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Article

Anthropogenic and Environmental Factors Influence Adult Survival in a Conservation Reliant Coastal Wader Population

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Simple Summary

Shorebirds are affected by both natural conditions and human activities, but the long-term consequences of these pressures are often difficult to detect. We analysed nearly 30 years of monitoring data from a Kentish plover population in north-western Spain to evaluate how survival and recapture probability was influenced by a major oil spill and climatic conditions. Survival declined after the spill and remained low for several years, suggesting that the effects of large pollution events can persist over time. Survival was also lower in wetter years, showing that weather conditions can further increase the pressure on bird populations. In addition, the probability of recapture was higher in males than in females, probably because behavioural differences make males easier to detect. Our results highlight the importance of long-term monitoring to understand how multiple environmental factors affect wildlife.

Abstract

Bird survival is influenced by both natural and anthropogenic factors, including weather conditions and oil spills. In this study, we examined the impact of a major oil spill (*Prestige* oil tanker) and climatic conditions (precipitation and wind) on survival and recapture probability in the Kentish plover (*Anarhynchus alexandrinus*) population in Galicia (NW Spain). To this end, we applied the Cormack-Jolly-Seber (CJS) live recapture model to a sample of 372 adult birds captured between 1994 and 2023. The best-fit model indicated that survival was best explained by the interaction between precipitation and the *Prestige* oil spill, indicating a decrease in survival post-spill, especially in the periods Post1 (years 2003–2007) ($\beta_{P1} = -0.70 \pm 0.26$) and Post2 (2008–2015) ($\beta_{P2} = -0.56 \pm 0.27$). Precipitation showed a negative influence on adult survival ($\beta_{pp} = -0.71 \pm 0.20$), but wind had no significant influence. Recapture probability was influenced by the interaction between time, sex and *Prestige*, with males showing higher values ($\beta_{sexMale} = 3.67 \pm 1.47$), probably due to behavioural and detectability differences. Environmental monitoring and preparedness for pollution events are therefore essential to improve the long-term viability of the species.

Keywords: *Anarhynchus alexandrinus*; climatic factors; Kentish plover; *Prestige* oil spill; survival

1. Introduction

Bird survival, including that of waders, is determined by a complex interaction between natural and anthropogenic factors. Abiotic factors, such as precipitation, wind and temperature, can directly

affect the availability of food resources [1,2] and breeding conditions [3-6], thus affecting survival [7-10]. Biotic interactions, including predation [11-14], also play a crucial role in population dynamics.

Human activities also cause additional pressures, especially in coastal and other wetland ecosystems. The most important types of anthropogenic disturbance include habitat degradation [15], chemical pollution [16,17], and oil spills [18,19]. Oil spills have had a particularly serious impact on marine ecosystems in the past five decades, with more than 10,000 incidents recorded since 1970 [18]. Such events can affect birds both directly and indirectly, impacting their physiology, reproduction and behaviour, as well as the availability of key habitats and ultimately survival [19-21]. However, although oil spills have been shown to have detrimental effects on waders [22-24], survival of these birds has not been found to be significantly affected [25,26].

On 13 November 2002, the *Prestige* oil tanker sank off the coast of Galicia (NW Iberian Peninsula), releasing 77,000 tons of oil [27]. Wind and ocean currents spread the oil from Portugal to Brittany (France), threatening the Atlantic coast of northwestern Spain from Galicia to the Basque Country and the southern Bay of Biscay and producing one of the largest oil spill events to date in Europe [28]. Clean-up activities were mainly carried out between November 2002 and the summer of 2003, continuing until 2004 in the most affected areas. Signs of contamination were detected on 503 of the 723 beaches in Galicia [29]. The oil spill directly killed thousands of birds [27]. Galicia received the largest number of affected birds, more than 50% of the total [27]. In addition, the oil remained on the coast for months [30] and even years in some sites [31], possibly with adverse physiological responses and eventually leading to a decline in populations, as in the case with the European shag (*Gulosus aristotelis*) [32].

The Kentish plover (*Anarhynchus alexandrinus*) is a small wader that inhabits the coasts and wetlands of Eurasia and North Africa [33]. Most breeding populations of this species in Europe have undergone a marked decline since the early 20th century [34]. The main factors involved in the decline are human use of nesting, feeding and resting areas, destruction of dunes, habitat fragmentation, abandonment of traditional salt farms and coastal regression [35-37]. In the Spanish population, negative trends in both the numbers and the area of occupancy have been observed, with disappearance of populations in coastal areas, especially along the Mediterranean coast [36,38]. The northwest Iberian population, which mainly consists of resident birds [39,40], exclusively inhabits sparsely vegetated beaches [38,41].

After the *Prestige* oil spill, although no evidence of direct mortality of Kentish plovers was observed [27], many breeding birds were partly oiled during the winter and spring of 2003 [42]. In addition, between 2004 and 2007, high levels of polycyclic aromatic hydrocarbons (PAHs) were detected in the plovers' eggs [43] and the oil adversely affected the reproductive performance of the birds by altering the condition of individual members of the population and by changing egg quality for years rather than only immediately after the spill event [44].

Several studies have examined survival of the Kentish plover in different regions [4,45-49], although there is little information on the effect of oil spills on the survival of small waders. Studies focusing on these aspects would be of great interest to better understand the threats faced by the species and to guide the design of effective conservation measures.

In this study, we aimed to test two hypotheses related to the survival of the Galician Kentish plover during the period 1994–2023. First, we hypothesised that the *Prestige* oil spill has negatively affected the survival of the species. Secondly, we hypothesised that higher precipitation and stronger winds have negatively affected the survival of the species. This integrative approach provides new perspectives on the challenges of conservation in the context of both anthropogenic and climatic disturbance.

2. Study Area and Methods

2.1. Study Area

The NW Iberian Kentish plover population relies on open coastal sandy beaches backed by low, sparsely vegetated foredunes. The study area included the 62 known breeding and/or wintering beaches along NW Iberian coast (Figure 1). The average breeding population size in the period 1999–2023 was 81.4 ± 2.53 pairs (range: 62–108 pairs)[41,50].

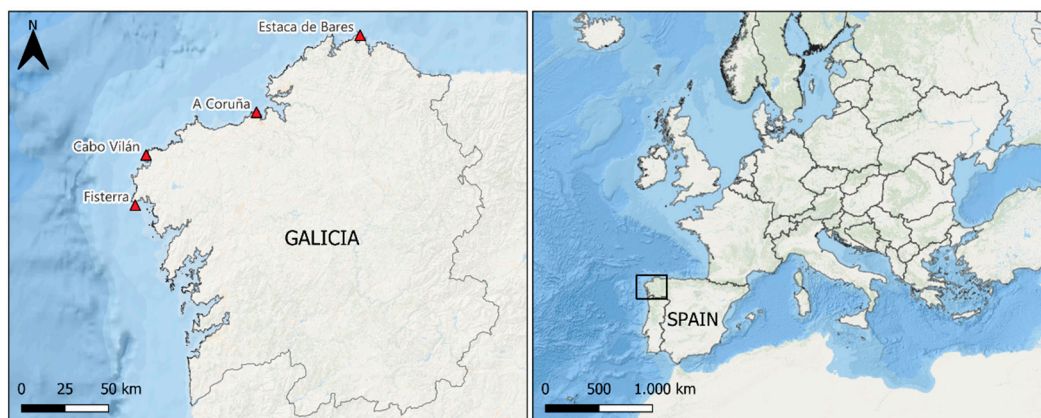


Figure 1. Study area. ▲ location of the weather stations where climatic data were recorded.

2.2. Methods

Adult plovers were captured in the nest with a funnel trap. Care was taken to avoid damaging eggs or attracting aerial or terrestrial predators to the nests. The sex of adult birds was determined based on dimorphic plumage characteristics [51]. Each adult was marked with a unique combination of one to four colour leg rings and an alpha-numeric metal ring. Body mass, bill length, tarsus length and wing length were measured in all individuals captured. Individuals were subsequently resighted when they were recaptured in the nest or mostly by visual resighting with binoculars or telescope. Resightings were conducted regularly: during the breeding season, all potential and confirmed breeding beaches were intensively surveyed, and during the post-breeding season, wintering beaches were periodically monitored. In addition, records of marked birds observed outside these areas, both by our team and by other observers, were also included.

Apparent Adult Survival

Encounter histories of banded birds were compiled from 29 occasions (each corresponding to a full calendar year, January–December), including adults, birds in at least second calendar year [52], captured between 1994 and 2023. We used a Cormack-Jolly-Seber (CJS) live recapture model [53–55], implemented in the “RMark” package [56] in the R programming environment version 4.1.3, together with the program MARK version 10 [57], to generate estimates of apparent annual survival (ϕ) and recapture probability (p). We estimated the apparent annual survival, rather than true survival, as it was not possible to distinguish between emigration and mortality. However, the large resight area, the percentage of known breeders and the high site fidelity of individuals [39, unpublished data] help prevent emigration being confounded with death [48,58], and the apparent survival of this population is probably close to the true survival [45,49].

We created a set of candidate models using different ecological factors that could a priori affect the apparent annual survival. The following predictors were used: time (year); sex, because we expected survival to be affected by annual variation differently in females and males [48,59,60]; precipitation, accumulated annual precipitation in mm; wind, number of days per year with wind gusts ≥ 60 km/h [3]; and *Prestige* oil spill, divided into four periods: years 1994–2002 (Pre), 2003–2007 (Post1), 2008–2015 (Post2) and 2016–2023 (Post3). This division was based on an initial period in which negative effects were documented both in the Kentish plover population [42–44,61] and in other species [62–65], followed by two subsequent periods defined symmetrically, as the passage of time evidenced a gradual recovery in different ecosystem components [31,66]. This approach allowed

us to explore the effects of the oil spill in the short, medium and long term, considering that previous studies indicated that this event did not appear to affect long-term population growth [50].

As the Kentish plover population in Galicia is mainly resident or short-distance migrant, we used the meteorological data for the whole year. Meteorological data from 1994 to 2023 were obtained from the network of stations belonging to the State Meteorological Agency (AEMET). The data were mainly obtained from the Fisterra weather station but, as no data were available for some years, were supplemented by data from the Cabo Vilán, Estaca de Bares or A Coruña weather stations (Figure 1). To facilitate comparison between continuous variables and ensure the stability of the model estimates, the precipitation, wind and time variables were standardised before inclusion in the models. The coefficients obtained in the model thus reflect the impact of a one standard deviation change in these variables on the probability of survival and detection, rather than a change in the original units of the variables. Different combinations of time, sex, *Prestige* oil spill, precipitation and wind were generated, although only the 50 candidate models with the lowest AICc values were retained for analysis (Table S1). The RELEASE program was used to test whether the data met the basic assumptions of the CJS model and to estimate overdispersion of the data by using the variance inflation factor ($\hat{c}$), where values of $\hat{c} < 3$ indicate that the global model is acceptable [67]. We compared models using Akaike's Information Criterion corrected for small sample sizes (AICc) [68]. The Akaike weight (w_i) was calculated for each model. Models with $\Delta AICc \leq 2$ (difference between a model and the best model) were considered to have substantial support and were treated as competitive models [69]. The percentage of variation explained by addition of covariates was determined by analysis of deviance (ANODEV), calculated as the difference in deviance between the constant model and the covariate model, divided by the difference in deviance between the constant model and the time dependent model [70]. Data are presented as means $\pm$ SE.

3. Results

A total of 372 adult plovers (226 females and 146 males) were captured and ringed during the 29 years of study. Of the total number of adults ringed, 256 (68.8%) were recaptured on at least one occasion: 158 females (69.9% of the marked females) and 98 males (67.1% of the marked males).

Goodness-of-fit tests indicated that the CJS assumptions were met in the overall model including all covariates and their possible interactions $\varphi(\text{sex} \times \text{precipitation} \times \text{Prestige} \times \text{wind} \times \text{time})p(\text{sex} \times \text{precipitation} \times \text{Prestige} \times \text{wind} \times \text{time})$ ($p = 0.74$). Overdispersion of the data was not detected ($\hat{c} = 0.90$).

The best fit model indicated that the survival of adult plovers is best explained by the interactive effect of precipitation and oil spill, a model that has 3.2 times more support than the next best model (Table 1, Figure 2). Recapture probability was explained by the interactive effect of time, sex and oil spill (Table 1, Figure 3). This model explained 15.8% of the additional variation (ANODEV) in the annual survival data compared to a base model with no covariates.

Table 1. The five best-fit models used to estimate adult Kentish plover survival (φ) and recapture probability (p) in Galicia (NW Iberian Peninsula) between 1994 and 2023.

Model ¹		AICc	$\Delta AICc$	w_i	NP ²	Deviance
$\varphi(PP^*P)$	$p(t^*P^*\text{sex})$	1710.23	0	0.3424	24	649.00
$\varphi(PP+P+W)$	$p(t^*P^*\text{sex})$	1712.53	2.30	0.1085	22	655.51
$\varphi(PP+P)$	$p(t^*P^*\text{sex})$	1713.35	3.12	0.0720	21	658.44
$\varphi(\text{sex}+PP+P+W)$	$p(t^*P^*\text{sex})$	1713.40	3.18	0.0700	23	654.28
$\varphi(P^*PP)$	$p(t^*P)$	1714.05	3.82	0.0507	16	669.58

¹ Model notation: sex, t = time, PP = precipitations, W = wind, P = *Prestige*, + = additive model, * = interactive model. ² NP = Number of estimable parameters in the model.

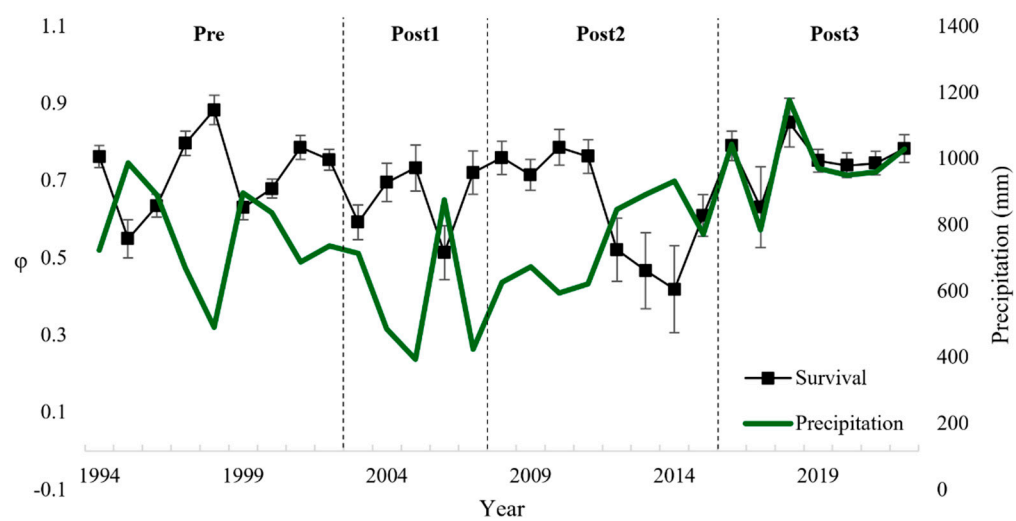


Figure 2. Apparent annual survival ($\varphi \pm SE$) of the Kentish plover population in Galicia (NW Iberian Peninsula) and precipitation (accumulated annual precipitation in mm) between 1994 and 2023. The different periods related to the *Prestige* oil spill are shown (Pre-Post3).

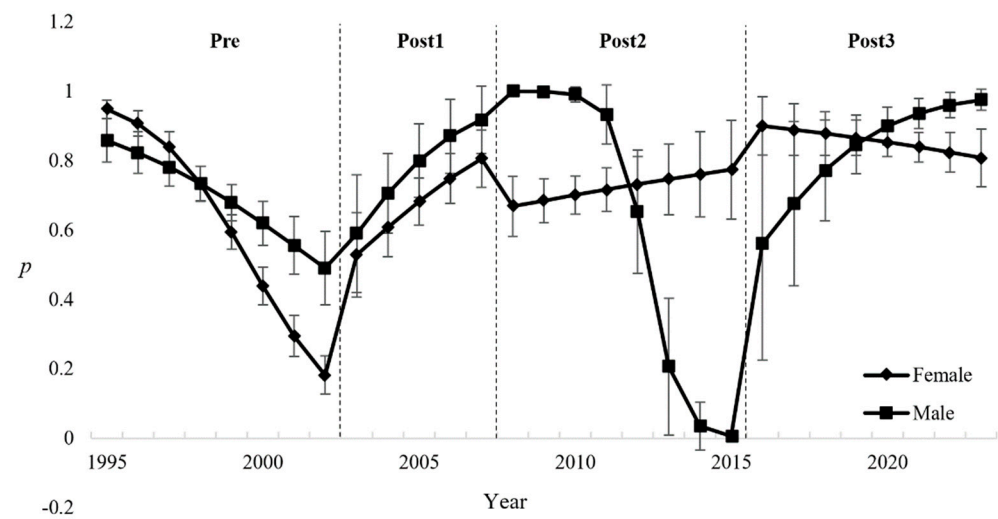


Figure 3. Recapture probability ($p \pm SE$) of the Kentish plover population in Galicia (NW Iberian Peninsula) from 1994 to 2023. The different periods related to the *Prestige* oil spill are shown (Pre-Post3).

The model $\varphi(\text{precipitation} \times \text{Prestige})p(\text{time} \times \text{Prestige} \times \text{sex})$ (Table 1) indicated that survival was lower at higher precipitation levels (Table 2, Figure 2). In addition, the oil spill also played an important role, having a negative impact on survival, especially in the Post1 and Post2 period. It also had a small negative effect in the Post3 period, but not statistically significant as the 95% CI (−1.30, 0.51) included zero (Table 2).

Table 2. Beta value estimates, SEs, and upper and lower CIs for the φ variable in the best model.

Variable	Estimate	SE	Lower	Upper
Intercept	0.9371	0.1203	0.7012	1.1730
Precipitation	-0.7145	0.2025	-1.1115	-0.3175
Prestige Post1	-0.7053	0.2589	-1.2128	-0.1979
Prestige Post2	-0.5606	0.2713	-1.0925	-0.0287

<i>Prestige Post3</i>	-0.3935	0.4628	-1.3007	0.5136
<i>Precipitation*Prestige Post1</i>	0.3292	0.2745	-0.2087	0.8672
<i>Precipitation* Prestige Post2</i>	-0.2211	0.4121	-1.0288	0.5866
<i>Precipitation* Prestige Post3</i>	1.3079	0.4855	0.3562	2.2597

The mean survival was 0.69 ± 0.02 . For the different periods, the mean survival was as follows: Pre, 0.72 ± 0.03 ; Post1, 0.65 ± 0.04 ; Post2, 0.63 ± 0.05 , and Post3, 0.76 ± 0.02 .

Recapture probability was influenced in complex ways by the combination of time, sex and oil spill (Table 1). Males and the *Prestige* Post3 period had higher recapture probabilities, but these effects were modulated by time and interactions between variables (Figure 3). According to the model, males were significantly more likely to be recaptured than females, as indicated by the parameter estimates ($\beta_{\text{sexMale}} = 3.67 \pm 1.47$, upper and lower 95% CI 6.56 and 0.78, respectively).

4. Discussion

Survival of adult plovers varied with the interactive effect of precipitation and the *Prestige* oil spill, while the probability of recapture varied with the interactive effect of time, sex and the *Prestige* oil spill.

The oil spill played an important role, with different impacts depending on the period. Oil pollution can directly affect seabirds or birds living in coastal environments through contamination or ingestion [19,24,71,72]. It can also have indirect effects by reducing the availability of key food species [65,73]. The oil spill occurred in 2002, and the significant negative impact of the Post1 period on survival seems to be related to this event. Although direct Kentish plover mortality was not observed in the months following the spill [27], the oil spill affected the beaches where the plovers were present [29,61]. Thus, there was a decrease in the abundance and diversity of the macrofauna on beaches in Galicia after the spill [29,74], which probably affected the food available for the birds. The oil spill also negatively affected various aspects such as individual condition and reproductive performance, plumage oiling and polycyclic aromatic hydrocarbon levels in eggs between 2004 and 2007, indicative of prolonged exposure to the pollutant [42-44]. In Western sandpipers (*Calidris mauri*) small amounts of oil on the trailing edges of the wings and tail affected takeoff flight performance [24]. Thus, slower and lower takeoff would make oiled birds more likely to be targeted and captured by predators reducing survival [24]. Nonetheless, this oil spill did not appear to impact the long-term population growth [50]. Lower values of mean survival were observed in the Post1 and Post2 periods, with recovery in the Post3 period. In comparison to other marine birds and Bald eagle (*Haliaeetus leucocephalus*) populations affected by the Exxon-Valdez oil spill, where recovery was rapid [75-78], the population of Kentish plovers in Galicia did not show the same resilience. Other studies on related plovers reported that oil spills did not affect bird survival [25,26].

In adverse weather conditions, birds may die or be forced to move [79,80]. This often occurs because the birds are unable to obtain enough food due to a change in prey availability or difficulty in obtaining the prey [2]. For example, birds that rely on visual foraging clues may not be able to forage effectively when these clues are obscured, for example, by precipitation [81]. Several studies on waders have shown a negative relationship between severe weather and survival [9,25,79,81]. Precipitation influences different stages of plovers biology, both positively and negatively, such as nest survival [6], chick survival [82], juvenile survival [4] and adult survival [1].

In our study, precipitation showed a negative influence on adult survival. For example, survival rates were lowest between 2012 and 2014, a period marked by anomalous weather conditions on the Galician coast, with the occurrence of numerous storms [83,84] and a marked decline in the number of breeding pairs [41]. During the Post3 period, the relationship between precipitation and survival changed, with a significant positive effect of the precipitation**Prestige* post 3 interaction. It is possible that the effects derived from the *Prestige* oil spill contributed to modifying this relationship over time. The progressive recovery of coastal ecosystems after the event [31,66,85], may have altered habitat structure and resource availability, thus influencing how survival responded to precipitation

variability. Overall, our results indicate that the impact of precipitation on survival should be interpreted in combination with other environmental and anthropogenic factors rather than in isolation.

Wind did not significantly affect the bird survival, as also observed in another study on Snowy plover (*Anarhynchus nivosus*) [86]. However, extreme wind events such as hurricanes did have a negative effect on Piping plover (*Charadrius melodus*) survival [25,87]. In NW Iberia, although phenomena such as hurricanes are not a direct threat, climate change could manifest in other forms of extreme weather events, which could affect the survival of sensitive species.

Climate change is expected to lead to an intensification of the hydrological cycle resulting in increased climate variability, with more extreme events such as severe droughts or torrential precipitation [88-91]. For the Iberian Peninsula, projections indicate a generalized decline in total precipitation throughout the 21st century [92-94]. However, several studies have also reported or projected statistically significant increases in the frequency and/or intensity of extreme precipitation events in many parts of the world [95-98], including the Iberian Peninsula [93,94,99-101]. In Galicia, these trends have been reinforced by positive temperature anomalies since the late 1980s and by sea surface warming [102,103], which favours the intensification of storms and extreme precipitation. In addition, changes in wind dynamics are also expected under future climate scenarios. Projections for the Iberian Peninsula suggest an overall decrease in mean surface wind speed [104,105], but significant increases in the number of occurrences of extreme wind events were also identified, mainly in northwestern Iberia [105]. Moreover, an increase in the occurrence of compound extreme wind and precipitation events is projected, especially during the winter and spring months by the end of the century [106]. Future research should therefore address how the increasing frequency and severity of extreme weather events may affect the demographic dynamics of this species.

There was no difference in the probability of survival between sexes, in contrast to other studies in which differences in survival of males and females have been observed, with males having higher survival rates [45,48,59,60]. The difference in survival appears to be related to a higher recapture probability in males, as females tend to be more widely dispersed [45,47,107-109]. Higher mortality in females has also been linked to a higher risk of heterogamety, a greater demand for reproductive effort and the competitive disadvantages of smaller body size [48,110]. Sandercock, Székely and Kosztolanyi [58] concluded that the variation in survival of different *Charadrius* species may be due to interspecific differences in body size, with the smaller Kentish plovers having lower survival rates. In Galicia, the *Prestige* oil spill was found to have negative effect on the body mass of female Kentish plovers [44], which may have had affected their survival. As only females were analysed, it remains uncertain whether males also experienced a reduction in body mass. Although it cannot be confirmed with the available data, if both sexes were similarly affected, this could have contributed to the lack of differences in survival observed in the present study.

The recapture probability was determined by a complex interaction between time, sex and oil spill. Recapture probability was highest for males and the Post3 period; however, this effect was conditioned by temporal variations and relationships between variables, indicating that the specific context of the *Prestige* oil spill and sex is crucial to understanding recapture dynamics. Differences in recapture rates of adult male and female *Charadrius* have been observed in other studies, with higher recapture rates in males [58,111,112]. This species can breed successfully several times a year, and a high proportion of females leave the clutch before fledging and start a new breeding attempt with a new partner [113-116]. During this process females may select higher quality habitats and not return to lower quality sites [59]. In the Galician population, most females nest again on nearby beaches or, in any case, within the resight area (unpublished data). The difference in recapture rate cannot therefore be explained by dispersal tendency but perhaps by differences in behaviour and coloration, which make the males more conspicuous to observers during the day [58].

5. Conclusions

In conclusion, the survival of adult plovers has been significantly affected by precipitation and a major oil spill, highlighting the vulnerability of this species to pollution events and weather conditions, an effect that could be intensified by climate change. The study findings highlight the importance of environmental monitoring and targeted conservation measures that address both climate impacts and pollution to ensure the long-term viability of plover populations.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org. Table S1: Full model selection results for apparent survival (φ) and recapture probability (p) for adult Kentish plover in Galicia (NW Iberian Peninsula) between 1994 and 2023.

Author Contributions: Conceptualization, Andrea Gestoso, María Vidal and Jesús Domínguez; methodology, María Vidal and Jesús Domínguez; software, Andrea Gestoso; validation, Jesús Domínguez; formal analysis, Andrea Gestoso; investigation, María Vidal, José A. de Souza, Manuel Martínez-Lago, Francisco Rosende and Jesús Domínguez; writing—original draft preparation, Andrea Gestoso; writing—review and editing, Andrea Gestoso, María Vidal, José A. de Souza, Manuel Martínez-Lago, Francisco Rosende and Jesús Domínguez; supervision, María Vidal, José A. de Souza and Jesús Domínguez; funding acquisition, Jesús Domínguez. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from the Dryad Digital Repository: <https://doi.org/10.5061/dryad.70rxwdc8m>.

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

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