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Optimized Monitoring and Conservation of Farmland Bird Species through Bayesian Modelling: The Montagu's Harrier *Circus pygargus* Population in Central Italy

Alessandro Ferrarini [1,*], Enzo Calevi [2], Dina Brozzetti [2], Alessia Colle [2], Riccardo De Santis [2], Stefano Laurenti [2], Enzo Savo [2] and Marco Gustin [1]

1 Lipu-BirdLife Italy, Via Udine 3/a, I-43122 Parma, Italy
2 GSCA—Gruppo Studi e Conservazione dell'Albanella minore, Lipu Viterbo, Strada Teverina 13, I-01100 Viterbo, Italy
* Correspondence: sgtpm@libero.it; Tel.: +39-0521-1910728

Abstract: The Montagu's harrier *Circus pygargus* is considered a rare species at the Italian level, and vulnerable at the European level. The main threat for these farmland birds is represented by agricultural practices; in fact, it nests on the ground in agricultural environments; therefore, at harvest time nests are often destroyed (with the eggs and chicks) by farm machinery. We examined the reproductive traits (clutch size, laying date, hatching, and fledging date and success) of the Montagu's harrier population in central Italy (about 10% of its population in Italy) where nest protection has been implemented through electric fences and metallic meshes. By using a Bayesian probabilistic network, we modeled the sequence of events that determine its reproductive success (percentages of eggs hatched and chicks fledged) and simulated the effects of different environmental and management scenarios. Our model explained the hatching and fledging success with 90.20% and 95.12% accuracies, respectively. We found that crop type and height, laying date, type and delay of nest protection have specific effects on the reproductive success of this population. Our findings demonstrate that it is possible to optimize the monitoring of this population and significantly increase its reproductive success by acting selectively upon the environmental and management attributes of the breeding area. Our decision tool allowed us to produce several rules for the optimized monitoring and conservation of the Montagu's harrier population in central Italy. The methodological approach proposed here is suitable for application to any farmland bird population on a local scale.

Keywords: clutch size; crop height; crop type; farmland bird conservation; farmland bird monitoring; hatching success; fledging success; nest protection; what-if simulations

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1. Introduction

The expansion of intensive forms of agricultural land-use has led to the complete disappearing of various habitats worldwide [1,2]. Consequences have been especially severe for grassland birds; in fact, many species declined dramatically during the past decades [3–5]. As a consequence of the loss of grassland habitats, birds that traditionally bred in open natural habitats increasingly occupied arable lands and cultivated areas during reproduction [6]. However, breeding in agricultural landscapes may be costly: the increasing use of pesticides and herbicides and reduction of field margins and fallow land have decreased food availability, particularly for granivores and insectivores [7–10]. In addition, the intensification of agricultural practices has affected the nesting success of ground-breeding species in numerous ways, including direct elimination of nests, chicks and adults by mowing, use of agricultural machineries, irrigation and drainage [11–14]. This is particularly problematic in Europe where farmland occupies almost 40% of the land area [15]. Results from the Pan-European Common Bird Monitoring Scheme for 39 common farmland birds monitored between 1980 and 2017 showed that this bird group is undergoing the steepest population declines (PECBMS: http://pecbms.info/european-wild-bird-indicators-2020-update; accessed on 8 January 2023). Several raptors are among the most threatened species because of their frequent or exclusive use of arable lands and cultivated areas for breeding and foraging, e.g., the lesser kestrel *Falco naumanni* [16–18] and the red-footed falcon *Falco vespertinus* [19–21].

The Montagu's harrier *Circus pygargus* (Linnaeus, 1758; order Accipitriformes; family Accipitridae) is a typical raptor of agricultural habitats. It is considered a rare species at the Italian level (where it is protected by Law 157/92) and vulnerable at the European level (where it is protected by the Bern and Bonn conventions and the Birds Directive 79/409/EEC). According to the International Union for Conservation of Nature (IUCN), the Montagu's harrier has been included in the red list of threatened species, and categorized as Least Concern [22]. In the Palearctic it is a nesting and migratory species, with wintering quarters in sub-Saharan Africa. This ground-nesting raptor uses crops as its habitat in various ways, building nests and hunting mainly within cereal fields, ray-grass, alfalfa or rape-seed fields [22]. The Montagu's harriers seem to have substituted their original habitat with crops in most of their breeding range, and in the late twentieth century the proportion of Montagu's harriers breeding in crops exceeded 90% in the Iberian Peninsula, and was between 70 and 80% in France, and 40 and 50% in other western European countries [23]. The dependence on such a man-made environment makes this species particularly vulnerable to all potential stressors occurring in this habitat [23]. In addition, the high degree of philopatry is an obstacle to the colonization of new areas and favors local extinctions of this species. In Italy, the Montagu's harrier nests in late spring in various central-northern regions, and its population is estimated between 260 and 380 breeding pairs with stable trend [24].

Strategies to protect nest sites from harvesting activities are in place throughout much of its European breeding range [25]. The Montagu's harrier is monitored by systematic breeding bird surveys in twelve European countries, representing 35% of the European countries in which it breeds [26]. Accordingly, in this study, we aimed to: (a) analyze the reproductive traits (clutch size, laying date, hatching and fledging date and success) of the Montagu's harrier's population in central Italy; (b) build a modelling framework linking its reproductive traits to environmental and management variables; (c) use such framework to simulate the effects of different environmental and management scenarios on the reproductive success of this population; (d) use results to propose a set of policies and management interventions to better monitor and preserve this population. In addition, we aimed to conceive a cost-effective methodological approach that could be readily applied to any farmland bird population on a local scale to produce rules for optimized monitoring and conservation. We also aimed to demonstrate that probabilistic Bayesian modelling and simulations can successfully fit this goal by mimicking the sequence of events that determine the reproductive success of farmland birds.

2. Materials and Methods

2.1. Study Area and Study Population

The study area corresponded to the province of Viterbo (central Italy; Figure 1), whose agricultural landscape hosts the most southern population along the Tyrrhenian coast [27].

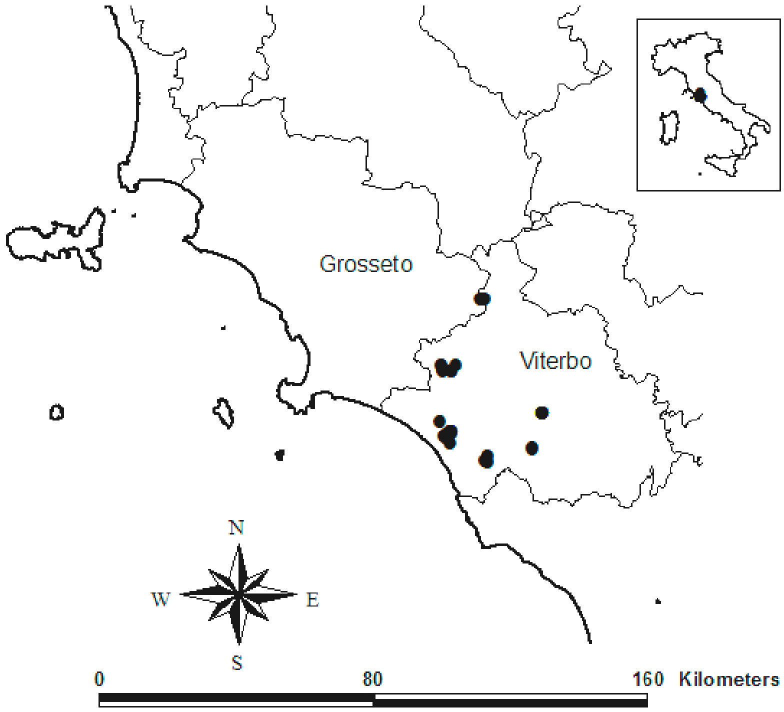

Figure 1. Study area (province of Viterbo; central Italy). The black points indicate 43 Montagu's harrier breeding sites where the field data were collected from 2020 to 2022 during April–July.

This Montagu's harrier population is estimated between 25 and 30 breeding pairs (about 10% of the Montagu's harrier population in Italy) in small and isolated 'pseudo-colonies' (at a few dozen kilometers' distance from each other; Figure 1) where several pairs (2–4 breeding pairs) nest in the same field. This population feeds on rodents, lizards, passerines and insects, and is preyed upon (adults, chicks and eggs) by foxes, snakes and corvids. In the study area, the main threat factor is given by agricultural practices; in fact, crop gathering causes frequent breeding failure in this population through nest destruction (along with the eggs and chicks) by farm machinery and increased risk of predation by native species. The Montagu's harrier is also very highly vulnerable to the impacts of potential wind energy developments [28], but fortunately these are absent in the study area.

2.2. Data Collection and Pre-Processing

From 2020 to 2022, during April–August we accomplished intensive sampling sessions in the study area to identify the sites where the Montagu's harriers nested. We regularly visited all the nesting sites once a week to check clutch size and other breeding parameters. We used safety distance monitoring with binoculars so as to avoid any possible interference with the reproductive success of this population. For each site we recorded several variables (Table 1), including: environmental (crop type and crop height), biological (clutch size, laying date, hatching date, hatching success, fledging date and fledging success) and management (type of nest protection and delay in nest protection). To protect the Montagu's harriers' nests from the agricultural practices and predators, we used electric fences and metallic meshes, as compatible with our budget limitations.

Table 1. Description of the variables used in this study.

Variable	Data Type	Range	Discretization	Description
Clutch size	continuous	1–5 eggs	5 classes (1, 2, 3, 4, 5)	number of eggs laid
Crop height	continuous	50–115 cm	3 classes (50–75 cm, 75–100 cm, 100–125 cm)	mean crop height during April–July
Crop type	categorical	barley—hay—wheat		
Delayed protection	continuous	0–25 days	4 classes (0–10, 10–20, 20–30, unprotected)	delay in nest protection in days from the laying date
Fledging date	continuous	172–221 days	4 classes (170–185, 185–200, 200–215, none)	fledging date in days from 1 January
Fledging success	continuous	0–100%	3 classes (low: 0–33%; intermediate: 33–66%; high: 66–100%)	% of chicks fledged with respect to the clutch size
Hatching date	continuous	143–185 days	4 classes (140–155, 155–170, 170–185, none)	hatching date in days from 1 January
Hatching success	continuous	0–100%	3 classes (low: 0–33%; intermediate: 33–66%; high: 66–100%)	% of eggs hatched with respect to the clutch size
Laying date	continuous	114–164 days	4 classes (< 120, 120–135, 135–150, 150–165)	laying date in days from 1 January
Type of nest protection	categorical	electric fence—metallic mesh—none		

During data pre-processing, we excluded those nesting sites for which data were not complete (i.e., at least one variable was absent). The continuous variables were converted into discrete counterparts according to the following rules [29]: (a) equal width discretization; (b) no more than five classes.

2.3. Exploratory Analyses

Prior to model building, we used univariate (χ^2 test) and bivariate (ANOVA test and Pearson's correlation coefficient r) statistics to analyze all the variables and explore the pairwise relationships between them. Tests were considered significant for $p < 0.01$. This step was also propaedeutic to the construction of the probabilistic Bayesian model.

2.4. Bayesian Network Modelling

2.4.1. Model Setup

First, we built a conceptual model (Figure 2) to explain the reproductive success of the Montagu's harrier population in the study area. The conceptual model was based on the expert opinions and previous exploratory analyses, and followed the April–July temporal succession of the events. The aim of this step was to provide a visual summary of how the drivers (e.g., crop type and nest protection) are linked to the other variables and model outputs (hatching success and fledging success). Therefore, it entailed identifying the key variables that are considered to directly or indirectly influence the model outputs, and mimicking the processes that link them. Building a conceptual model was valuable for structuring the problem and determining the causal chains, and helped the construction of the successive Bayesian probabilistic network.

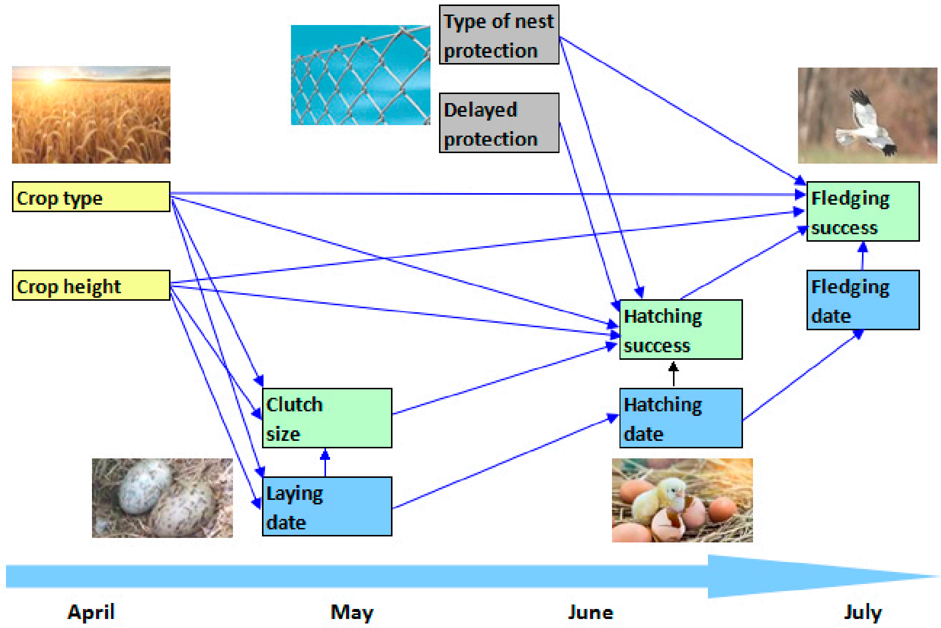

Figure 2. The conceptual model (expert knowledge) of the reproductive success (hatching success, fledging success) of the Montagu's harrier population in the province of Viterbo (Italy). Variables are ordered from left to right based on the April–July temporal succession. The crop related nodes are colored yellow. The nodes related to species reproduction are in green. The time related nodes are in blue. The management related nodes are in grey. Arrows indicate the hypothesized direct influences of the source variables upon the destination variables.

Second, we translated our conceptual model into a Bayesian probabilistic network (BPN; [30]). A BPN is a multivariate model for a set of variables $\mathbf{x} = \{x_1,\ldots, x_n\}$ which is defined in terms of two components: (a) a directed acyclic graph where each vertex represents one of the variables (observable quantities) in the model, and arcs (links) represent conditional relationships from one node (parent) to another (child); (b) a conditional distribution $p(x_i/\boldsymbol{P}(x_i))$ for each variable x_i (with $i = 1, \ldots, n$) given its parents in the graph, denoted as $\boldsymbol{P}(x_i)$. The joint distribution over all the variables is equal to the product of the conditional distributions attached to each node, as follows:

$$p(x_1,\ldots,x_n) = \prod_{i=1}^{n} p(x_i/P(x_i)) \quad \forall x_1 \ldots x_n \in \Omega_{x_1\ldots x_n}$$

where Ω_{x_i} represents the set of all possible values of variable x_i.

We used a semi-supervised approach to structure learning, i.e., the process of learning the dependent (presence of links) and independent (absence of links) relationships among the variables x_i. Following our conceptual model (Figure 2), we imposed several constraints on the BPN by assigning the variables x_i to temporal tiers. Temporal tiers specify the temporal order among the variables: in the resulting network, arcs from variables that occur later in time (higher tiers) to nodes occurring earlier in time (lower tiers) are disallowed. In fact, causality never works backwards in the real world. Specifically, we set the following temporal constraints:

$$\begin{cases} \text{tier 1: crop height, crop type} \\ \text{tier 2: clutch size, laying date} \\ \text{tier 3: delayed protection, hatching date, hatching success, type of protection} \\ \text{tier 4: fledgling date, fledgling success} \end{cases}$$

We then used the PC algorithm [31] for structure learning within the previous constraints. It uses independences observed in data to deduce the structure that has generated them, and produces a p-value in order to make a decision to remove or not an edge between two variables. The PC algorithm begins with all pairwise unconditional associations and removes the edge between pairs that are not statistically related in a significant manner. The PC algorithm has three parameters: (1) max adjacency size (which limits the number of neighbors of a node); (2) statistical significance (which is the alpha value (α) used in classical independence tests); (3) max time (which sets a time limit on the search phase of the PC algorithm). We set the following values during structure learning: max adjacency size = 9; α = 0.10; no time limit. With 10 variables in the model, these values for the max adjacency size implied that any variable could in theory be linked to any other, although within the constraints due to the temporal tiers and the statistical significance α.

With the model structure in place, the available information was incorporated into the structure. The probabilities of the marginal nodes and the conditional probabilities between nodes (conditional probability tables) were thus populated using the empirical data available from our field sampling.

2.4.2. Model Evaluation

We generated 10,000 trials from the BPN resulting from the model setup, and measured model accuracy (i.e., explanatory power) with regard to the two variables of the reproductive success (i.e., hatching success and fledging success) as:

$$E_{\%} = 100 * \frac{N_C}{N_T} = 100 * \frac{\sum_{i=1}^{n} \frac{N_{C_i}}{N_{T_i}}}{n}$$

where N_c is the number of trials correctly classified by the BPN, N_T is the total number of trials (i.e., 10,000 in our study), n is the number of classes (i.e., three: low success, intermediate success and high success) to be correctly classified by the model, N_{Ci} is the number of trials belonging to class i correctly classified by the BPN, N_{Ti} is the total number of trials belonging to class i.

2.4.3. Simulations

After the model was positively evaluated, future environmental and management scenarios (what-if counterfactuals) were simulated as inputs to the BPN in order to predict the effects of such scenarios on the reproductive success of the Montagu's harrier in the study area. Inference in a Bayesian network is the ability to compute posterior probabilities given some evidence [32], and refers to the process of computing the change (in terms of probability) of some variables after obtaining/simulating some observations of other variables as:

$$p(\mathbf{x}_T/\mathbf{e}) = p(\mathbf{x}_T, \mathbf{e})/p(\mathbf{e})$$

where $\mathbf{x}_T$ represents the vector of states of the target variables (e.g., intermediate hatching success and high fledging success) and $\mathbf{e}$ represents the vector of evidence of parent variables (e.g., crop type = "wheat", crop height = "100–125", type of nest protection = "electric fence" etc.). By using Bayesian inference, changes in the probability of the hatching and fledging success (low, intermediate and high) were calculated given the changes of some other variables for each of the scenarios simulated. Bayesian network modeling and simulations were carried out using Netica 6.08 [33–35].

3. Results

During field surveys, we found 43 Montagu's harriers' nesting sites (Figure 1). As data were incomplete for two sites, the successive analyses, model and simulations relate to 41 nesting sites (i.e., n = 41), if not stated otherwise.

3.1. Exploratory Data Analysis

3.1.1. Univariate Statistics

The Montagu's harriers positively selected the hay crops for nesting (21 nests out of 41) over barley (11 nests) and wheat (9 nests) (χ^2 = 82.0; d.f. = 4; $p < 0.01$).

The laying date ranged from day 114 of the year (25 April) to day 164 (15 June). Most pairs started laying in the first half (48.9%) and second half (31.3%) of May.

The mean clutch size was 3.71 eggs (±1.01 SD) and ranged from one to five eggs. The most common clutch size was four eggs (37.4%).

After egg deposition, we were able to protect 29 nests out of 41 (70.7%), 22 of which by using electric fences and 7 by metal meshes. On average, electric fences were put in place 14 days (±7.0 SD) after egg deposition, while metal meshes 11 days (±4.6 SD).

The hatching date ranged from day 143 of the year (24 May) to day 188 (9 July). Most eggs hatched between day 143 and 170 (24 May–21 June; 47.6% of the eggs laid). The mean interval from egg laying to hatching was 28.62 days (±3.02 SD).

Only 55.6% of the eggs laid hatched. The mean hatching success was 38.66% (±41.49 SD). The mean brood size was 1.61 (±1.77 SD). If we only consider clutches in which at least one egg hatched (n = 21), the mean hatching success was 72.04% (±26.89 SD) and the mean brood size was 3.14 (±1.11 SD).

The fledging date ranged from day 172 of the year (23 June) to day 221 (12 August). The mean fledging date was 187 (8 July) (±11.64 SD). The mean interval from egg laying to fledging was 56.95 days (±3.00 SD), while the mean interval from hatching to fledging was 28.65 days (±2.13 SD).

Only 53.4% of the eggs laid produced young that fledged. The mean number of chicks fledged per nest was 1.37 (±1.70 SD). If we only consider clutches in which at least one egg fledged (n = 20), the mean fledging success was 67.48% (±29.82 SD) and the mean of young that fledged was 2.80 (±1.36 SD).

3.1.2. Bivariate Statistics

Crop height was greater in the hay crops (92.4 cm ± 19.2 SD) than in barley (84.6 cm ± 5.8 SD) and wheat (82.3 cm ± 5.6 SD) crops (ANOVA test = 1.78; p = 0.18).

Egg laying in the hay crops occurred about 20 days earlier (day 127 of the year ± 6.2 SD, i.e., within the first 10 days of May) than in the barley (147 ± 8.9 SD) and wheat (149 ± 9.0 SD) fields. The difference was statistically significant (ANOVA test = 33.16; $p < 0.01$).

The nests present in the hay crops produced one egg more (4 ± 0.8 SD) than the nests in wheat (3 ± 1.2 SD) and barley (3 ± 0.7 SD) fields. The difference was statistically significant (ANOVA test = 8.16; $p < 0.01$).

The hatching success was significantly different among crop types (ANOVA test = 12.73; $p < 0.01$). The hay crops allowed 63% (±35.9 SD) of hatching, while barley and wheat fields allowed only 5% (±14.4 SD) and 23% (±36.4 SD), respectively. The hatching success was negatively correlated (Pearson's $r = -0.57$; $p < 0.01$) with the laying date (i.e., the sooner the eggs were laid, the more likely they were to hatch), and positively correlated with crop heights (Pearson's r = 0.36; $p < 0.05$) (i.e., the higher the crop was, the higher the percentage of eggs that hatched).

The effect of the nest protection was statistically significant (ANOVA test = 14.30; $p < 0.01$). If the nests were not protected, there were no hatches. Electric fences performed significantly better (61% ± 37.5 SD of eggs hatched) than metallic meshes (33% ± 34.5 SD). The longer the nest protection was delayed with respect to the laying date, the higher the percentage of eggs that hatched (Pearson's r = 0.31; p = 0.19).

The fledging success was significantly different among crop types (ANOVA test = 9.14; $p < 0.01$). The hay crops allowed 54% (±38.8 SD) of chicks that fledged with respect to the eggs laid, while barley and wheat fields allowed only 5% (±14.4 SD) and 18% (±31.5 SD), respectively. The fledging success was positively correlated with crop heights (Pearson's r = 0.30; $p < 0.05$) (i.e., the higher the crop was, the higher the fledging success). The fledging success was significantly different depending on the nest protection (ANOVA test = 10.22; $p < 0.01$). The electric fences allowed 53% (±38.5 SD) of fledging success; in contrast, the metal meshes only enabled 26% (±35.5 SD). In the absence of protection, the fledging success was always equal to 0%.

3.2. The Bayesian Network Model

The Bayesian model resulted is presented in Figure 3. It resembled the conceptual model shown in Figure 2; however, the PC algorithm did not confirm some edges between nodes, which were not statistically significant ($\alpha > 0.10$).

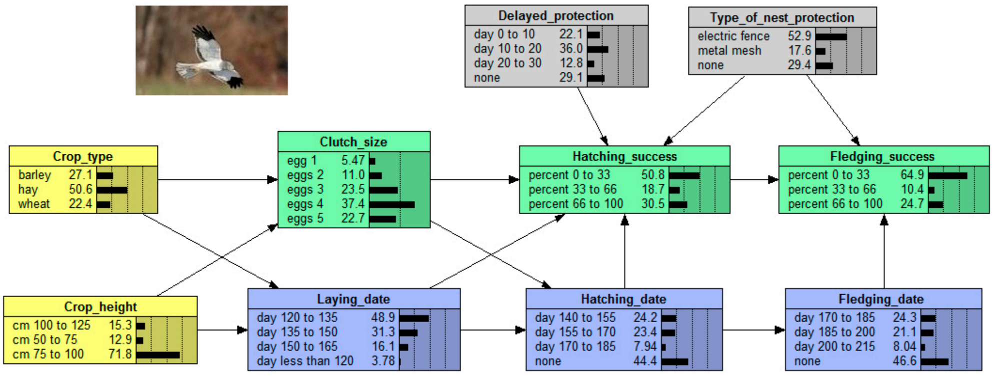

Figure 3. The Bayesian network used to model and predict the reproductive success (hatching and fledging success) of the Montagu's harrier population in the province of Viterbo (Italy). It should be read from left to right. The node colors have the same meaning as those in Figure 2. Nodes show variable priors (e.g., 50.6% of survey sites corresponded to hay crops). Arrows indicate direct influences of the source nodes upon the destination nodes.

The explanatory power (i.e., accuracy) of this model was high for both the hatching success and the fledging success (Figure 4). Overall, the hatching success was classified with 90.20% accuracy (i.e., 9020 trials out of 10,000), and the fledging success with 95.12% accuracy (i.e., 9512 trials out of 10,000).

Hatching success

Hatching success	Actual: **low** (0 − 33%)	Actual: **intermediate** (33 − 66%)	Actual: **high** (66 − 100%)	Σ
Predicted: **low** (0 − 33%)	95.43%	3.01%	5.80%	104.24
Predicted: **intermediate** (33 − 66%)	1.11%	87.07%	6.09%	94.27
Predicted: **high** (66 − 100%)	3.46%	9.92%	88.11%	101.49
Σ	100	100	100	**90.20%** Overall accuracy

Fledging success

Fledging success	Actual: **low** (0 − 33%)	Actual: **intermediate** (33 − 66%)	Actual: **high** (66 − 100%)	Σ
Predicted: **low** (0 − 33%)	96.78%	4.33%	6.65%	107.76
Predicted: **intermediate** (33 − 66%)	0.68%	95.35%	0.13%	96.16
Predicted: **high** (66 − 100%)	2.54%	0.32%	93.22%	96.08
Σ	100	100	100	**95.12%** Overall accuracy

Figure 4. Explanatory power (model accuracy) of the Bayesian network used to model and predict the reproductive success (hatching and fledging success) of the Montagu's harrier population in the province of Viterbo (Italy). We simulated 10,000 trials to be generated from the Bayesian network. Columns report the actual class (low, intermediate and high success) of trials, while rows report the predicted class. Percentages on the diagonal measure the predictive accuracy for each class. Key to reading: 95.43% of trials with low hatching success (i.e., between 0 and 33% of eggs hatched) were correctly classified, while 1.11% were classified as intermediate success and 3.46% as high success.

We found that, in April and May, the crop type and height directly and significantly influence the laying date and the clutch size. By contrast, we have not found evidence that the laying date significantly influences the clutch size. In June, the hatching success is directly and significantly determined by three biological (laying date, clutch size and hatching date) and two management (type and delay of nest protection) variables. Instead, we could not find evidence that the environmental factors (crop type and height) directly affect the hatching success, thus their influence resulted only indirect through their effects on the laying date and clutch size. In July, the fledging success is directly and significantly regulated by one management (type of nest protection) and two biological (hatching success and fledging date) factors. Again, we have not found evidence that the environmental factors directly affect the fledging success; thus, their influence is only indirect through their effects on the parent variables.

3.3. What-If Simulations

3.3.1. Effects of Crop Type and Height on Egg Deposition

The crop type heavily influences the laying date. In the hay crops, there is 85% probability that egg laying occurs between days 120 and 135 of the year (i.e., between 1 and 15 May). In the wheat and barley crops, the probability that egg deposition occurs by mid-May is <14%; in fact, deposition shifts between mid-May and the end of May with probability around 50%, or even between 1–15 June with a probability around 30%. The crop type also influences the number of eggs laid. In the hay crops there is 80% probability that 4–5 eggs are laid; this percentage drops to 40% and 36% for wheat and barley, respectively.

The crop height influences the laying date, but not the number of eggs laid. When the crop height is between 50 and 75 cm, eggs are laid after mid-May with 63% probability. If crop height is between 75–100 cm, then there is 52% probability that egg deposition will occur in the first half of May. When the crop height exceeds 100 cm, there is >70% probability that deposition will occur by 15 May.

By combining the effects of crop type and crop height, the best scenario for egg deposition is: (crop type = "hay") and (crop height > 100 cm). Under these optimal conditions, there is 14% probability that deposition will occur in the second half of April, and 83% probability that it will occur between 1 and 15 May. Furthermore, there is 81% probability that 4–5 eggs are laid. By contrast, the worst scenario is: (crop type = "barley") and (50 cm < crop height < 75 cm). Under these conditions, the most probable outcome is three eggs laid between 15 and 30 May.

3.3.2. Effects of Egg Deposition and Nest Protection on Egg Hatching

The laying date heavily influences the hatching success. If the eggs are laid by mid-May, then there is 40% probability that between 66 and 100% of eggs hatch (high hatching success). If the eggs are laid between 15 and 30 May, this probability is 22%, while if they are laid after 1 June then this probability drops to 11%.

The clutch size influences the success and, to a lesser extent, the date of hatching. With five eggs laid, the probability that 66–100% of the eggs hatch (high hatching success) is 36%. With four eggs, this probability decreases to 33%; with three eggs the probability is 25%, and with two eggs it is 21%. If 4–5 eggs are laid, the most likely hatching date is between the day 140 (20 May) and the day 155 (4 June) of the year. If fewer eggs are laid, the most probable hatching date is between 5 and 20 June.

The type of nest protection has a huge influence on the hatching success. In the absence of nest protection, the hatching probability is 0%. In case of metal mesh, there is a 12% probability of hatching success between 66 and 100% (high hatching success) and 36% probability of hatching success between 33 and 66% (intermediate hatching success). If electric fences are used, there is 44% probability of high hatching success and 10% probability of intermediate hatching success.

By placing the nest protection within 10 days of egg deposition, there is a 25% probability of high hatching success. If the nest protection is positioned between days 10 and

20, this probability increases to 29%; if it is placed between days 20 and 30, the probability rises to 52%.

By considering the previous variables together, the ideal scenario for hatching success is: (a) egg deposition by 15 May, (b) 5 eggs laid, (c) protection type = "electric fence", (d) protection delay between 20 and 30 days from egg deposition. Under these optimal conditions, the probability of high hatching success (i.e., between 66 and 100% of eggs that hatched) is 89%. Conversely, the worst scenario (when the nest protection is present, otherwise the hatching probability is 0%) occurs when 1–2 eggs are laid after 1 June, and nests are protected through a metal mesh within 10 days of hatching. Under these unfavorable conditions, the probability of high hatching success is <5%.

3.3.3. Effects of Egg Hatching and Nest Protection on Fledglings

The hatching date affects both the fledging date and success. If the hatching occurs between 20 May and 4 June then the fledging takes place between 19 June and 4 July with 87% probability, and has 44% probability of high success (i.e., between 66 and 100% of chicks fledged with respect to the eggs laid). If the egg hatching occurs between 4 and 19 June, then fledging occurs between 4 and 19 July with 77% probability, and has 38% probability of high success. If egg hatching occurs after 19 June, fledging occurs between 19 July and 3 August with a 63% probability, and has <30% probability of high success.

The hatching success influences fledging success. If the hatching success is high (66–100% of the eggs laid) then the fledging success has 76% probability of being high. If the hatching success is intermediate (33–66% of the eggs laid) then the fledging success has 48% probability of being intermediate and 46% probability of being low.

The nest protection heavily determines the fledging success. In absence of nest protection, fledging has 0% probability. In case of metallic mesh, there is 12% probability of high fledging success, and probability rises to 34% in case of electric fence.

4. Discussion

Agricultural intensification is one core reason for the recent collapses in farmland species [36–39]. Accordingly, in this study we developed a decision tool for the optimized monitoring and conservation of farmland birds, and used it to model the reproductive success (hatching and fledging success) of the Montagu's harrier population in central Italy as a function of several environmental (crop type and height), biological (laying date and clutch size) and management (nest protection and protection delay) variables. Our decision tool detected how these variables determine the reproductive success of this population in the study area, and how alterations to these drivers can alter such success.

We found that, in the study area, the Montagu's harrier significantly prefers the hay crops to wheat and barley for nesting. This finding confirms the results by [40–43]. We suppose that this is because in the study area the hay crops attain more height than the other crop types during April–May; therefore, they can better hide the nests from predators [40]. Our field observations confirm that in the study area the nidification in the cereal crops is often a secondary choice: if the nest construction or egg deposition in the hay crops fail due to human disturbance or the presence of predators, then the Montagu's harriers opt for a second nesting attempt in wheat or barley crops. It is thus plausible that the Montagu's harriers choose the suitable nesting sites by using the crop height as a primary criterion [41]. In fact, this aspect is immediately evident to the Montagu's harriers which arrive to the breeding areas, while other factors (e.g., differences in agricultural practices between the hay crops and cereals) become evident only at a later time, and therefore cannot be evaluated by birds in the early phase of the nesting season. However, we hypothesize three further reasons behind the clear preference of the Montagu's harriers for the hay crops in the study area: (a) the hay crops are usually denser than barley and wheat crops, and thus they better hide nests from the view of the predators [42,43]; (b) because barley and wheat crops are shorter and harder, they are more difficult for birds to bend during the nest construction; (c) because the hay crops are denser, the terrestrial predators (foxes and snakes) of the Montagu's harrier are more frequent in the barley and wheat crops, where in fact they can move and spot prey more easily. Instead, our field experience suggests that the aerial predators (corvids) of the Montagu's harrier are less influenced by the crop density. Alternatively put, the variable "crop type" was a good proxy for the predator density in the breeding sites. These reasons would explain why our Bayesian model found that also "crop type", and not only "crop height", significantly regulates the laying date and clutch size.

We discovered that the laying date heavily influences the hatching success, i.e., early breeding pairs rear more chicks than late ones. This result confirms findings from previous studies on the Montagu's harrier [44,45]. We believe that lower reproductive success as the season progresses results from an increased overlap between breeding and agricultural activities in harvest and post-harvest periods [46]. There are probably also endogenous factors (genetics, age of breeders etc.) which influence breeding success however, in the agricultural habitats where this species breeds, the role of such factors is likely to be largely overwhelmed by the negative effects of farming practices [47]. This seasonal decline in clutch size was also found for other raptors [48] and more generally in bird species [49].

We found out that the longer the nest protection is delayed, the higher the percentage of eggs that successfully hatch. Clearly, the nest protection must always precede the mowing date in order to prevent agricultural practices from destroying the nests and eggs; however, early nest protection lowers the hatching success. This is probably because the electric fences and metal meshes can signal the presence of nests and thus increase the attacks by the predators. The nest protection may also keep some prey (lizards, passerines and rats) away from the nest, thus making the capture of prey more difficult. Therefore, the proper delay in nest protection is a key aspect of the conservation strategies for this farmland species.

The *Circus pygargus* can be characterized by polygamous relationships [24–26], which was not considered in our model. However, we note that: (1) this species is a seasonal monogamous species, with only rare cases of polygamy [24]; (2) the elevated accuracy (>90%) of our model suggests that we have not forgotten any important predictor variable, i.e., if polygamy occurred in our breeding sites then it was sporadic or irrelevant. However, in future studies it could be useful to take this point into account by adding a categorical variable (monogamous/polygamous) to the Bayesian model.

The adoption of Bayesian modelling provided a valuable tool to assist with understanding the probability of the reproductive success of the study species, to anticipate the potential effects of changed conditions on such success, and to establish relevant management procedures. No less important than the quantitative aspects has been the usefulness of Bayesian modelling as a means of communicating between experts from different fields (analyst and modeler, field ornithologists, theoretical biologists). A typical problem with such groups is a lack of common understanding and consensus about concepts that are relevant to the problem (optimized field surveys and sampling strategy, relevant variables, relevant interactions among variables, temporal hierarchy of the variables etc.). Creating and refining a conceptual model and the correspondent Bayesian model has allowed misunderstandings between group members to be identified and resolved, allowing for increased communication and fostering the ability to examine the problem from a wider perspective.

Implications for the Monitoring and Conservation of the Montagu's Harrier Population

Our decision tool allowed us to produce several rules for the optimized monitoring and conservation of the Montagu's harrier population in central Italy.

Firstly, in order to improve the nesting habitat of this population, it is highly advisable to encourage the expansion of the hay crops over wheat and barley crops in the study area through an open dialogue and cooperation with local stakeholders supported by funds from the Rural Development Programmes (2021–2027).

Secondly, the localization of the nesting sites is not an easy task due the huge dimension of the study area. Our work suggests that it should begin in the second half of April exclusively for the hay crops, starting with taller ones (i.e., >100 cm). Successively, field surveys should be carried out in the hay crops with height between 75 and 100 cm, and then where heights are between 50 and 75 cm. By contrast, it is useless to survey wheat and barley crops until mid-May; from this date ahead, field surveys in wheat and barley crops can start from those with greater height (>100 cm), and then progressively continue with shorter ones.

Thirdly, the monitoring of egg depositions should begin in the hay crops on 1 May, starting with the higher crops (>100 cm) and then moving on to shorter ones. Instead, in wheat and barley crops, it should be monitored from mid-May onward.

Fourthly, the choice of the type and timing of nest protection is decisive. The electric fences perform much better than the metal meshes (probably because the electric shock is a stronger deterrent for predators), and their cost is only a little more. Therefore, electric fences should be preferred and, due to the usual budget constraints, priority should be given to the nests present in the taller hay crops as they have the greatest probability of high reproductive success. Next, protection should be applied to the nests in the hay crops with heights between 75 and 100 cm. If budget permits, nest protections can be applied in the shorter hay crops (50–75 cm) and, lastly, in the wheat and barley crops (where reproductive success is much lower). The nest protection should be positioned at least 10 days after egg deposition, and if possible, between 20 and 30 days, as compatible with the mowing date. It is useful to know in advance from the farmland owners when mowing is scheduled in their fields so as to place the electric fences a few days before mowing, thus delaying the nest protection as much as possible.

Fifthly, the monitoring of the hatching success in the hay crops should begin on 20 May, starting with taller crops (>100 cm) and then proceeding with shorter ones. In the hay crops, monitoring should stop by 19 June when >96% of the eggs have hatched or can no longer hatch (preyed or damaged). In the wheat and barley crops, the monitoring of egg hatching should start from 20 May and end by 4 July.

Sixthly, the monitoring of the fledging success in the hay crops should begin on 20 June, and stop on 19 July when >94% of youngs have either fledged or can no longer fledge. In the wheat and barley crops, the fledging success should be monitored from 20 June as well, but should end later (3 August).

5. Conclusions

Farmland birds are among the most important biodiversity indicators worldwide. Populations of farmland birds have declined since the second half of the 20th century, both in Europe and North America; thus, decision tools are necessary to set the proper conditions for the effective monitoring and conservation of bird diversity in farmland.

In this study, we fed field data collected from 2020 to 2022 into a probabilistic Bayesian model to produce rules for the optimized monitoring and conservation of the Montagu's harrier population in central Italy. Our approach was shown to successfully mimic the sequence of events that determine the reproductive success of this population, and allowed us to simulate the effects of different environmental and management scenarios. This knowledge can serve as information for planners to design more effective monitoring activities and policy instruments for this important farmland species in central Italy. The cost-effective methodological approach proposed in this study can be readily applied to any farmland bird population on a local scale.

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Data Availability Statement: The dataset used in this study is available from the first author on reasonable request.

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