002) and has been reported in other bird species (Stanton et al. 2014; Staggenborg et al. 2017).

Winter crops, hay crops, fallows, marginal areas, and arboreal vegetation were either not selected or avoided by breeding lapwings, with summer crops (in particular, maize fields) being the only cultivation to be positively selected. Thirty-eight out of 67 lapwings (37.3%) nested in this kind of cropland, with wetlands usually nearby. The likelihood of a northern lapwing nesting in a specific field was inversely proportional to its plant height and plant ground cover, confirming the importance of sparsely vegetated ground for this wader (Petersen and Trolliet 2009; Kubelka et al. 2012). This finding is in accordance with the ecology of the species (Cramp and Simmons 1993; Mischenko and Sukhanova 2016), as its typical breeding habitat consists of mostly flat terrain that allows for easy walking, possibly with unobstructed views (i.e., cropland, pastures, meadows, wetlands, or wet natural and seminatural grasslands). Cropland-dwelling birds' home ranges were significantly less disjointed than wetland-dwelling ones. Summer crops were positively selected as foraging habitats, and wetlands were used in proportion to their availability. Another study reached a similar conclusion for northern lapwings breeding in the UK, showing that farmland-dwelling breeding lapwings are significantly more likely to forage and nest closer

Fig. 5 Foraging habitat selection for seven phenological habitat categories by northern lapwings (*Vanellus vanellus*) breeding in wetlands (upper panel) and croplands (lower panel) in Italy. $SR > 1$ (falling above the dotted line) denotes positive selection, $SR < 1$ (falling below the dotted line) denotes avoidance, and $SR \approx 1$ indicates habitat used in proportion to availability (Manly et al. 2002)



to wet features in the field, regardless of the field type (Bertholdt et al. 2017). However, in intensive agroecosystems, bare-ground crops occur primarily in fields with spring cereals (already sown at the start of the breeding season) and in fields with late-sown summer crops (ploughed during the breeding season). This means that when northern lapwings do not breed in wetlands, they tend to prefer tillage or maize fields (Schmidt et al. 2017; present study). However, maize fields and other summer crops may act as ecological traps for the species because they are bare ground at the start of incubation but then quickly undergo farming operations (Horvat and Denac 2019), with a high risk of breeding failure due to the destruction of nests by farming machinery.

The most likely explanation for the dual nesting and feeding strategy of northern lapwings could be that nest site habitat is selected based on the proximity of suitable foraging areas for the adults, during incubation, and for the chicks, after hatching. In contrast, if adults select the nesting habitat that is safest for the clutch, matching between the foraging site and the nesting site would not necessarily be expected (Cramp and Simmons 1993). Indeed, arable fields are reportedly important nesting and foraging areas for breeding lapwings (Galbraith 1989; Berg et al. 1992; Berg 1994), but when they do not fulfil their foraging requirements, wetlands are preferred (Galbraith 1988; Benton et al. 2003). This dual strategy can be adopted by the same individual in different contexts, as demonstrated by tagged individuals in our study that nested in both habitats during the two years of study (and the following one, 2024). Nesting and foraging habitat selection during breeding may be dependent on the current environmental conditions found upon arrival at the breeding grounds. In the Po Plain, both wetlands and croplands are very dynamic environments that change from year to year. Restored wetlands are not always properly managed and can be covered by high vegetation, which is unsuitable for the species (O'Brien and Wilson 2011), while fields undergo yearly crop rotation. The maintenance of the dual nesting strategy is likely because one habitat is not inherently better than the other for breeding. Reproductive success is generally very low in croplands (unpublished data), but the flood of 2023, which led to the failure of all wetland pairs, demonstrated that wetlands likewise do not guarantee breeding success. This further highlights the crucial importance of maintaining adequate environmental conditions for ground-foraging waders in both croplands and restored wetlands.

Management implications

Management plans targeting northern lapwing conservation should address specific actions in both wetland and cropland habitats to ensure the long-term protection of the

species in the Po Plain. For wetlands, re-establishing wet in-field features and restoring former wet habitats interspersed in the intensive agroecosystem matrix are crucial (Wilson et al. 2004; Eglington et al. 2010; Smart et al. 2013). Long-term management should then ensure that the sward height is kept short and open to create and maintain suitable feeding areas. For croplands, lower-intensity farmland activities may improve northern lapwing breeding habitat, especially delayed farming operations occurring for summer crops (O'Brien and Wilson 2011). Given the small spatial scale of foraging habitat use found in our study, the field scale may be too large for the implementation of suitable farmland habitat improvement measures. In contrast, more attention should be given to intra-field heterogeneity (Verhulst et al. 2007), increasing the frequency with which bare ground occurs in agroecosystems during the whole breeding period (March-June). Therefore, agri-environmental schemes carried out in the Po Plain should increase the value of the cropped area of fields as a foraging and nesting habitat for cropland-dwelling shorebirds (Eggers et al. 2011) while likewise ensuring long-term management in restored wetlands. In this way, overall habitat features would be kept within those limits that facilitate breeding lapwings' foraging movements throughout the entire breeding period in both cropland and wetland settings (O'Brien and Wilson 2011; Smart et al. 2013; Sakseide and Dale 2023). Insight into the exact breeding productivity in the two habitat typologies may further aid in determining which specific management strategy would be the most effective for the conservation of the species in this area.

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Author contributions JGC, GA, and DC contributed to the study conception and design with guidance from LS. LS, JGC, and VK provided the necessary materials. Fieldwork (GPS deployment and landcover surveys) was conducted by DC, JGC, and FDP. RT monitored the restored wetlands. DC and GA performed the analysis, with inputs from JGC, FDP, LS, AP, and VK. DC wrote the first draft of the manuscript with guidance from GA and all authors participated in the final version. All authors have read and agreed to the published version of the manuscript.

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Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethical approval The study has been carried out under the permission for research on wildlife of ISPRA (Art. 4 (1, 2) and Art. 7 (5) Italian law 157/1992). All the experimental procedures were conducted in accordance with the EU and Italian scientific legislation.

Competing interests The authors declare no competing interests.

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