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EVALUATION OF METHODS FOR ESTIMATING DENSITY OF BREEDING FEMALE MALLARDS

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Abstract.—Density estimates are important to investigations of population dynamics and the effectiveness of management activities. Methods currently used to estimate density of breeding female Mallards (*Anas platyrhynchos*) on localized study areas were derived *ad hoc* and have never been validated. The accuracy of *ad-hoc* estimates was tested by comparing them to mark-resight estimates of female density. During spring 1993, 61 females were color- and radio-marked in southcentral Saskatchewan, and density was estimated via *ad-hoc* and mark-resight methods using data from four surveys. The assumptions and minimum data requirements of the mark-resight technique were met, and a reliable benchmark estimate of density was developed using data from the second survey (3.7 females/km^2, SE = 0.8). *Ad-hoc* and mark-resight estimates were significantly different ($P = 0.046$), with the *ad-hoc* estimate being greater by 1.5 females/km^2. For many research and monitoring applications, this level of error may be inconsequential, and the *ad-hoc* estimator, which is more easily applied than the mark-resight estimator, may be adequate. The mark-resight estimator can be used to provide more accurate estimates with measured precision but requires that large samples of females be color- and radio-marked, monitored and resighted.

EVALUACIÓN DE MÉTODOS PARA ESTIMAR DENSIDADES DE HEMBRAS DE *ANAS PLATYRHYNCHOS* ANIDANDO

Sinopsis.—Los estimados de densidad son importantes al investigar dinámicas poblacionales y la eficacia de actividades de manejo. Los métodos usados comunmente para estimar la densidad de hembras de *Anas platyrhynchos* anidantes en áreas de estudio localizadas no se derivaron en propiedad ni se han validado nunca. Se comprobó la exactitud de los estimados tradicionales al compararlos con estimados de marca-redetección de densidad de hembras. Durante la primavera del 1993, 61 hembras se marcaron con colores y con radios en la parte sur-central de Saskatchewan, y la densidad fue estimada usando los métodos tradicionales y de marca-redetección usando datos de cuatro censos. Se obtuvieron los requisitos de asunciones y de mínimo de datos del método de marca-redetección, y se desarrolló un estimado confiable de la densidad utilizando datos del segundo censo (3.7 hembras/km^2, SE = 0.8). Los estimados tradicionales y por marca-redetección fueron significativamente diferentes ($P = 0.046$), el estimado tradicional siendo mayor por 1.5 hembras/km^2. Este nivel de error puede tener pocas consecuencias para muchos planes de investigación y manejo, y como el estimado tradicional es más facilmente obtenido que el estimado por marca-redetección, puede ser adecuado. El estimado proveniente de marca-redetección puede usarse para proveer estimados más exactos con precisión medida pero requieren que se marquen con color y radios grandes números de hembras y que sean monitoreadas y redetectadas.

Reliable estimates of breeding density are critical to numerous studies of Mallard ecology and management (Cowardin and Blohm 1992, Johnson et al. 1992). For example, modeling productivity of local Mallard populations (Johnson et al. 1987), testing for density-dependence in recruitment rate (Pospahala et al. 1974) and evaluating the effectiveness of various management strategies for achieving stated population goals (U.S. Fish and Wildlife Service and Canadian Wildlife Service 1986) all require knowledge of local density.

Methods used to monitor continental Mallard numbers have been carefully considered and standardized (Martin et al. 1979, U.S. Fish and Wildlife Service and Canadian Wildlife Service 1987). In contrast, methods for estimating the size of local populations have not been rigorously developed or tested, with very little research conducted on the topic in recent decades (see review by Cowardin and Blohm 1992).

Given the importance of density information, it seems prudent to evaluate currently used techniques for estimating density at the local level and to develop better techniques if necessary. Techniques for estimating other parameters critical to localized studies of population dynamics have been rigorously developed, have reasonable assumptions and good statistical properties and are regularly employed. For example, the Mayfield (1961, 1975) method as modified by Johnson (1979) is used to estimate daily survival rates for nests, and the Kaplan-Meier product-limit estimator (Pollock et al. 1989) is used to estimate survival rates for females and broods from telemetry data.

To date, female density has been estimated using data collected from standardized pair counts conducted along strip transects or roads and an estimator derived *ad hoc* (Cowardin and Blohm 1992, Dzubin 1969, Hammond 1969). *Ad-hoc* estimators, which are based on an enumeration model, have been used in almost all previous studies of breeding population size because more statistically rigorous methods are either inappropriate (e.g., assumptions of absolute censuses [Seber 1973] or distance sampling [Buckland et al. 1993] cannot be met), or have been impossible to use (e.g., budgetary constraints have ruled out the possibility of using radio- and color-marked birds to produce mark-resight estimates [White and Garrott 1990:255–270]).

Ad-hoc estimators are not, however, "mathematical representation[s] of a postulated set of assumptions concerning a[n] . . . experiment," provide no estimates of precision and may provide quite poor estimates (White et al. 1982:15–18). Nichols and Pollock (1983) reported that probabilistic models (e.g., mark-resight estimators), which estimate differences in sighting/capture probabilities among surveys, are preferred over enumeration models (e.g., the *ad-hoc* estimator), which assume constant sighting/capture probabilities among surveys and may produce biased estimates. Thus, it is important to test the accuracy of *ad-hoc* estimators and to consider alternative estimators.

We designed this study to test the validity of *ad-hoc* estimates of female density and to evaluate the feasibility and necessity of using mark-resight techniques (White and Garrott 1990:255–270). To meet these objectives, we simultaneously collected data for the *ad-hoc* estimator and a mark-resight estimator derived from likelihood theory and estimated female density by both methods. Our study was conducted as part of the assessment of the Prairie Habitat Joint Venture of the North American Waterfowl Management Plan (U.S. Fish and Wildlife Service and Canadian Wildlife Service 1986).

STUDY AREA AND METHODS

We conducted the study in 1993 on a 54.6-km^2 area that was centered approximately 4 km south of Punnichy, Saskatchewan (51°20′N, 104°17′W) in the Touchwood Upland subregion of the Parkland ecoregion (Poston et al. 1990). Topography of the area was gently rolling with a high wetland density (38 wetlands/km^2) and a diversity of wetland types (Stewart and Kantrud 1971). The area's native aspen parkland has been largely replaced by cereal crops, fallow fields and pastures.

Data collection.—During April, female Mallards were captured using decoy traps (Sharp and Lokemoen 1987) and outfitted with 22-g abdominally implanted transmitters (Korschgen et al. 1984, Olsen et al. 1992, Rotella et al. 1993), nylon nasal markers (Lokemoen and Sharp 1985) and U.S. Fish and Wildlife Service aluminum leg bands. We followed a federally approved animal-welfare protocol (920007) during the course of our research. Daily locations of all radio-marked females were estimated by triangulating with elevated, truck-mounted, null-antenna systems.

Pair counts were scheduled to coincide with the period when paired, lone and grouped males comprised approximately equal proportions of the total number of males recorded on weekly roadside surveys (Sauder et al. 1971). This criterion was believed to time pair counts such that most migrants but few failed breeders had left the area (Dzubin 1969).

The study area was divided into 21 strip transects (4.84 × 0.54 km/transect). We conducted four weekly surveys during the month surrounding the optimal counting period and collected data for four pairs (1 pair/week) of *ad-hoc* (Dzubin 1969, Hammond 1969) and mark-resight estimates (Chapman 1951) on a randomly selected set of six transects (15.6 km^2/set). Each survey transect was bounded by two unsurveyed transects or a study area boundary (e.g., set 3 consisted of transects 3, 6, 9, 12, 15 and 18) to minimize recounting birds flushed from other surveyed transects. On each survey, observers visited all wetlands on all six transects (one observer/transect) and recorded group size, sex composition and number of marked birds present for each Mallard sighting. Observers approached each wetland until they were close enough to observe the wetland's entire open-water area, took advantage of hillside vantage points, counted all birds present and avoided flushing birds.

While observers were surveying transects, a telemetry crew used five truck-mounted, null-antenna systems to determine which radio- and color-marked birds were on survey transects. The telemetry system had a mean bearing error of 0.5° (SD = 3.2). The telemetry crew stayed ≤0.8 km ahead of the transect crew to monitor which color-marked birds were present via triangulation. Each triangulation consisted of multiple bearings that were all recorded within 15 min. If triangulations from multiple bearings indicated that a female had moved during the triangulation process, additional bearings were immediately taken to confirm the female's location. Transect crews had no knowledge of which color-marked birds, if any, were on the transects.

Data analysis.—Ad-hoc estimates of females/km^2 were calculated for each survey using standard methods (Dzubin 1969): females/km^2 = [females with ≤2 males + lone males + (male groups of 2–5/sex ratio for Mallards)]/15.6 km^2. We used a sex ratio of 1.1 males/female (Bellrose 1980:230). All females were considered resident breeders. Each male in a group of ≤5 was considered a resident breeder that represented a breeding female, and males in groups of >5 were considered non-breeders or migrants and, therefore, were excluded from calculations (Dzubin 1969). For each count that occurred on a day when paired, lone and grouped males each comprised similar proportions (0.26–0.40) of the total number of males seen (Dzubin 1969), we calculated the *ad-hoc* estimate and compared it to that day's mark-resight estimate (see below).

We estimated the number of females/km^2 from the mark-resight data using Chapman's (1951) estimator, which is a maximum-likelihood estimator based on the hypergeometric probability density function when there is only one resighting occasion (White and Garrott 1990:260). Chapman's estimator is preferred over others in terms of: (1) estimate bias if capture probabilities are ≥0.1 (i.e., ≥10% of the population is marked and ≥10% of the markers are resighted) and (2) confidence-interval coverage and width if capture probabilities are ≥0.2 (Otis et al. 1978, White et al. 1982, White and Garrott 1990:267).

We believe that we met the assumptions of the mark-resight technique (Otis et al. 1978, White et al. 1982, White and Garrott 1990), which included: (1) the number of marked animals present on the transects was determined for each survey via telemetry, (2) loss of nasal markers, which were held on with stainless steel pins, was very unlikely within the 1–2 mo of marking when we conducted our surveys, (3) observations of marked birds were well dispersed, not typically at trap sites and thus, independent of marking, (4) sighting probabilities were likely the same for marked and unmarked animals because birds were initially detected from a distance as observers approached wetlands and subsequently checked for markers using binoculars and (5) we likely saw and reported all marked birds because markers were colorful and obvious, though small, when seen through binoculars at the distances encountered.

To assess further the reliability of single-occasion mark-resight estimates, we conducted computer simulations and estimated accuracy, con-

TABLE 1. *Ad-hoc* estimates of female Mallards/km^2 based on data from four transect surveys (15.6 km^2) of Mallards in Punnichy, Saskatchewan in spring 1993.

Date	Female with ≤2 males	Lone male	Group of 2–5 males[a]	Group of ≥5 males[b]	Females/km^2 [c]
4 May	44	22	13	0	4.99
11 May	38	24	21	10	5.20
18 May	23	30	28	6	5.03
25 May	33	11	22	17	4.10

[a] In groups of 2–5 males, 90.9% of males were assumed to be paired based on a sex ratio of 1.1 males/female.

[b] None of the males in groups of ≥5 males were assumed to be paired.

[c] Estimated number of females/km^2 = [females with ≤2 males + lone males + (groups of 2–5 males/1.1)]/15.6.

fidence-interval width and the percentage of confidence intervals that covered the simulated true population size of females. Simulations were conducted using SAS (SAS Institute, Inc. 1985) and programming code provided by White and Garrott (1990:367–372). We used the number of radio-marked birds present and resighted on survey transects and the mark-resight estimate of population size for each survey to estimate the proportion of the population marked and resighted on each survey. One thousand simulations were conducted for each survey's combination of mark-resight estimates of population size and estimated proportions marked and resighted.

We compared weekly estimates from *ad-hoc* and mark-resight methods using z tests, [z = (mark-resight estimate − *ad-hoc* estimate)/(SE of mark-resight estimate)]. We only compared estimates from surveys occurring on days when lone, paired and grouped males each comprised similar proportions of the number of males seen (see above).

RESULTS AND DISCUSSION

We captured 122 females during April 1993. We radio- and nasal-marked 61 of the captured females. The other 61 females were radio- but not nasal-marked to allow us to evaluate possible negative effects of nasal markers on reproductive effort (D. Howerter, unpubl. data). During surveys conducted on 4, 11, 18 and 25 May 1993, the numbers of doubly marked females alive on the study area were 44, 44, 34 and 36, respectively.

Estimates of female density.—Paired, lone and grouped males comprised approximately equal proportions of all males seen during surveys 2 (0.38, 0.27 and 0.35, respectively) and 3 (0.26, 0.35 and 0.39, respectively) but not during surveys 1 (0.55, 0.28 and 0.16, respectively) or 4 (0.35, 0.14 and 0.51, respectively). Therefore, we used data from surveys 2 and 3 to calculate *ad-hoc* estimates of female density (5.20 and 5.03 females/km^2, respectively) (Table 1) and to conduct comparisons with mark-resight estimates.

TABLE 2. Mark-resight estimates of female Mallards/km^2 based on data from four transect surveys (15.6 km^2) of Mallards in Punnichy, Saskatchewan in spring 1993.

Date	Markers present[a]	Markers sighted	Unmarked sighted	Females/ km^2 [b]	SE	95% CI[c]
4 May	13	4	40	8.01	2.49	3.4–12.9
11 May	8	5	33	3.69	0.75	2.6–5.2
18 May	7	2	21	4.04	1.52	1.8–7.0
25 May	15	2	32	11.90	5.15	3.0–22.0

[a] Number of radio- and nasal-marked Mallards present on a set of six surveyed transects (15.6 km^2). Sixty-one female Mallards were radio- and nasal-marked on the study area. Telemetry was used to determine how many marked birds were present on surveyed transects during each survey.

[b] The Chapman (1951) estimator was used to estimate female density.

[c] Lower confidence bounds were set to the minimum number of animals known to be alive on the transects (number of marked birds present + number of unmarked birds seen), which was larger than the calculated lower bound for each survey.

As a result of the small bearing errors in our telemetry system, the gentle terrain and short triangulation distances used, we accurately estimated locations and determined which doubly marked females were on surveyed transects. We estimated that 7–15 doubly marked females were present on surveyed transects during each of the four surveys (Table 2). Mark-resight estimates for surveys 2 and 3 are 3.69 females/km^2 (SE = 0.75) and 4.04 females/km^2 (SE = 1.52), respectively (Table 2). Estimates from surveys 1 and 4 provide little information about density because of their low precision and emphasize the importance of using estimators that measure precision.

Reliability of mark-resight estimates.—We estimated that 14 and 11% of the total population was radio- and color-marked (100 × number of marked birds/estimated population size) and that 63 and 29% of marked birds were resighted during surveys 2 and 3, respectively. Thus, capture and resighting probabilities for surveys 2 and 3 exceeded the minimum requirements suggested by Otis et al. (1978) and White et al. (1982) as necessary for achieving unbiased estimates, narrow confidence intervals and good confidence-interval coverage. In contrast, the low resighting probability during survey 4 (13%) resulted in poor precision for that survey's estimate.

Simulation results indicate that given sample sizes, population sizes and mark/resight probabilities similar to those estimated on survey 2, the Chapman estimator provides unbiased estimates of density with confidence-interval coverage that is high but below the stated 95% level. The average estimate from simulations using data from survey 2 was 3.71 females/km^2 (SE = 1.05), with 83% of confidence intervals (average width = 2.81 females/km^2) including the value of 3.69 females/km^2 that was simulated to be the true population size.

The average estimate from simulations that used data from survey 3 was biased low (3.70 females/km^2, SE = 1.88), with 72% of confidence intervals covering the simulated true value of 4.04 females/km^2. The increased bias and reduced confidence-interval coverage for simulated results of survey 3 were probably consequences of lower proportions of the population being marked and resighted in survey 3 as compared to survey 2.

Reliability of ad-hoc *estimates.*—Assuming that the mark-resight estimate from survey 2 accurately reflected true density, *ad-hoc* estimates may be biased high. Estimates of density calculated by *ad-hoc* and mark-resight estimators for survey 2 were significantly different ($z = -2.02$, $P = 0.046$), with the *ad-hoc* method overestimating density by 1.51 females/km^2. *Ad-hoc* and mark-resight estimates for survey 3 were not different ($z = -0.65$, $P = 0.515$). The large standard error associated with the mark-resight estimate for survey 3, however, caused the power of this test to be low despite a large difference in the two point estimates.

The *ad-hoc* estimator would overestimate density if: (1) some birds were counted more than once, (2) not all males in groups of 2–5 males represented breeding females and/or (3) the sex ratio on the study area was greater than 1.1 males/female (the ratio used in the analysis). We were unable to assess the validity of these three assumptions and therefore, do not know which attributes of the *ad-hoc* estimator require adjustment.

Usefulness of mark-resight as a technique.—We believe that radio- and color-marked birds can successfully be used to estimate density of breeding females if large samples can be captured, monitored and resighted. Marking 61 females allowed us to estimate female density with a 95% confidence bound of 1.5 females/km^2 on survey 2. If resighting rates are low (e.g., a large percentage of females are using large wetlands with dense stands of emergent vegetation that obscures visibility), however, the estimator cannot be expected to perform well. For highly mobile Mallards, useful mark-resight estimates require the use of telemetry to determine how many color-marked birds are present on survey transects.

Recommendations for estimating density of breeding females.—Our results indicate that *ad-hoc* methods (Cowardin and Blohm 1992, Dzubin 1969, Hammond 1969) currently used to estimate female density in many intensive, localized studies may overestimate density. *Ad-hoc* and mark-resight estimates differed by only 1.5 and 1.0 females/km^2 on surveys 2 and 3, respectively, however. For monitoring purposes and many research applications, such a difference may be inconsequential. As our study was only conducted on one study area for 1 yr, however, we cannot make inferences about the average performance of the *ad-hoc* estimator in other areas and/or years.

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