diversity

MDPI

Article

Anthropogenic Pressure and Climate Change Could Severely Hamper the Avian Metacommunity of the Sicilian Wetlands

Alessandro Ferrarini *, Claudio Celada and Marco Gustin

Lipu-Birdlife Italy, Via Udine 3, I-43122 Parma, Italy
* Correspondence: sgtpm@libero.it; Tel.: +39-0521-191-0728

Abstract: Our study shows that the current levels of anthropogenic exploitation of the Sicilian wetlands (Italy), combined with the likely exacerbation of climate-driven variables, are unsustainable and could soon exclude many bird species from this metacommunity. Sicily is the largest island in the Mediterranean Sea, and its wetlands represent a network of unreplaceable stopover sites that allow waterbirds to rest and refuel during migratory journeys along the central-eastern Mediterranean bird flyway. During the summer period, these species experience higher levels of environmental stress as water scarcity and anthropogenic pressure are at their peak. Through field surveys, geoprocessing and statistical analyses, we investigated: (a) the structure of the avian metacommunity of the largest Sicilian wetlands during July–September and (b) the effects of 10 (geographic, hydrological and anthropogenic) wetland attributes on avian diversity. We sampled 73 bird species, of which 30 are listed in annex I of the Birds Directive. The avian metacommunity was significantly nested and non-modular; in addition, it presented elevated beta diversity and random species assemblage. Environmental filtering superseded biotic interactions in determining species composition. Avian diversity was significantly favored by higher water levels, water-level fluctuations and water discharges, and disfavored by water diversion, salinity and tourism pressure. The knowledge concerning the particular structure of the avian metacommunity of the Sicilian wetlands can facilitate the implementation of conservation policies that could mitigate and compensate the effects of short- and mid-term risks.

Keywords: climate change; environmental filtering; Mediterranean bird flyway; metacommunity structure; species traits; trans-Saharan migrators; wetland characteristics; wetland exploitation

check for updates

Citation: Ferrarini, A.; Celada, C.; Gustin, M. Anthropogenic Pressure and Climate Change Could Severely Hamper the Avian Metacommunity of the Sicilian Wetlands. *Diversity* **2022**, *14*, 696. https://doi.org/10.3390/d14090696

Academic Editor: Tamer Albayrak

Received: 30 July 2022
Accepted: 21 August 2022
Published: 23 August 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The long-range distances covered by migratory birds make them among the most difficult species to preserve [1]; in fact, threats to migratory species that occur in one geographic region may endanger their population size even at distant breeding and wintering regions [2]. Birds make use of intermediate stopover sites along migratory journeys to rest and refuel; thus, the effective conservation of migratory birds depends upon the availability of habitats both at and between their breeding and non-breeding areas [3]. Waterbirds in particular are at risk because of their reliance on wetlands [4]. Migratory waterbirds congregate in large numbers at these key sites, making them extremely vulnerable to localized threats; therefore, deterioration or loss of such wetlands have significant impacts at species level [5]. Regrettably, with the increasing impact of anthropogenic and climatic changes, the degradation and loss of wetlands are taking place worldwide, and are occurring faster than for any other type of ecosystems [6]. The causes include, among others, land conversion, water withdrawals, altered hydrology, eutrophication and pollution, overharvesting and overexploitation [7,8].

The flyway-level conservation of migratory birds requires shifting the attention from individual sites to the network of sites that provide stepping stones along migration routes [9]. Italy is a natural bridge between Africa and Europe; thus, it constitutes a flyway

of high importance for a large number of avian species crossing the Mediterranean Sea [10]. Sicily, due to its central position in the Mediterranean, plays a strategic role for birds during migration, especially for trans-Saharan waders, as its wetlands supply the food and protection that allow waterbirds to make migratory journeys whose success depends on the integrity of this wetland network [11]. Therefore, the Sicilian wetlands behave as bottleneck areas for many migratory bird species [12] and are ranked among the most interesting natural sites at a European level [13].

Despite the utmost importance of the Sicilian wetlands for avian diversity, during 1990–2012, their surroundings were severely impacted by anthropogenic activities, with a constant increase (about 50 ha/year) in agricultural areas and decrease (about 62 ha/year) in natural and semi-natural ones, respectively [14]. These dynamics are now severely threatening the Sicilian wetlands; in fact, water diversion for agricultural activities, anthropization and degradation of close surroundings, and tourism pressure are now usual threats to these wetlands and the associated avian diversity [15]. The ongoing climate change, by inducing the risks of complete wetland drainage (due to increased evaporation in summer) and increased saltwater intrusion (due to sea level rise), will further impact these wetlands by 2040 [15]. These recent land-use dynamics came after a massive process of transformation that affected the Sicilian wetlands, whose total surface area in the last century dropped from about 100,000 ha in 1865, to about 47,000 in the 1930s and to less than 5000 ha nowadays, for the most part artificial [16].

In this work, we investigated for the first time the structure of the avian metacommunity of the largest Sicilian wetlands (Figure 1) in summer (July–September), and the effects of wetland (geographic, hydrological and anthropogenic) attributes on avian diversity. The average distance between the studied wetlands was 11.8 km and the total surface area was 676 ha. In summer, this avian metacommunity experiences high levels of environmental stress as water scarcity and anthropogenic pressure are at their peak. We used results to: (a) raise firm hypotheses on the mid-term development of this metacommunity of utmost importance for many avian species of the central-eastern Mediterranean flyway and (b) advance proposals for its preservation in the face of increasing anthropogenic pressure and climate change.

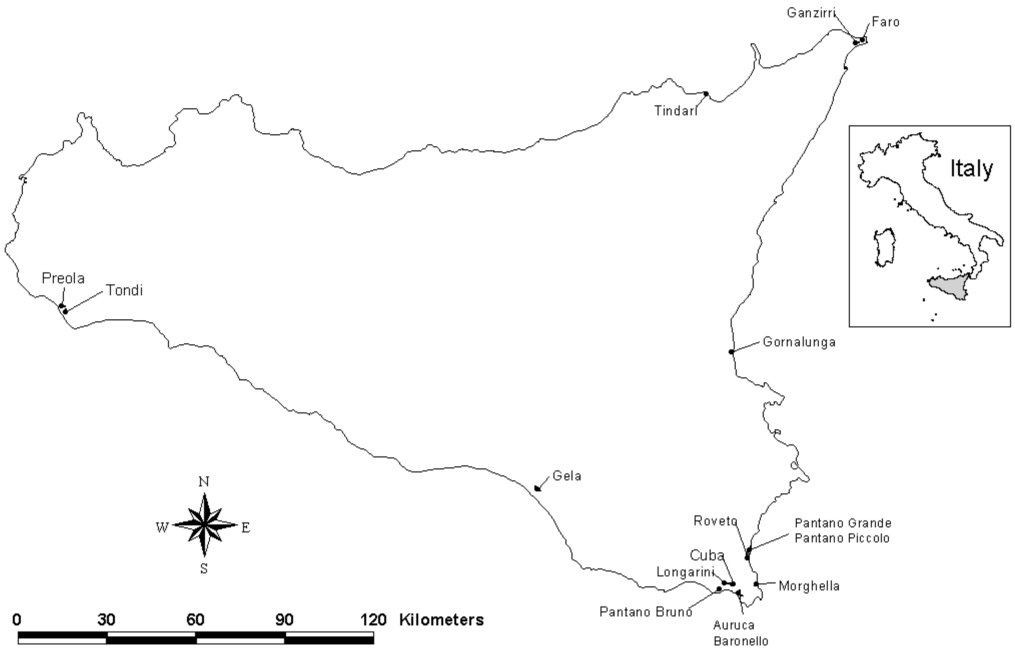

Figure 1. The Sicilian wetlands under study (Italy). Wetlands are marked with arrows and names.

2. Materials and Methods

2.1. Field Surveys

For each wetland during July–September 2016, we accomplished six sampling sessions of avian diversity, with intervals of 15 days between successive sessions. We used regularly spaced sampling points with 200 m minimum distance in order to minimize spatial autocorrelation [17]. In total, we employed 58 sampling points using the standard point count sampling method [18], i.e., 100 m observation distance around each sampling point during 15 min observation time with recording of visual or vocal contacts. The list of bird species sampled in the Sicilian wetlands is shown in Table S1.

2.2. Wetland Attributes

For each wetland, we assigned 3 geographic (wetland size, isolation and distance to the coastline), 3 hydrological (mean water level, water-level fluctuation and salinity) and 4 anthropogenic (water diversion for farming activities, water discharges, tourism pressure and anthropization level) attributes. We did not consider hunting among the anthropogenic attributes as there was a complete hunting ban in all the studied sites; in fact, 14 wetlands out of 16 belong to the Natura 2000 network, while the remaining 2 (Faro and Ganzirri) lie within the oriented natural reserve Laguna Capo Peloro. The 10 wetland attributes are described in Table S2.

2.3. Species Functional Traits

Based on the available literature [19], we assigned 3 functional traits to each bird species (Table S3): dietary guild (7 categories), foraging guild (6 categories) and migratory guild (4 categories).

2.4. Avian Diversity

We measured α diversity (mean number of species per wetland), γ diversity (total number of species in the metacommunity) and β diversity. The latter was calculated from the matrix of pairwise dissimilarities in species composition [20] as:

$$\beta = \sum_{j=1}^{n} \sum_{\substack{i=1 \\ i \neq j}}^{n} \frac{D_{ij}}{n\,(n-1)}$$

where n is the number of wetlands and D_{ij} is the compositional dissimilarity between the ith and jth wetlands measured using Jaccard's dissimilarity index for binary data:

$$D_{ij} = 1 - \frac{m_{ij}}{m_{ij} + p_{ij}}$$

where m_{ij} is the number of matches (species with presences in both wetlands) and p_{ij} is the number of mismatches (species with presence in just one wetland) between the ith and jth wetlands. D_{ij} could range from 0 ($p = 0$; i.e., no mismatches) to 1 ($m = 0$; i.e., no matches). As β was the average D_{ij} among the $n \times (n-1)$ off-diagonal pairs of wetlands, it also ranged in the [0,1] interval.

2.5. Metacommunity Structure

2.5.1. Metacommunity Modularity

In the species-by-site incidence matrix of a metacommunity, a module corresponds to groups of sites and species that are strongly linked together [21]. We used the Q metric [22] to test whether our metacommunity was formed by distinctive and repeated species compositions across an ordered set of sites. Q was calculated as:

$$Q = \sum_{q=1}^{r} \left[\frac{L_q}{L} - \left(\frac{K_q}{2L} \right)^2 \right]$$

where r was the number of modules in the network, L was the total number of links, L_q was the number of links between all the nodes within module q and K_q was the sum of the number of links of all the nodes in module q (i.e., the number of links within module q plus the number of links connecting members of module q to other modules).

We used the fast greedy algorithm to perform the search for the partition of the network into modules that maximized Q. To verify whether the modularity found by the maximization significantly differed from a theoretical benchmark, we used the Erdős–Rényi null model [23] and the null model 2 [24]. The first null model generated networks of the same size and connectance as those of our metacommunity, with edges randomly distributed among the nodes. The second null model also preserved the original distribution of edges per node. We performed 10^4 null model simulations, after which the resulting probability p was the proportion of random networks with $Q_{sim} \geq Q$, i.e., the probability that a more modular metacommunity could occur just by chance [22]. We accepted the null hypothesis of non-modularity if $0.05 < p < 0.95$ and rejected the null hypothesis if p exceeded these bounds.

2.5.2. Metacommunity Nestedness

A nested metacommunity is a type of hierarchical organization where the species that exist on a few sites tend to be found also on those sites inhabited by many different species [25]. To quantify the degree of nestedness of our avian metacommunity, we utilized the index T [25] that provides a measure of the metacommunity nestedness by assessing the deviation of the observed presence–absence matrix from one of the same rank and fill that is perfectly nested. T ranges from 0 (perfectly nested matrix) to 100 (completely disordered). We used a genetic algorithm to find the minimum value of T that could be obtained by permuting rows and columns of the observed presence–absence matrix [26] as:

$$\min(T) = \min\left(\frac{100 \times \sum_{ij} u_{ij}}{n \times s \times U_{\max}}\right)$$

where n and s are the number of wetlands and species in the metacommunity, respectively, u_{ij} is the unexpectedness of the generic matrix element and $U_{\max}$ is approximately the maximum possible disorder of any given matrix ($U_{\max} \sim 0.04145$; [26]). We tested the significance of min(T) against the T values of 10^4 randomly simulated matrices, and the proportion of random matrices having the same or lower T (i.e., same or higher nestedness) was the p-value [25]. We used three null models to generate random matrices; thus, we had three different p-values associated with different row and column constraints during randomizations.

In nested metacommunities, there could be species or sites, termed "idiosyncratic", that do not follow the nestedness rule [26]. We thus identified also the species and sites that violated the ecological and geographic gradients of nested species distributions.

2.5.3. Species Assemblage

We used two indices, the checkerboard score C-score [27] and the number of checkerboard species pairs N_c [28], to test for non-random patterns of species co-occurrences. The C-score measures the average number of "checkerboard units" (i.e., 0–1, 1–0), between all possible pairs of species. For s species, there are s x (s–1)/2 species pairs; therefore, the C-score was:

$$C = 2 \times \frac{\sum_{k=1}^{s} \sum_{l>k} (t_k - t)(t_l - t)}{s(s-1)}$$

where s is the number of species, t is the number of shared sites (sites containing both species) and t_k and t_l are the number of occurrences of species k and l, respectively.

Instead, N_c counts the number of species pairs in the presence–absence matrix that form perfect checkerboards, i.e., the number of unique pairs of species that never occur together in the same wetland. The observed indices (C_{obs} and Nc_{obs}) were compared with

those derived from 10^4 randomly assembled null matrices (C_{sim} and Nc_{sim}), and results were classified into three possible categories of outcomes: species aggregation (C_{obs} and Nc_{obs} significantly lower than in a random assemblage), species segregation (C_{obs} and Nc_{obs} significantly higher than in a random assemblage) and random pattern.

As we wished to retain the differences among sites and among species, we used the fixed rows–fixed columns null model with the sequential swap randomization algorithm [29]. Species frequencies and the number of species in each wetland were retained in the random matrices (rare species remained rare and common species remained common; hospitable wetlands remained hospitable and inhospitable wetlands remained inhospitable). This was biologically realistic as species and wetlands had very different traits (Tables S2 and S3); in addition, this null model has low Type I and II errors [29].

2.6. Effects of Wetland Attributes on the Avian Metacommunity

2.6.1. Effects on Species Richness

To test if, and to what degree, species richness was influenced by habitat filtering, we calculated correlations between the number of species and wetland attributes. To avoid possible collinearities among wetland attributes, we used the partial (i.e., correlation of the residuals after regression on the controlling variables) Spearman rank correlation coefficient *rho* to distinguish their independent effects on species richness.

2.6.2. Effects on Species Guilds

We used the fourth-corner method [30] to evaluate the significance of the associations between avian traits (diet, foraging and migration) and the hydrological attributes (mean water level, water-level fluctuation and salinity) of wetlands. We chose the permutation model based on the results of the species assembly analysis (paragraph 2.5.3); thus, we opted for the environmental control model [30]. Realizations of this null hypothesis were generated by permuting at random the values within each row vector (species), independently from row to row. We assessed the one-tailed significance based on 9999 permutations. We used Holm's procedure to accommodate the increased probability of committing a Type I error due to multiple simultaneous tests [30].

2.6.3. Effects on Single Species

We used randomizations [31] to test the hypothesis that wetland attributes were affecting the commonness and rarity of bird species. The test calculated for each species was:

$$E_k = P_k - A_k$$

where P_k was the average of the wetland attribute where species k was present and A_k was the average of the environmental variable where species k was absent. E_k was compared to 10^4 null model randomizations that assigned species occurrences randomly and independently to wetlands. Next, for each pair of species and wetland attribute, we calculated the Z-score:

$$Z = \frac{E_k - \mu_{sim}}{\sigma_{sim}}$$

where μ_{sim} and σ_{sim} were the mean and standard deviation of the simulated E_k, respectively. Z was thus the number of standard deviation units that the observed E_k lay above or below the expectation of the simulated distribution.

For each attribute, we calculated the number of positive ($Z > 0$; i.e., the more the better) and negative ($Z < 0$; i.e., the less the better) effects on the avian species. To test for the statistical significance of the overall effect of each wetland attribute on the avian metacommunity, we computed the cumulative binomial probability p_b to find at least the observed number of positive and negative Z-scores.

3. Results

The wetland attributes are shown in Table 1, with the matrices of species-by-site incidence and pairwise dissimilarities in species composition shown in Figure 2 and Table S4,

respectively. The diversity indices were 19.25 (α diversity), 73 (γ diversity) and 0.808 (β diversity). The wetlands with the highest species richness were Roveto (52 species), Gela (42), Gornalunga (28), Baronello (28) and Cuba (24). The most common species were the Grey Heron (13 presences out of 16 wetlands), the Little Egret (13), the Eurasian Coot (11), the Black-headed Gull (9) and the Little Grebe (9). The bird species were unevenly distributed with respect to two functional traits out of three (Figure 3).

The most common diet was based on invertebrates (24 species out of 73), while surface feeders (19 species) were the largest foraging guild. Trans-Saharan migrators (28 species) were the predominant migratory guild.

Modularity was equal to 0.254 and both resultant models were non-significant (Erdős–Rényi model: $p = 0.70$; null model 2: $p = 0.39$).

The avian metacommunity was significantly nested for all the null models (p-values < 0.001). The T of the packed matrix (Figure S1) was 12.85. The average T values generated by the three null models were 54.40 (±3.29 SD), 44.02 (±2.81 SD) and 38.08 (±3.20 SD), respectively. We detected several idiosyncratic wetlands (Faro, $T = 29.43$; Longarini, $T = 24.99$; Preola, $T = 22.29$; Tindari, $T = 20.43$; Table S5) and species (Eurasian Wigeon, $T = 90.84$; Common Sandpiper, $T = 52.98$; Kentish Plover, $T = 46.98$; Yellow-legged Gull, $T = 42.81$; Table S6).

The analysis of species assemblage did not show any aggregated or segregated patterns. C^{obs} was 3.934 and was non-significant ($p(C^{obs} \leq C^{sim}) = 0.896$; $p(C^{obs} \geq C^{sim}) = 0.104$; Figure S2). ${N_c}^{obs}$ was 637 and was also not significant ($p({N_c}^{obs} \leq {N_c}^{sim}) = 0.838$; $p({N_c}^{obs} \geq {N_c}^{sim}) = 0.162$; Figure S2).

After controlling for other independent variables, species richness was positively correlated with water-level fluctuations (partial Spearman $rho = 0.48$, $p < 0.05$), wetland size ($rho = 0.20$), mean water level ($rho = 0.16$), isolation ($rho = 0.10$) and water discharges ($rho = 0.08$). Negative correlations occurred with water diversion ($rho = -0.25$), salinity ($rho = -0.21$), tourism pressure ($rho = -0.13$), anthropization ($rho = -0.04$) and distance to the coastline ($rho = -0.04$).

The fourth-corner analysis showed that the mean water level had many significant impacts on the species guilds (Figure 4).

Table 1. Attributes of the 16 wetlands under study in Sicily (Italy). The last five attributes were measured on a semi-quantitative scale of 0 to 3 (0 if it was absent, 1 if localized, 2 if scattered and 3 if widespread), using both technical (the authors) and local (the natives, local policymakers and landowners) expertise. Refer to Table S2 for a detailed description of each attribute.

Wetland	Wetland size (ha)	Isolation (m)	Distance to the Coastline (m)	Mean Water Level (cm)	Water-Level Fluctuation (cm)	Salinity	Water Diversion	Water Discharges	Tourism Pressure	Anthropization
Auruca	31.4	461	1009	0.0	0.0	1	3	2	0	3
Baronello	20.5	461	779	24.3	10.7	0	1	2	1	2
Cuba	61.5	208	1499	2.9	3.0	0	2	0	0	1
Faro	26.9	818	409	1849.3	1.4	2	3	2	3	3
Ganzirri	34.1	816	990	497.6	2.6	2	3	3	3	3
Gela	107.8	65,943	2326	99.5	42.2	0	3	3	1	3
Gornalunga	13.9	63,208	0	33.9	11.9	2	0	2	2	3
Longarini	109.9	208	1674	1.2	1.5	3	3	3	3	3
Morghella	49.6	4798	19	0.6	1.2	1	3	2	1	3
Pantano Bruno	16.5	1419	1162	11.2	6.8	0	2	2	1	3
Pantano Grande	28.3	0	274	4.9	3.0	2	0	0	3	0
Pantano Piccolo	15.9	0	19	26.3	5.0	1	0	0	2	0
Preola	30.8	488	1318	145.6	6.4	0	0	0	1	2
Roveto	124.1	628	0	14.1	10.2	3	1	2	1	1
Tindari	7.4	50,349	198	200.1	86.4	3	0	0	3	0
Tondi	6.1	488	1916	506.1	17.4	0	0	0	0	1

Figure 2. Species-by-site incidence matrix. Darker cells indicate presences and lighter ones stand for absences.

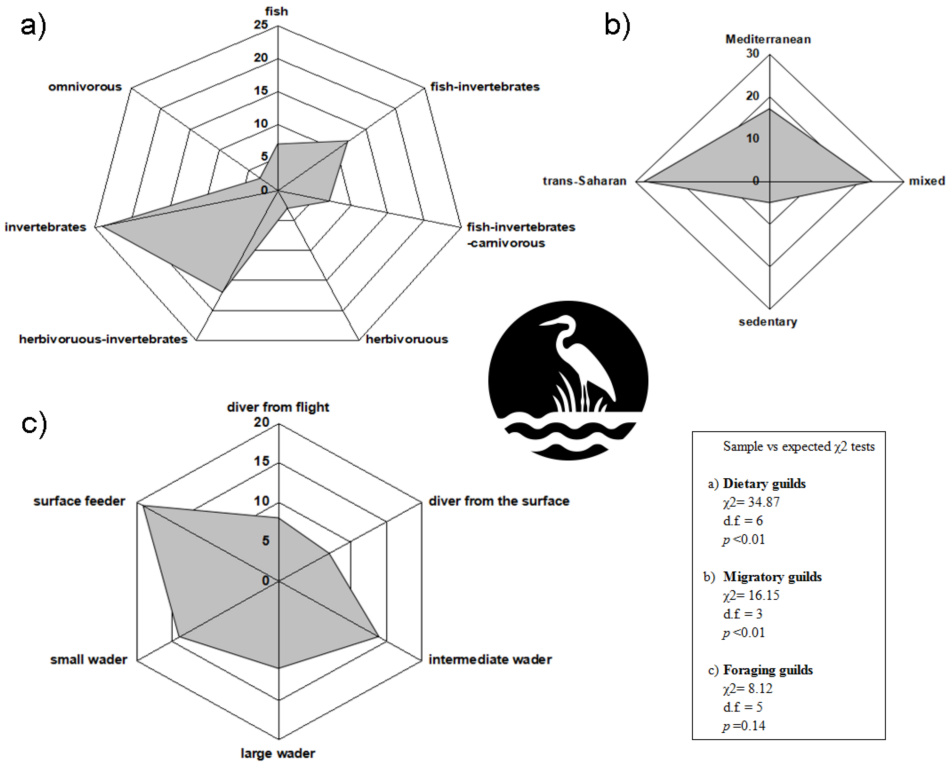

Figure 3. Functional traits ((**a**): diet; (**b**): migration; (**c**): foraging) of the avian species sampled in 16 Sicilian wetlands in summer. Numbers in the spider diagrams indicate how many species belong to a particular guild. See Table S3 for a detailed description of the functional traits.

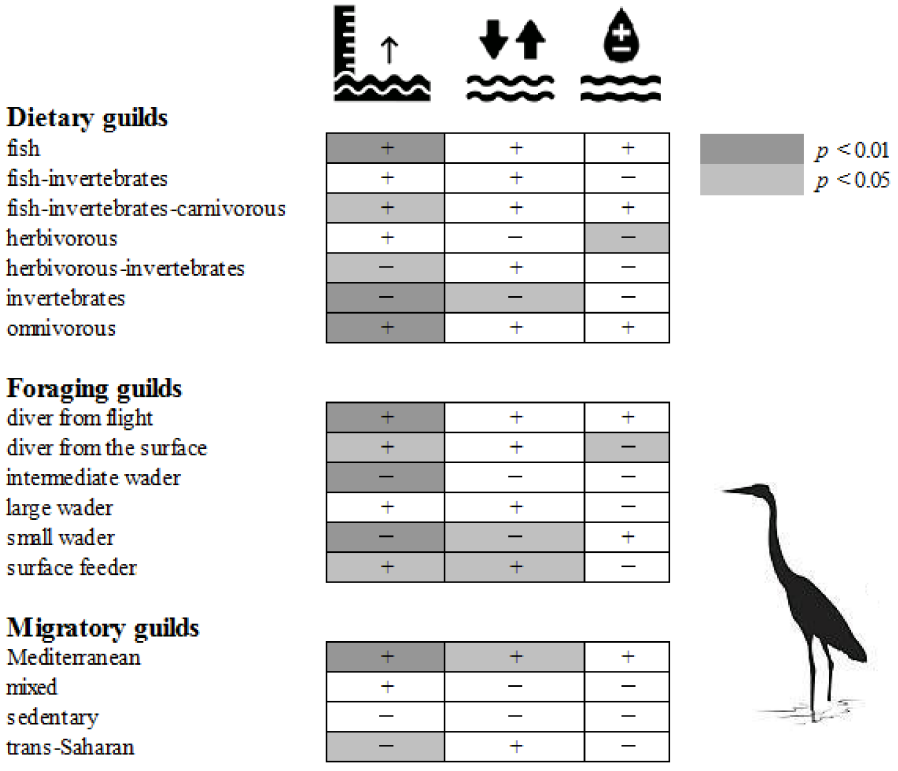

Figure 4. Results of the fourth-corner analysis. The negative or positive effects of the hydrological variables (in order from left to right: mean water level, water-level fluctuations, salinity) on the species guilds are shown. See Table S3 for a detailed description of species guilds.

With regard to the dietary guilds (Figure 4), higher water levels significantly favored: (a) omnivores, (b) carnivores also feeding on fish and invertebrates and (c) piscivores. Species feeding on invertebrates were significantly favored by lower water levels. As for the foraging guilds, more elevated water levels significantly favored divers from flight, divers from the surface and surface feeders; by contrast, small waders and intermediate waders were significantly disfavored. Of the migratory guilds, Mediterranean migrants were significantly favored by higher water levels as most of them had types of diet favored by higher water levels (Table S7). By contrast, most of the trans-Saharan migrants were disadvantaged because of a diet mainly based on invertebrates. Water-level fluctuation and salinity were less relevant at guild level as diversified effects occurred within guilds, thus preventing the overall effect from being significant.

The randomization tests of the effects of wetland attributes on the avian metacommunity (Figure 5) showed that five wetland attributes significantly and positively affected avian diversity: water-level fluctuations (positive effect on 62 species out of 73; $p_b < 0.01$), wetland size ($p_b < 0.01$), mean water level ($p_b < 0.01$), water discharges ($p_b < 0.01$) and isolation ($p_b < 0.05$). Conversely, water diversion (negative effect on 48 species out of 73; $p_b < 0.01$), salinity ($p_b < 0.05$) and tourism pressure ($p_b < 0.05$) significantly and negatively impacted the avian diversity of the metacommunity.

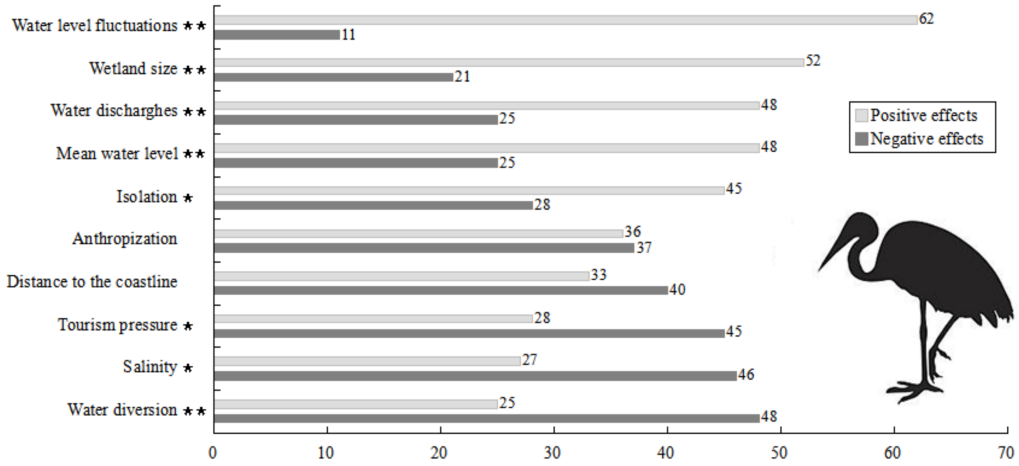

Figure 5. The number of bird species favored or disfavored by each wetland attribute is shown. Asterisks indicate the statistical significance (* $p < 0.05$, ** $p < 0.01$) of each attribute's effect on the avian diversity (73 species) of the Sicilian wetlands based on the cumulative binomial probability.

4. Discussion

In summer, the avian metacommunity was significantly nested and non-modular; in addition, it presented random species assemblage and elevated beta diversity. This knowledge concerning the metacommunity structure has clear implications for the conservation of the avifauna.

Modularity indicates areas and species more closely related with each other than with other areas and species [32], i.e., sets of sites with biotic affinity that could be considered biodiversity management units. The absence of modularity detected in this study implies that conservation approaches based on biodiversity management units (i.e., clusters of contiguous wetlands for which similar conservation policies can be applied) would fail. The structure of the avian metacommunity of the Sicilian wetlands requires conservation plans customized to fit the attributes of each single wetland and the ecological requirements of its bird species.

Nestedness unveils a type of metacommunity where generalists interact with other generalists, and specialists only interact with generalists but not other specialists [33]. Nestedness can be caused by several ecological mechanisms, e.g., habitat quality (habitats of higher quality are preferably colonized [34]). Whatever the reason, in nested species assemblages,

the species present in species-poor sites are a proper subset of those present in species-rich sites [35,36], which proves the priority for conservation of the most hospitable wetlands.

Random species assemblage indicates that bird species individualistically colonized the available wetlands, i.e., species were found at locations where they encountered appropriate living conditions [37], which was likely favored by the high dispersal and mobility of avian species and short distances among wetlands (Table S8). In this type of metacommunity, species act independently of one another, species associations are weak and environmental control is predominant [30].

The elevated β diversity (0.808 out of a maximum of 1) detected in this study can be explained in light of localized habitat filtering. When anthropogenic and environmental impacts are patchy in space, β diversity is likely to increase at the regional scale as many species become rarer [38]. In fact, in our case study, 15 avian species occurred in only one wetland out of 16, while 39 species occurred in three or less wetlands (Table S9).

The detected random species assemblage and elevated β diversity imply that environmental filtering superseded biotic interactions in determining species composition in this avian metacommunity. In fact, our analyses showed the significant effects of several wetland attributes on the avifauna, which in turn suggests that proper interventions on such attributes will have substantial beneficial effects.

Implications for the Conservation of the Avian Metacommunity of the Sicilian Wetlands

While all the studied wetlands are important stepping stones for this avian metacommunity and deserve conservation measures, the preservation, or betterment, of the hydrological and anthropogenic attributes of the most hospitable wetlands (Roveto, Gela, Gornalunga and Baronello; Figure S1) is essential as they provide the precondition for the presence of most species, independently of their taxonomic or functional group. For instance, the first two wetlands in terms of species richness (Roveto and Gela) hosted 64 species out of 73. However, this approach would fail to preserve some idiosyncratic species, including the Eurasian Wigeon, the Common Sandpiper, the Kentish Plover, the Yellow-legged Gull, the Slender-billed Gull, the Common Kingfisher and the Common Ringed Plover (Table S6). Preserving or improving the attributes of some idiosyncratic wetlands, such as Preola and Faro (Table S5), would favor the idiosyncratic species as well.

Water depth significantly affected species composition. Water depth influences the accessibility of foraging habitats for waterbirds due to bird morphology (e.g., the lengths of tarsometatarsi or necks [39]). The wetlands with higher avian diversity had mean water levels between 14 and 34 cm (Baronello, Gornalunga and Roveto; Table 1), with the exception of Gela (99 cm) that, however, compensated with an elevated water-level fluctuation (42.2 cm). Water-level variations create habitats with different water depths in time and space, which provides more foraging opportunities and consequently supports higher species richness [40]. This suggests that, in summer, the avian diversity of this metacommunity can be properly sustained by: (a) intermediate water levels <35 cm) with low fluctuations (<10 cm) or (b) higher water levels (<100 cm) with higher water-level variations (>40 cm). These hydrological characteristics should be maintained in these wetlands, and also promoted at other sites, using water control structures to artificially regulate water depth and fluctuation.

Water diversion for agricultural activities negatively impacted many bird species; in fact, scattered or widespread water uptakes, combined with natural evaporation, caused many wetlands to have a water shortage or complete drainage (Table 1). While this can temporarily favor small and intermediate waders, on a mid-term basis, water diversion will represent a major threat to all the bird species due to the risk of wetland drainage in summer, with the exception of the few wetlands where water levels are elevated (Preola, Tindari and Tondi) or artificially controlled (Faro and Ganzirri). Unrestrained water diversion should be thus prohibited before and during the summer period in the most hospitable wetlands (Roveto, Gornalunga and Baronello) and where water levels are already low (Auruca, Cuba, Longarini, Morghella, Pantano Bruno and Pantano Grande).

Unexpectedly, water discharges had positive effects on many bird species. Due to the low mean water levels (<15 cm) in many wetlands (Cuba, Longarini, Morghella, Pantano Bruno, Pantano Grande and Roveto; Table 1), water discharges, although rich in pollutants, often represent the only alternative to complete drainage. As things stand, the prohibition or limitation of water discharges in summer would negatively impact many bird species. However, even if short-term effects of water discharges on bird richness were prevalently positive, the mid- and long-term consequences of contaminants on these waterbirds are unknown, and water pollution could arguably cause illness and decrease the reproductive success [41]. Accordingly, alternative solutions are necessary in the near future, based on: (a) the prohibition of water diversion for agricultural activities and (b) water control structures to artificially raise and lower water levels. In this scenario, water discharges would no longer be useful to sustain avian diversity; rather, their pollutant effects would be disadvantageous.

Salinity proved harmful for many avian species. Most birds avoid saline water as it causes weight loss by dehydration, reduction in the waterproofing of feathers and an increase in the energy costs of thermoregulation [42]. Water salinity also affects the species composition of aquatic plant communities [43]; in fact, we found negative significant effects on herbivorous species. Accordingly, limiting water salinity is critical in order to support the foraging habitats for most species of this metacommunity. However, several wetlands (Longarini, Roveto and Tindari) already experience widespread saltwater intrusions, while others (Faro, Ganzirri, Gornalunga and Pantano Grande) have scattered ones (Table 1). In addition, sea level is expected to increase by almost 9 cm by 2040 [15]; therefore, the construction of artificial dune cordons at least 10 cm high and the reinforcement of natural ones are urgently required around the wetlands near the coastline (Roveto, Gornalunga, Morghella, Pantano Piccolo and Tindari), with the highest priority assigned to the most hospitable wetlands.

Tourist and recreational activities (e.g., walking, camping, angling) are a further significant impingement on this avian metacommunity. Their manifold effects include, among others, noise disturbance leading to reduced breeding success and modified habitat use, damage to nests and increased water pollution [8]. Tourist and recreational activities should be prohibited around the most hospitable wetlands (Roveto, Gela, Gornalunga and Baronello) and limited around those wetlands where they are already widespread (Faro, Ganzirri, Longarini, Pantano Grande and Tindari).

5. Conclusions

Our study emphasized the critical condition of the avian metacommunity of the Sicilian wetlands during the summer period. Severe threats are affecting most wetlands, with significant negative effects on the associated avifauna. Climate change will further worsen the risk of water shortage and salinization. Our study also evidenced that the particular structure of this avian metacommunity would facilitate the implementation of conservation policies that could mitigate and compensate these effects.

As 14 wetlands out of 16 belong to the Natura 2000 network, these policies seem highly practicable. In addition, the massive processes of: (a) size reduction of the Sicilian wetlands in the last century and (b) anthropization of the surroundings in the past 30 years urge the application of measures of wetland enhancement by increasing the size of the existing wetlands and creating new ones, which would support the objectives of the Birds Directive and would be deliverable under the EU 2030 Biodiversity Strategy.

However, in a worst-case scenario where these conservation measures will not be applied, or at least not pro-actively, our study indicates that the likely consequence will be the exclusion of many bird species from this metacommunity, and a drastic reduction in the number of migrating individuals for the remaining species. Considering the crucial placement of these wetlands as last stopover sites before crossing the Mediterranean Sea, new scientific questions arise: What would be the effect on the central-eastern Mediterranean flyway if many avian species could no longer use the most important platform for migra-

tion along the Italian peninsula? How could different species and populations cope with longer migration distances if the last stopover sites before crossing the Mediterranean were instead the wetlands situated hundred kilometers further north in Campania, Apulia and Latium (assuming that their habitat quality and extent will be preserved in the near future)? What would be the ecological trade-off of this epochal change for the migratory avifauna?

Although ad hoc studies are required to answer these questions, we speculate that the dismissal of the Sicilian wetlands as migratory stepping stones could seriously hinder the migratory flow of many bird species along the central Mediterranean.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/d14090696/s1, Figure S1: Nested distributions of 73 avian species at 16 wetlands in Sicily during the summer period; Figure S2: Results of 10,000 null model simulations for the two indices C-score and number of checkerboard species pairs; Table S1: List of the avian species sampled in the Sicilian wetlands; Table S2: Description of the attributes of the 16 wetlands under study in Sicily; Table S3: Functional traits (diet, foraging, migration) of the bird species sampled in the Sicilian wetlands; Table S4: Pairwise dissimilarities in species composition among wetlands; Table S5: Idiosyncratic wetlands in Sicily; Table S6: Idiosyncratic bird species in the Sicilian wetlands; Table S7: Cross-tabulation analysis of species guilds; Table S8: Boundary-to-boundary distances among the wetlands under study; Table S9: List of the bird species with three or less occurrences out of 16 wetlands.

Author Contributions: Conceptualization, A.F., C.C. and M.G.; methodology, A.F.; software, A.F.; validation, C.C. and M.G.; formal analysis, A.F.; investigation, A.F., C.C. and M.G.; resources, C.C. and M.G.; data curation, M.G.; writing—original draft preparation, A.F.; writing—review and editing, A.F., C.C. and M.G.; visualization, A.F.; supervision, C.C. and M.G.; project administration, C.C. and M.G.; funding acquisition, C.C. and M.G. All authors have read and agreed to the published version of the manuscript.

Funding: Field surveys and geoprocessing were supported by the MAVA Foundation ("Mediterranean Mosaics II" project) for the period 2016–2019, and analyses by LIPU-UK in 2021.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

Acknowledgments: We are grateful to Andrea Corso for his involvement in field surveys. All individuals included in this section have consented to the acknowledgment. We thank the assistant editor and two anonymous reviewers for their useful suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Elphick, J. *The Atlas of Bird Migration: Tracing the Great Journeys of the World's Birds*; Natural History Museum: London, UK, 2007.
2. Runge, C.A.; Watson, J.E.M.; Butchart, S.H.M.; Hanson, J.O.; Possingham, H.P.; Fuller, R.A. Protected areas and global conservation of migratory birds. *Science* **2015**, *350*, 1255–1258. [CrossRef] [PubMed]
3. Alerstam, T. *Bird Migration*; Cambridge University Press: Cambridge, UK, 1990.
4. Boere, G.C.; Galbraith, C.A.; Stroud, D.A. (Eds.) *Waterbirds around the World*; The Stationery Office: Edinburgh, UK, 2006.
5. Barnard, J.; Bennun, L.; Iyer, S.; Keil, F.; Ponziani, C. *Wings over Wetlands (WOW)—Flyway Conservation at Work across Africa and Eurasia. Enhancing the Conservation of the Critical Network of Sites Required by Migratory Waterbirds on the African–Eurasian Flyways*; UNEP-GEF: Geneva, Switzerland, 2010.
6. Gardner, R.C.; Finlayson, C.M. *Global Wetland Outlook: State of the World's Wetlands and Their Services to People*; Ramsar Convention: Gland, Switzerland, 2018.
7. Gardner, R.C.; Barchiesi, S.; Beltrame, C.; Finlayson, C.M.; Galewski, T.; Harrison, I.J.; Paganini, M.; Perennou, C.; Rosenqvist, A.; Walpole, M.; et al. *State of the World's Wetlands and Their Services to People: A Compilation of Recent Analyses*; Social Science Electronic Publishing: Gland, Switzerland, 2015.
8. Mitsch, W.J.; Gosselink, J.G. *Wetlands*; John Wiley & Sons: New York, NY, USA, 2015.
9. Dodman, T.; Boere, G.C. *The Flyway Approach to the Conservation and Wise Use of Waterbirds and Wetlands: The Flyway Training Kit*; Wetlands International and BirdLife International: Ede, The Netherlands, 2010.
10. Berthold, P. *Bird Migration: A General Survey*; Oxford University Press: New York, NY, USA, 2001.

11. Spina, F.; Volponi, S. *Atlante della Migrazione Degli Uccelli in Italia*; Ministero dell'Ambiente e della Tutela del Territorio e del Mare, Istituto Superiore per la Protezione e la Ricerca Ambientale: Rome, Italy, 2008.
12. Bijlsma, R.G. *Bottleneck Areas for Migratory Birds in the Mediterranean Region: An Assessment of the Problems and Recommendations for Action*; International Council for Bird Preservation: Cambridge, UK, 1990.
13. Heath, M.F.; Evans, M.I. (Eds.) *Important Bird Areas in Europe. Priority Sites for Conservation. 2 Vols*; BirdLife International: Cambridge, UK, 2000.
14. Ferrarini, A.; Gustin, M.; Celada, C. Twenty-Three Years of Land-Use Changes Induced Considerable Threats to the Main Wetlands of Sardinia and Sicily (Italy) along the Mediterranean Bird Flyways. *Diversity* **2021**, *13*, 240. [CrossRef]
15. Ferrarini, A.; Celada, C.; Gustin, M. Preserving the Mediterranean bird flyways: Assessment and prioritization of 38 main wetlands under human and climate threats in Sardinia and Sicily (Italy). *Sci. Total Environ.* **2020**, *751*, 141556. [CrossRef] [PubMed]
16. De Pietro, R.; Ientile, R.; Puccia, S.; Sabella, G. Birds of Gelsari and Lentini marshes, special protection area for the protection and maintenance of aquatic avifauna in central Mediterranean. *Ocean Coast. Manag.* **2019**, *169*, 96–103. [CrossRef]
17. Griffith, D.A. *Spatial Autocorrelation: A Primer*; Association of American Geographers: Washington, DC, USA, 1987.
18. Hutto, R.L.; Pletschet, S.M.; Hendricks, P. A fixed-radius point count method for nonbreeding and breeding season use. *Auk* **1986**, *103*, 593–602. [CrossRef]
19. Cramp, S.E.; Simmons, K.E.L.; Brooks, D.J.; Perrins, C.M. *Handbook of the Birds of Europe, the Middle East and North Africa: The Birds of the Western Palearctic*; Oxford University Press: Oxford, UK, 1977–1994; Volume 1–9.
20. Legendre, P.; De Cáceres, M. Beta diversity as the variance of community data: Dissimilarity coefficients and partitioning. *Ecol. Lett.* **2013**, *16*, 951–963. [CrossRef]
21. Leibold, M.A.; Mikkelson, G.M. Coherence, species turnover, and boundary clumping: Elements of meta-community structure. *Oikos* **2002**, *97*, 237–250. [CrossRef]
22. Newman, M.E.J.; Girvan, M. Finding and evaluating community structure in networks. *Phys. Rev.* **2004**, *69*, 026113. [CrossRef]
23. Erdős, P.; Rényi, A. On random graphs. *Publ. Math. Debr.* **1959**, *6*, 290–297.
24. Bascompte, J.; Jordano, P.; Melian, C.J.; Olesen, J.M. The nested assembly of plant–animal mutualistic networks. *Proc. Natl. Acad. Sci. USA* **2003**, *100*, 9383–9387. [CrossRef]
25. Rodríguez-Gironés, M.A.; Santamaría, L. A new algorithm to calculate the nestedness temperature of presence-absence matrices. *J. Biogeogr.* **2006**, *33*, 924–935. [CrossRef]
26. Atmar, W.; Patterson, B.D. The measure of order and disorder in the distribution of species in fragmented habitat. *Oecologia* **1993**, *96*, 373–382. [CrossRef]
27. Stone, L.; Roberts, A. The checkerboard score and species distributions. *Oecologia* **1990**, *85*, 74–79. [CrossRef]
28. Diamond, J.M. Assembly of species communities. In *Ecology and Evolution of Communities*; Cody, M., Diamond, J.M., Eds.; Harvard University Press: Cambridge, UK, 1975; pp. 342–444.
29. Gotelli, N.J. Null model analysis of species co-occurrence patterns. *Ecology* **2000**, *81*, 2606–2621. [CrossRef]
30. Legendre, P.; Galzin, R.; Harmelin-Vivien, M.L. Relating behavior to habitat: Solutions to the fourth-corner problem. *Ecology* **1997**, *78*, 547–562. [CrossRef]
31. Gotelli, N.J.; Ulrich, W.; Maestre, F.T. Randomization tests for quantifying species importance to ecosystem function. *Methods Ecol. Evol.* **2011**, *2*, 634–642. [CrossRef]
32. Thébault, E. Identifying compartments in presence–absence matrices and bipartite networks: Insights into modularity measures. *J. Biogeogr.* **2013**, *40*, 759–768. [CrossRef]
33. Krishna, A.; Guimaraes, P.R., Jr.; Jordano, P.; Bascompte, J. A neutral-niche theory of nestedness in mutualistic networks. *Oikos* **2008**, *117*, 1609–1618. [CrossRef]
34. Simberloff, D.; Martin, J.-L. Nestedness of insular avifaunas: Simple summary statistics masking complex species patterns. *Ornis Fenn.* **1991**, *68*, 178–192.
35. Wright, D.H.; Reeves, J.H. On the meaning and measurement of nestedness of species assemblages. *Oecologia* **1992**, *92*, 416–428. [CrossRef]
36. Patterson, B.D.; Atmar, W. Nested subsets and the structure of insular mammalian faunas and archipelagos. *Biol. J. Linn. Soc. Lond.* **1986**, *28*, 6582. [CrossRef]
37. Weiher, E.; Keddy, P. *Ecological Assembly Rules: Perspectives, Advances, Retreats*; Cambridge University Press: Cambridge, UK, 1999.
38. Kessler, M.; Abrahamczyk, S.; Bos, M.; Buchori, D.; Putra, D.D.; Gradstein, S.R.; Höhn, P.; Kluge, J.; Orend, F.; Pitopang, R.; et al. Alpha and beta diversity of plants and animals along a tropical land-use gradient. *Ecol. Appl.* **2009**, *19*, 2142–2156. [CrossRef]
39. Poysa, H. Resource utilization pattern and guild structure in a waterfowl community. *Oikos* **1983**, *40*, 295–307. [CrossRef]
40. Ntiamoa-Baidu, Y.; Piersma, T.; Wiersma, P.; Poot, M.; Battley, P.; Gordon, C. Water depth selection, daily feeding routines and diets of waterbirds in coastal lagoons in Ghana. *Ibis* **1998**, *140*, 89–103. [CrossRef]
41. Kirby, J.; Davidson, N.; Giles, N.; Owen, M.; Spray, C. *Waterbirds and Wetland Recreation Handbook. A Review of Issues and Management Practice*; The Wildfowl and Wetlands Trust Publisher: Gloucester, UK, 2004.
42. Rubega, M.A.; Robinson, J.A. Water salinization and shorebirds: Emerging issues. *Int. Wader Stud.* **1997**, *9*, 45–54.
43. Holm, T.E.; Clausen, P. Effects of water level management on autumn staging waterbird and macrophyte diversity in three Danish coastal lagoons. *Biodivers. Conserv.* **2006**, *15*, 4399–4423. [CrossRef]