Wilson Bull., 109(2), 1997, pp. 307–313

USING EGGSHELL EVIDENCE TO DETERMINE NEST FATE OF SHOREBIRDS

TODD J. MABEE[1]

ABSTRACT.—I collected eggshell evidence at nest sites of Piping Plover (*Charadrius melodus*), Snowy Plover (*C. alexandrinus*), and Killdeer (*C. vociferus*) in southeastern Colorado during 1994–1995, and determined nest fate independently. Successful nests of all three species generally contained eggshell fragments (ca 1–4 mm) in the scrape and eggshell membranes separated from the eggshell. In comparison, eggshell "tops" or "bottoms" were found only near successful nests of Piping Plovers and Snowy Plovers. I used discriminant function analysis to predict the probability of correctly classifying a nest's fate given different types of eggshell evidence. The use of eggshell fragment evidence resulted in the correct classification of the fate of Snowy Plover and Killdeer nests in 90% and 96% of the cases, respectively. Eggshell evidence can be used in future studies to determine nest fate of shorebirds and increase the precision of estimates of reproductive success. *Received 14 April 1996, accepted 1 March 1997.*

Assessing nest fate of precocial species such as shorebirds is problematic because chicks leave the nest soon after hatching and shortly thereafter their parents may move them a considerable distance to feeding areas. Consequently, establishing rigorous standards for determining nest fate is critical to understanding the biology of these species. Several criteria exist for classifying successful nests of shorebirds, such as the presence of at least one chick in or near the nest (Haig and Oring 1988), small eggshell fragments in the scrape produced during hatching (Hill 1985, Page et al. 1985, Paton 1995), and the absence of predator sign at nests whose clutches were old enough to have hatched. Conversely, failed nests have been classified by the absence of chicks and eggshell fragments and the presence of predator sign at nests too early in incubation to have hatched (Page et al. 1985, Paton 1995). Hill (1985) used the above criteria except for the absence of eggshell fragments.

The lack of a standard basis for determining nest fate can bias estimates of nest success and make comparisons among studies difficult. Two methods are used commonly to estimate reproductive success, and their precision depends on the accurate determination of nest fate. Observed nest success (the proportion of successful nests to total number of nests) utilizes only known-fate nests and, therefore, its accuracy is sensitive to the number and fate of unknown-fate nests removed from the analysis. By contrast, the Mayfield method (Mayfield 1961, 1975) utilizes unknown-fate nests in the analysis but the estimated daily survival rate is inflated

[1] Dept. of Biology, Colorado State Univ., Fort Collins, Colorado 80523.

by the number of unknown-fate nests. For both methods, the classification of unknown-fate nests would increase the precision of the estimate of reproductive success.

To date, no study has examined in detail the characteristics of successful or failed nests of shorebirds and the reliability of these characters in determining the fate of nests. My objectives here are to (1) describe the types of eggshell evidence collected at nests of three plover species in Colorado and (2) assess the utility of eggshell evidence in classifying nests as successful or failed.

STUDY AREA AND METHODS

I collected eggshell evidence at nest sites of Piping Plover (*Charadrius melodus*), Snowy Plover (*C. alexandrinus*), and Killdeer (*C. vociferus*) during the summers of 1994–1995 in southeastern Colorado as part of a research project that tested the effectiveness of predator exclosures on nesting success of plovers (Mabee and Estelle, unpubl. data). Study sites (reservoirs, altered and unaltered playa lakes) and water levels varied among years. In 1995, I floated eggs in tap water twice during incubation (mean = 12 d apart) to estimate the age of a clutch and to predict its hatching date. This technique has been used widely without reducing nest success (Hill 1985, Alberico 1995). Causes of nest failure included snakes, rodents, coyote (*Canis latrans*), raccoon (*Procyon lotor*), domestic dog (*Canis familiaris*), Great Blue Heron (*Ardea herodias*), Black-billed Magpie (*Pica pica*), cattle trampling, and inclement weather.

During both years, I searched at least a 10-m radius around a nest when it became inactive (either hatched or failed) and looked for eggshell tops, bottoms, or pieces. I also inspected the nest for the presence of eggshell fragments that are produced during pipping. I defined *eggshell tops* or *eggshell bottoms* as those parts of an eggshell that exhibited a nearly equidistant length from the center of the top or bottom eggshell to the broken edge of the shell and *eggshell pieces* as any part larger than 4 mm in length that did not exhibit the shape of an eggshell top or bottom. I used the term *eggshell fragments* to refer to parts that ranged from ca 1 to 4 mm. When I found eggshell tops, bottoms, or pieces, I inspected the eggshell membrane to see if it was partially separated from the eggshell. Waterfowl eggs that hatch exhibit an eggshell membrane separated from the eggshell (Klett et al. 1986). I considered an eggshell membrane to be separated from an eggshell if it was separated from the broken edge of the eggshell and if I could peel part of the membrane away from the eggshell.

Determining nest fate.—Determination of nest fate was independent of eggshell evidence. I classified failed nests only in 1995 because I did not float eggs in 1994. I classified a nest as successful when I observed at least one chick in or near a scrape and as failed when a clutch of eggs disappeared too early in incubation to have hatched (based on egg flotation) or when an entire clutch was abandoned. I assumed an average incubation period of 27 d for Piping Plovers (Haig 1992), 27.4 d for Snowy Plovers (Warriner et al. 1986, this study unpubl. data), and 26 d for Killdeers (Powers 1978) and considered any clutch <23 d, <23.4 d, or <22 d of age, respectively, to have failed.

Statistical analyses.—I used linear discriminant function analysis (Minitab 10.5 Xtra) to calculate the probability of correctly classifying the fate of a nest given the different types of eggshell evidence collected in 1995. I also ran a cross-validation procedure that omitted the first observation from the data set, developed a classification function using the remaining observations, and then classified the omitted observation. This iterative procedure was

TABLE 1

EGGSHELL EVIDENCE FOUND NEAR SUCCESSFUL AND FAILED NESTS OF PIPING PLOVER, SNOWY PLOVER, AND KILLDEER DURING 1994–1995. VALUES REPRESENT PERCENT OF TOTAL NESTS FOR EACH TYPE OF EGGSHELL EVIDENCE

		Eggshell fragments in scrape			Eggshell parts			Eggshell membrane		
Species	N	Present	Absent	Unknown[a]	None found	Piece	Top or bottom	None found	Separated	Attached
					Successful–1994[b]					
Piping Plover	6	83	0	17	0	0	100	0	83	17
Snowy Plover	15	73	7	20	40	7	53	40	53	7
Killdeer	5	100	0	0	60	40	0	60	40	0
					Successful–1995[c]					
Snowy Plover	10	100	0	0	30	10	60	30	70	0
Killdeer	6	100	0	0	100	0	0	100	0	0
					Failed–1995					
Piping Plover	5	20	60	20	40	60	0	40	0	60
Snowy Plover	9	22	78	0	56	44	0	56	0	44
Killdeer	20	5	95	0	75	25	0	75	0	25

[a] Represents nests that were not searched for eggshell fragments.
[b] Unable to classify nests as failed due to lack of egg flotation data.
[c] No Piping Plover data available because all Piping Plover nests failed in 1995.

performed on all observations. Cross validation produced a less biased value because it removed bias due to observations having a large influence. All values presented were obtained from the cross-validation procedure. In cases where I found eggshell tops or bottoms and eggshell pieces at a nest site, I used eggshell tops or bottoms in the analysis because they provided the strongest indication of a nest's fate.

RESULTS

Eggshell evidence found near nests.—In 1994, most successful nests of Piping Plovers and Snowy Plovers and all successful nests of Killdeers contained eggshell fragments in the scrape (Table 1). All eggshell pieces and most eggshell tops or bottoms found near successful nests of Piping Plovers (5 of 6) and Snowy Plovers (7 of 8) contained an eggshell membrane that had separated from the eggshell, whereas no eggshell tops or bottoms were found in the vicinity of successful Killdeer nests.

In 1995, all successful nests of Snowy Plovers and Killdeers contained eggshell fragments in the scrape. Eggshell pieces and tops or bottoms found near successful nests of Snowy Plovers always contained an eggshell membrane that had partially separated from the eggshell. As in 1994, no eggshell tops or bottoms were found near successful Killdeer nests (Table 1). Because all Piping Plover nests failed in 1995 due to weather,

TABLE 2

EGGSHELL EVIDENCE AND ITS PROBABILITY OF CORRECTLY CLASSIFYING SNOWY PLOVER AND KILLDEER NESTS DURING 1995 USING LINEAR DISCRIMINANT FUNCTION ANALYSIS

Eggshell evidence	Successful nest	Failed nest	Oveall nest fate[a]
Snowy Plover			
Eggshell fragments	100	78	90
Eggshell parts	60	100	79
Eggshell membrane	70	100	84
Fragments and parts	90	78	84
Fragments and membrane	100	78	90
Killdeer			
Eggshell fragments	100	95	96

[a] Overall nest fate is the probability of correctly classifying a nest as successful or failed.

predation, or humans, I could not classify eggshell evidence for successful nests.

In 1995, most failed nests of Piping Plovers, Snowy Plovers, and Killdeers did not contain eggshell fragments in the scrape (Table 1). However, eggshell fragments were found in one Piping Plover nest that failed due to hail, in Snowy Plover nests that failed due to a rodent (N = 1) and an unknown predator (N = 1), and in one Killdeer nest that failed due to an unknown predator. All eggshell pieces found near failed nests contained attached eggshell membranes, however, no eggshell tops or bottoms were found near failed nests.

Classification of nest fate.—In general, results from the linear discriminant function analysis corroborated the patterns exhibited in the descriptive summary of eggshell evidence. To assess the strengths and biases of the various types of eggshell evidence (predictors) in classifying nest fate, one needs to examine the probability of correctly and incorrectly classifying nest fate. For example, presence or absence of eggshell fragments in Snowy Plover nests correctly classified 100% of successful nests and 78% of failed nests (Table 2). Therefore eggshell fragments overestimated nest success by incorrectly classifying 22% of failed nests as successful nests. To compare the overall ability of predictors to classify nest fate correctly, it is necessary to examine *overall nest fate*, the probability of correctly classifying a nest as successful or failed (Table 2).

For Snowy Plovers, eggshell fragments were the best predictor of successful nests, whereas eggshell parts (tops, bottoms, or pieces) and eggshell membrane were the best predictor of failed nests. Eggshell fragments or the combination of eggshell fragments and eggshell membrane classified overall nest fate with equal strength (Table 2). Multiple predictors such as eggshell parts, eggshell membrane, or the combination of eggshell fragments with these predictors could not be used to classify nest fate of Snowy Plovers or Killdeers because they were highly intercorrelated.

Eggshell fragments were the single best predictor of both successful and failed nests, and overall nest fate of Killdeers (Table 2). Because eggshell parts were not found near successful Killdeer nests, neither eggshell parts, eggshell membrane, nor combinations of these predictors with eggshell fragments could be evaluated for successful Killdeer nests. Unsuccessful Killdeer nests were classified correctly only 25% of the time by either eggshell parts or eggshell membrane. I could not analyze Piping Plover eggshell evidence because there were no successful Piping Plover nests in 1995.

DISCUSSION

The accuracy of eggshell evidence, particularly eggshell fragments, in classifying nest fate for plovers is demonstrated clearly by both descriptive evidence and linear discriminant function analysis. I found eggshell fragments in 88% of successful nests and in only 12% of failed nests of all three species. Eggshell fragments are expected in successful nests because chicks break through the eggshell and produce small pipping fragments when hatching. Eggshell fragments should not be used to classify nest fate in species that reuse the same nest site, unless nest sites are seasonally obliterated by environmental conditions.

Eggshell tops or bottoms were also useful indicators of nest fate as they were found at 65% of successful nests and 0% of failed Piping Plover and Snowy Plover nests. It appears that chicks pip through an eggshell at a fairly uniform level around the top of the egg and produce well-defined shell tops and bottoms. Killdeer must have taken eggshell tops and bottoms >10 m away from the nest, a behavior documented for other shorebirds (Sordahl 1994, Page et al. 1995).

Eggshell pieces >4 mm in length were found in both successful and failed nests and were not as useful in classifying nest fate as eggshell fragments or eggshell tops or bottoms. Pieces can be produced during a predation event or hail storm, or they may be part of a deteriorated eggshell top or bottom. Likewise, eggshell fragments may be produced by the same events, but it was usually possible to determine nest fate when predator sign, eggshells, clutch age, and recent weather were taken into consideration.

Eggshell membranes were also useful indicators of nest fate because they are tightly adhered to an eggshell early in incubation but separate as the embryo develops and resorbs calcium from the eggshell (Packard and

Clark 1996). During this study, depredated eggs of a young age contained transparent eggshell membranes that were tightly adhered to the eggshell, whereas eggshell tops or bottoms from successful nests contained white eggshell membranes that were partially separated from the eggshell.

The pattern of eggshell evidence exhibited near nests of the three plovers was consistent between years and among locations for each species. The high variability of study areas and of environmental conditions between years suggest that eggshell evidence may be used to classify nest fate for shorebirds in other locations. I recommend using eggshell evidence to supplement methods used to determine nest fate and to classify unknown-fate nests. The type of eggshell evidence that classifies nest fate most accurately may vary depending on the predator assemblage and location. If determining nest fate is critical, eggs must be floated to strengthen the determination of nest fate. In general, shorebird nests should be monitored at regular intervals (e.g., every 3–4 d) and immediately examined for eggshell evidence in the nest and within at least a 10-m radius of the nest when it becomes inactive. If time to monitor nests is limited, I recommend using the presence or absence of eggshell fragments in the nest scrape to determine nest fate because it is the most objective piece of evidence gathered and is easy to obtain.

ACKNOWLEDGMENTS

I thank Veronica Estelle (Colorado Bird Observatory), Steve Earsom, Janet Lynn, and John Bishop for their valuable assistance in the field, and Chuck Loeffler and Jennie Slater (Colorado Division of Wildlife) for logistical support. I thank the Van Horne-Wiens lab, John Wiens, Bea Van Horne, and Gordon Rodda for reviewing this manuscript, and Tom Boardman for statistical advice. Financial support was provided by the Colorado Bird Observatory, Colorado Natural Areas Small Grants Program, Colorado Division of Wildlife, Frank M. Chapman Memorial Fund, U.S. Fish and Wildlife Service (Golden, CO), and Bureau of Land Management. This study was conducted under the U.S. Fish and Wildlife Service Federal Endangered and Threatened species permit number PRT-704930 and the Colorado Division of Wildlife scientific collection permit number 95-0119.

LITERATURE CITED

ALBERICO, J. A. R. 1995. Floating eggs to estimate incubation stage does not affect hatchability. Wildl. Soc. Bull. 23:212–216.

HAIG, S. M. 1992. Piping Plover. *In* The birds of North America, No. 2 (A. Poole, P. Stettenheim, and F. Gill, eds.). The Academy of Natural Sciences, Philadelphia, Pennsylvania, and The American Ornithologists' Union, Washington, D.C.

——— AND L. W. ORING. 1988. Mate, site, and territory fidelity in Piping Plovers. Auk 105:268–277.

HILL, L. 1985. Breeding ecology of Interior Least Terns, Snowy Plovers, and American Avocets at Salt Plains National Wildlife Refuge, Oklahoma. M.S. thesis, Oklahoma State University, Stillwater, Oklahoma.

KLETT, A. T., H. F. DUEBBERT, C. A. FAANES, AND K. F. HIGGINS. 1986. Techniques for studying nest success of ducks in upland habitats in the Prairie Pothole Region. U. S. Fish and Wildlife Service, Washington, D. C.

MAYFIELD, H. 1961. Nesting success calculated from exposure. Wilson Bull. 73:255–261.

———. 1975. Suggestions for calculating nesting success. Wilson Bull. 37:456–466.

MINITAB® 10.5 XTRA. 1995. State College, Pennsylvania.

PACKARD, M. J. AND N. B. CLARK. 1996. Aspects of calcium regulation in embryonic lepidosaurians and chelonians and a review of calcium regulation in embryonic archosaurians. Physiol. Zool. 69:435–466.

PAGE, G. W., L. E. STENZEL, AND C. A. RIBIC. 1985. Nest site selection and clutch predation in the Snowy Plover. Auk 102:347–353.

———, J. S. WARRINER, AND P. W. C. PATON. 1995. Snowy Plover (*Charadrius alexandrinus*). *In* The birds of North America, No. 154 (A. Poole and F. Gill, eds.). The Academy of Natural Sciences, Philadelphia, Pennsylvania, and The American Ornithologists' Union, Washington, D.C.

PATON, P. W. C. 1995. Breeding biology of Snowy Plovers at Great Salt Lake, Utah. Wilson Bull. 107:275–288.

POWERS, L. 1978. Record of prolonged incubation by a Killdeer. Auk 95:428.

SORDAHL, T. 1994. Eggshell removal behavior of American Avocets and Black-Necked Stilts. J. Field Ornithol. 65:461–465.

WARRINER, J. S., J. C. WARRINER, G. W. PAGE, AND L. E. STENZEL. 1986. Mating system and reproductive success of a small population of polygamous Snowy Plovers. Wilson Bull. 98:15–37.