Surveys

Optimized Survey Design for Monitoring Protocols: A Case Study of Waterfowl Abundance

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Abstract

Nationwide monitoring programs are important tools that quantify the status and trends of natural resources, providing important information for management and conservation decisions. These programs operate at large spatial scales with standardized protocols that require wide-spread participation. However, resource limitations can reduce participation, which can then compromise the spatial replication needed for nationwide inference. The Integrated Waterbird Management and Monitoring program is an example of a national monitoring program that could benefit from a reduction in sampling effort to facilitate increased participation and ultimately broader inference. Therefore, we examined various sampling schemes to determine whether it is possible to reduce the sampling effort while maintaining the statistical accuracy needed to support management. We found that instead of needing to census a National Wildlife Refuge, sampling effort could be reduced while accurately estimating waterfowl abundance to within 10% of the census count by surveying just two-thirds of all the sample units or three-fourths of the total survey area. Not only did this guideline apply to our five pilot National Wildlife Refuges, but it was also further validated by applying it to four additional National Wildlife Refuges. We hope that by applying this finding to other National Wildlife Refuges, we can increase participation in the program by reducing the logistical and financial burden of sampling.

Keywords: survey design; monitoring; sampling; waterfowl; IWMM

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Introduction

Nationwide wildlife monitoring programs fill an important gap in addressing management and conservation objectives at both local and landscape scales. Programs such as the North American Bat Monitoring Protocol and Integrated Monarch Monitoring Program provide large-scale population estimates and trends, track the spread of disease, and inform protection of migration habitat (Loeb et al. 2015; Cariveau et al. 2019).

These efforts rely heavily on partnerships and collaborations with various organizations to collect large amounts of data in a consistent and rigorous sampling framework, which is used to inform conservation and management (Loeb et al. 2015; Cariveau et al. 2019).

Another large-scale monitoring program, the Integrated Waterbird Management and Monitoring (IWMM) program, is designed to monitor nonbreeding waterbird populations as well as habitat conditions to provide guidance to wetland managers (Aagaard et al. 2015,
We examined whether alternative sampling protocols could produce accurate results with less sampling effort. Both random sampling and stratified random sampling produce unbiased estimates with associated measures of uncertainty (e.g., standard errors, confidence intervals, etc.) grounded in statistical theory (Cochran 1977; Thompson 2012). However, when considerable variation is present, random sampling will produce unbiased estimates with large uncertainty in the estimates (Cochran 1977; Thompson 2012). Stratification should reduce this variation (Cochran 1977; Thompson 2012). An alternative sampling method is selective sampling, which we defined as preferentially sampling some units over others based on one criterion such as unit-level waterbird abundance or unit size. Selective sampling is easier to implement relative to the other sampling methods, so it may be an appealing option and could provide counts close to the census count if unit-level variation is high. Although nonprobabilistic sampling methods (e.g., selective sampling) that rely on indices of abundance are generally not recommended because they lack measures of uncertainty and their inference is limited (Anderson 2001, Yoccoz et al. 2001; Mills 2013), few studies have compared these various sampling approaches with field data. A notable exception is McKelvey and Pearson (2001), who showed that under certain conditions, indices may be preferable to approaches that estimate detection probability. Herein, we compared the results of probabilistic vs nonprobabilistic sampling with IWMM field data.

Our overall objective was to identify a consistent methodology that maintained statistical accuracy for estimating abundance while reducing the number of units sampled. We first compared random sampling, stratified random sampling, and selective sampling across five pilot Refuges to determine which method more consistently yielded estimates within 10% of the true count of all the units. Next, we tested for an effect of unit size on relative abundance. Finally, we were ultimately interested in providing a recommendation to other Refuges, so we validated our findings at four additional Refuges to examine the robustness of our findings.

Methods

Bird surveys

Waterbirds were surveyed in the nonbreeding season (October–April) from 2015 to 2019 according to the IWMM protocol (Loges et al. 2017). Each Refuge established management units that were sampled for waterbirds during migration from October to April. Sampling consisted of an intensive area-search during...
Table 1. Site summaries for the five pilot National Wildlife Refuges. At each Refuge, we examined various sampling schemes to determine whether it is possible to reduce the area that needs to be sampled while maintaining accurate waterfowl abundance estimates. Refuge data spanned 2015–2019.

| Site                  | Location      | Flyway     | Total no. of units (no. of units included in analyses) | Total no. of years included in analyses |
|-----------------------|---------------|------------|-------------------------------------------------------|----------------------------------------|
| Alligator River       | North Carolina| Atlantic   | 18 (18)                                               | 3*                                     |
| Loess Bluffs          | Missouri      | Mississippi| 25 (25)                                               | 3                                      |
| Prime Hook            | Delaware      | Atlantic   | 6 (6)                                                 | 4                                      |
| Salt Plains           | Oklahoma      | Central    | 20 (16)                                               | 2                                      |
| Wallkill River        | New Jersey    | Atlantic   | 11 (8)                                                | 4                                      |

* Only 2 y of data were used in the use-day analysis for Alligator River.

which observers (agency staff and volunteers) recorded all birds detected to species level (Aagaard et al. 2015). There was no consistent way to account for detection probability because of the variety of habitats and species surveyed. Although not accounting for detection could increase uncertainty in the abundance estimates, bird surveys were conducted from fixed locations that maximized visibility (Aagaard et al. 2015). See Loges et al. (2021) for full protocol. We downloaded data from the IWMM database (https://data.pointblue.org/partners/iwmm/login/?returnUrl=%2Fpartners%2Fiwmm%2F) and made them available as Supplemental Material (Data S1–S9, Supplemental Material).

Selection of Refuges

We selected five pilot Refuges to analyze based on the following criteria: 1) each Refuge had to have a minimum of 2 (preferably 3–4) years of data using the revised IWMM protocol (Loges et al. 2017); 2) each Refuge had to have approximate biweekly sampling in the nonbreeding season (October thru April) of ≥50% of all units (preferably 75–100%); 3) a minimum of five (preferably 10–25) units had to be surveyed; 4) finally, there had to be a minimum recorded count of 10,000 waterfowl each year on each Refuge, ensuring that these Refuges provide substantial waterfowl habitat. The Refuges selected were Wallkill River National Wildlife Refuge in New Jersey, Salt Plains National Wildlife Refuge in Oklahoma, Alligator River National Wildlife Refuge in North Carolina, Loess Bluffs National Wildlife Refuge in Missouri, and Prime Hook National Wildlife Refuge in Delaware (Table 1, Figure 1). These Refuges span the Atlantic, Mississippi and Central flyways, providing inference for various habitat conditions for waterbirds across the United States.

Subsampling

To examine whether it is possible to maintain statistical accuracy while reducing sampling effort, we evaluated three different methods of subsampling. We compared random sampling, stratified random sampling, and selective sampling based on abundance of units. Before we began subsampling, we ensured that each Refuge evenly surveyed every unit by subsetting data, excluding units and dates that were only partially surveyed. This resulted in a data set where every unit on each Refuge was surveyed on every sampling occasion.

We tested subsampling methods with differing guilds and count metrics. We considered the response of waterfowl, dabbling ducks (subset of waterfowl), and shorebirds (only Prime Hook had enough data to include shorebirds). We considered three responses for each grouping of waterbirds. The first response was the abundance (total count of all birds on all units) on each survey date. The second response was the yearly abundance (total count of all birds on all units) from October to April of each year. The final response was yearly bird use-days from October to April, which approximates the total number of birds estimated to use the Refuge over the nonbreeding period. We downloaded use-days from the IWMM database, which converts bird observations to use-days by following the area under the curve approach (Farmer and Durbian 2006).

For all methods of random subsampling, we performed 10,000 simulations. For each iteration, we removed a unit(s) and calculated whether or not the estimated abundance was within 10% of the census value for relative abundance. We chose 10% as a threshold after consulting with biologists for a value that was close enough to truth for management purposes. Our approach for random sampling was to randomly remove units, then sum the remaining bird counts. That approach would lead to a negative bias because birds in the removed units would not be counted, so we then adjusted the summed count by extrapolating the count for the whole Refuge while assuming a uniform density throughout the Refuge (Cochran 1977; Thompson 2012; see Text S1, Supplemental Material for an example). We sequentially removed units one at a time until just one was left to sample.

We also subsampled each Refuge based on stratified random sampling. We ranked units on each Refuge by abundance and divided them into two equal strata: high and low, with the exception of Loess Bluffs, which had an odd number of units. In that case, we included one more unit in the large strata. We then randomly sampled each stratum in the same manner as above and summed the estimated abundance of each of the two strata, thus yielding an abundance estimate for each Refuge.

Lastly, we selectively subsampled each Refuge. We defined selective sampling as preferentially sampling...
Figure 1. Integrated Waterbird Management Monitoring survey units on (A) Wallkill River National Wildlife Refuge, Sussex and Orange counties, New Jersey; (B) Salt Plains National Wildlife Refuge, Alfalfa County, Oklahoma; (C) Alligator River National Wildlife Refuge, Dare and Hyde Counties, North Carolina; (D) Loess Bluffs National Wildlife Refuge, Holt County, Missouri; and (E) Prime Hook National Wildlife Refuge, Sussex County, Delaware. Red lines indicate unit boundaries as of 2019. See Figure 2 for the spatial context of each Refuge.
some units over others based on one criterion such as unit-level waterbird abundance or unit size. We first selectively sampled units with greater relative abundances. To simulate selective subsampling, we removed the unit with the lowest total abundance (across all years surveyed) and then summed the remaining bird counts. Next, we continued sequentially, by removing the two units with the lowest abundances and again summing the remaining bird counts. We continued this sampling scheme until only one unit was left. This yielded raw counts of birds resulting from selectively sampling varying amounts of units. We then compared three methods for assessing relative abundance from these raw counts. The first method was the unadjusted raw count, which was the summation of the actual counts of all the units included in the subsample. The other two methods adjusted for the fact that the subsample did not include our entire study area, so we corrected our count to reflect the abundance for the entire study area. With selective sampling, density from the unsurveyed area will almost certainly be lower than the density from the surveyed area because the unsurveyed area was chosen on the basis of its low abundance. This contrasts with random sampling, which assumes equal densities between the surveyed and unsurveyed areas. Therefore, instead of directly extrapolating from the surveyed area to the unsurveyed area, we instead tested two a priori but arbitrary corrections that assumed the unsurveyed area had half or one-quarter the abundance extrapolated from the surveyed area. We implemented those corrections by first calculating the extrapolated abundance for the unsurveyed area in the same manner as with the random sample and then dividing that extrapolated abundance by two or four for the half and quarter correction, respectively (see Text S1, Supplemental Material for an example).

**Effects of unit size on abundance**

Selective sampling relies on knowledge of each unit’s abundance; therefore, it might not be feasible for Refuges that have no prior data on abundance. We tested whether unit size could predict abundance as an alternative option. We built mixed-effects models using package “lme4” (Bates et al. 2015) in Program R (version 3.6.0; R Core Team 2019). For each Refuge, we constructed a Poisson generalized linear model with the count of each waterfowl species as the response and a fixed effect of unit size as the predictor. Finally, we tested whether selective sampling by removing the smallest units could provide similar inference as selective sampling by removing the units with the lowest abundances. We performed all analyses in Program R (version 3.6.0; R Core Team 2019).

**Results**

**Subsampling**

Selective sampling performed much better than both random sampling and stratified random sampling. A greater percentage of the estimates for waterfowl abundance from selective sampling were within 10% of the census values for waterfowl abundance than from random and stratified random sampling (Tables 2–6). Results for daily relative abundance and use-days have the same trends as do the results for dabbling ducks and shorebirds (Text S2, Supplemental Material).

Although the selective sampling methods all performed well, some methods outperformed others. The
Table 2. The percent of instances where various subsampling schemes at Alligator River National Wildlife Refuge (NC) are within 10% of the true yearly count of waterfowl abundance. Refuge data were from 2016 to 2019. Percent of area removed only applies to selective sampling.

| % of area removed | % of units removed | No. of units removed | Random | Stratified | Selective: uncorrected | Selective: quarter correction | Selective: half correction |
|-------------------|-------------------|----------------------|--------|------------|------------------------|-------------------------------|---------------------------|
| 1%                | 6%                | 1                    | 95%    | —          | 100%                   | 100%                          | 100%                      |
| 6%                | 11%               | 2                    | 86%    | 89%        | 100%                   | 100%                          | 100%                      |
| 10%               | 17%               | 3                    | 70%    | —          | 100%                   | 100%                          | 100%                      |
| 15%               | 22%               | 4                    | 52%    | 56%        | 100%                   | 100%                          | 100%                      |
| 18%               | 28%               | 5                    | 39%    | —          | 100%                   | 100%                          | 100%                      |
| 20%               | 33%               | 6                    | 29%    | 33%        | 100%                   | 100%                          | 100%                      |
| 25%               | 39%               | 7                    | 21%    | —          | 0%                     | 100%                          | 100%                      |
| 32%               | 44%               | 8                    | 15%    | 20%        | 0%                     | 100%                          | 100%                      |
| 41%               | 50%               | 9                    | 12%    | —          | 0%                     | 100%                          | 100%                      |
| 47%               | 56%               | 10                   | 11%    | 14%        | 0%                     | 100%                          | 100%                      |
| 54%               | 61%               | 11                   | 11%    | —          | 0%                     | 67%                           | 33%                       |
| 60%               | 67%               | 12                   | 12%    | 15%        | 0%                     | 100%                          | 0%                        |
| 68%               | 72%               | 13                   | 14%    | —          | 0%                     | 100%                          | 0%                        |
| 75%               | 78%               | 14                   | 15%    | 18%        | 0%                     | 100%                          | 0%                        |
| 79%               | 83%               | 15                   | 14%    | —          | 0%                     | 67%                           | 0%                        |
| 85%               | 89%               | 16                   | 13%    | 16%        | 0%                     | 100%                          | 0%                        |
| 92%               | 94%               | 17                   | 7%     | —          | 0%                     | 0%                            | 0%                        |

Table 3. The percent of instances where various subsampling schemes at Loess Bluffs National Wildlife Refuge (MO) are within 10% of the true yearly count of waterfowl abundance. Refuge data were from 2015 to 2019. Percent of area removed only applies to selective sampling.

| % of area removed | % of units removed | No. of units removed | Random | Stratified | Selective: uncorrected | Selective: quarter correction | Selective: half correction |
|-------------------|-------------------|----------------------|--------|------------|------------------------|-------------------------------|---------------------------|
| 0.2%              | 4%                | 1                    | 92%    | —          | 100%                   | 100%                          | 100%                      |
| 2%                | 8%                | 2                    | 83%    | 84%        | 100%                   | 100%                          | 100%                      |
| 4%                | 12%               | 3                    | 74%    | —          | 100%                   | 100%                          | 100%                      |
| 6%                | 16%               | 4                    | 61%    | 68%        | 100%                   | 100%                          | 100%                      |
| 8%                | 20%               | 5                    | 47%    | —          | 100%                   | 100%                          | 100%                      |
| 9%                | 24%               | 6                    | 35%    | 47%        | 100%                   | 100%                          | 100%                      |
| 10%               | 28%               | 7                    | 25%    | —          | 100%                   | 100%                          | 100%                      |
| 11%               | 32%               | 8                    | 18%    | 31%        | 100%                   | 100%                          | 100%                      |
| 12%               | 36%               | 9                    | 14%    | —          | 100%                   | 100%                          | 100%                      |
| 13%               | 40%               | 10                   | 11%    | 18%        | 100%                   | 100%                          | 100%                      |
| 14%               | 44%               | 11                   | 9%     | —          | 100%                   | 100%                          | 100%                      |
| 20%               | 48%               | 12                   | 8%     | 13%        | 100%                   | 100%                          | 100%                      |
| 25%               | 52%               | 13                   | 7%     | —          | 100%                   | 100%                          | 100%                      |
| 27%               | 56%               | 14                   | 6%     | 11%        | 100%                   | 100%                          | 100%                      |
| 28%               | 60%               | 15                   | 6%     | —          | 100%                   | 100%                          | 100%                      |
| 29%               | 64%               | 16                   | 5%     | 10%        | 100%                   | 100%                          | 100%                      |
| 31%               | 68%               | 17                   | 5%     | —          | 100%                   | 100%                          | 100%                      |
| 32%               | 72%               | 18                   | 6%     | 8%         | 100%                   | 100%                          | 100%                      |
| 34%               | 76%               | 19                   | 6%     | —          | 67%                    | 100%                          | 0%                        |
| 36%               | 80%               | 20                   | 6%     | 7%         | 33%                    | 100%                          | 0%                        |
| 43%               | 84%               | 21                   | 5%     | —          | 0%                     | 100%                          | 0%                        |
| 49%               | 88%               | 22                   | 3%     | 7%         | 0%                     | 67%                           | 33%                       |
| 67%               | 92%               | 23                   | 2%     | —          | 0%                     | 0%                            | 0%                        |
| 71%               | 96%               | 24                   | 3%     | —          | 0%                     | 0%                            | 0%                        |

Table 4. The percent of instances where various subsampling schemes at Prime Hook National Wildlife Refuge (DE) are within 10% of the true yearly count of waterfowl abundance. Refuge data were from 2015 to 2019. Percent of area removed only applies to selective sampling.

| % of area removed | % of units removed | No. of units removed | Random | Stratified | Selective: uncorrected | Selective: quarter correction | Selective: half correction |
|-------------------|-------------------|----------------------|--------|------------|------------------------|-------------------------------|---------------------------|
| 37%               | 17%               | 1                    | 41%    | —          | 75%                    | 100%                          | 0%                        |
| 48%               | 33%               | 2                    | 23%    | 6%         | 0%                     | 100%                          | 0%                        |
| 54%               | 50%               | 3                    | 18%    | —          | 0%                     | 50%                           | 50%                       |
| 80%               | 67%               | 4                    | 10%    | 3%         | 0%                     | 50%                           | 0%                        |
| 88%               | 83%               | 5                    | 4%     | —          | 0%                     | 0%                            | 0%                        |
half and quarter corrections generally outperformed the raw counts for selective sampling (Tables 2–6). The quarter correction consistently outperformed the half correction although there was some site-level variation. Nonetheless, we found that by applying the quarter area correction and sampling at least two-thirds of the units on the Refuge, the estimated abundance was always within 10% of the yearly census values for all five pilot Refuges. Alternatively, the guideline could also be reparametrized in terms of fraction of total area to survey instead of number of units. Under this alternative parameterization, applying the quarter area correction and sampling at least three-quarters of the total area of the units with the highest relative abundances provides abundance estimates that were always within 10% of the true yearly counts. To further test these rules and see if the quarter area correction continued to perform best, we validated these generalizations with four other Refuges.

Validation
We tested the generalizations we found with the five pilot Refuges with four additional Refuges: Mattamuskeet National Wildlife Refuge in North Carolina, Two Rivers National Wildlife Refuge in Illinois, Tishomingo National Wildlife Refuge in Oklahoma, and Shiawassee National Wildlife Refuge in Michigan. We again ensured that each Refuge evenly surveyed every unit throughout the nonbreeding season. Next, we excluded one-third of the units that had the lowest abundance and then applied the three methods of selective sampling to the subsample: no correction (raw counts), quarter correction, and half correction. All methods were within 5% of true abundance (Tables 7–10). The quarter correction method performed the best and was always within 2% of true abundance (Tables 7–10). Finally, we again excluded the units that had the lowest abundances, but this time cumulatively represented as close to but not over one-quarter of the total area of all the units, and we again applied the three methods of selective sampling to the subsample: no correction (raw counts), quarter, and half correction. Again, the quarter correction method performed the best and was always within 4% of true abundance (Tables 8–10). We did not include Mattamuskeet because the unit with the lowest abundance was greater than one-quarter of the total area.

| % of area removed | % of units removed | No. of units removed | Random | Stratified | Selective: uncorrected | Selective: quarter correction | Selective: half correction |
|-------------------|--------------------|---------------------|--------|------------|-----------------------|----------------------------|---------------------------|
| 1%                | 6%                 | 1                   | 90%    | —          | 100%                  | 100%                       | 100%                       |
| 3%                | 16%                | 2                   | 78%    | 79%        | 100%                  | 100%                       | 100%                       |
| 5%                | 19%                | 3                   | 59%    | —          | 100%                  | 100%                       | 100%                       |
| 8%                | 25%                | 4                   | 46%    | 45%        | 100%                  | 100%                       | 100%                       |
| 12%               | 31%                | 5                   | 35%    | —          | 100%                  | 100%                       | 100%                       |
| 13%               | 38%                | 6                   | 28%    | 28%        | 100%                  | 100%                       | 100%                       |
| 18%               | 44%                | 7                   | 22%    | —          | 100%                  | 100%                       | 100%                       |
| 23%               | 50%                | 8                   | 18%    | 18%        | 50%                   | 100%                       | 100%                       |
| 33%               | 56%                | 9                   | 17%    | —          | 0%                    | 100%                       | 100%                       |
| 41%               | 63%                | 10                  | 16%    | 16%        | 0%                    | 50%                        | 50%                        |
| 53%               | 69%                | 11                  | 15%    | —          | 0%                    | 100%                       | 0%                         |
| 58%               | 75%                | 12                  | 14%    | 13%        | 0%                    | 50%                        | 50%                        |
| 70%               | 81%                | 13                  | 13%    | —          | 0%                    | 50%                        | 50%                        |
| 79%               | 88%                | 14                  | 12%    | 11%        | 0%                    | 50%                        | 50%                        |
| 88%               | 94%                | 15                  | 3%     | —          | 0%                    | 0%                         | 0%                         |

Eight out of the nine Refuges had significant positive effects of unit size on abundance ($z$-value $> 51.07, P < 0.001$).
0.01), meaning larger units were associated with greater waterfowl abundances. Prime Hook Refuge also had a significant effect of size ($z$-value = −116.1, $P < 0.01$), but it was negative, indicating that larger units were associated with lower waterfowl abundances. Selective sampling according to unit size worked well for most Refuges but not all. All methods of selective sampling according to unit size were within 10% of true abundance for Salt Plains, Loess Bluffs, Alligator River, Mattamuskeet, Two Rivers, Tishomingo, and Shiawassee (Text S3, Supplemental Material). However, all selective sampling methods according to unit size underestimated true abundance by 20–30% in Wallkill River and Prime Hook (Text S3, Supplemental Material).

**Discussion**

We found that selectively sampling units with the largest overall abundances consistently outperformed random and stratified random sampling at all levels of subsampling. Specifically, selectively sampling at least two-thirds of the units or three-quarters of the total unit area and applying the quarter area correction consistently produced estimates within 10% of true abundance. This generalization held true when applied to other Refuges, which also provided support for the quarter area correction, yielding estimates closest to true abundance. Finally, although we found support for an effect of unit size on abundance, selectively subsampling by unit size instead of abundance did not yield consistently accurate abundance estimates in all cases.

Although random sampling is a hallmark of a strong study design (Cochran 1977; Thompson 2012; Mills 2013), we found that selective sampling outperformed it. Random sampling is needed to provide unbiased results (Cochran 1977; Thompson 2012). However, when considerable variation is present, such as unit-level estimates of relative abundance of waterbirds, random sampling will produce unbiased estimates with large confidence intervals indicating large uncertainty in the estimates (Cochran 1977; Thompson 2012). In our case, we were less interested in an unbiased estimate with high uncertainty than in an estimate closest to the true relative abundance, even if the estimate was biased, as in the case of uncorrected, raw counts. Thus, it proved better to focus sampling on the units that contributed the most information to our estimates.

Stratified random sampling generally resulted in modest increases in accuracy relative to simple random sampling. This was especially true for Refuges with more units (e.g., Alligator River Refuge [18] and Loess Bluffs Refuge [25]). However, selective sampling far outperformed both stratified and simple random sampling. Theoretically, stratification almost always lowers variance compared with simple random sample, although it can sometimes increase variance (Cochran 1977; Thompson 2012). We found that with small sample sizes, simple random sampling outperformed stratified random sampling. This result may be due to only using two strata or because stratification was based on abundance rather than density. Indeed, stratifying by density instead of abundance and increasing the number of strata resulted in improved estimates (Text S4, Supplemental Material). However, despite these improvements, selective sam-

**Table 7.** Deviation from true yearly abundance of waterfowl resulting from selectively sampling survey units with the highest abundances at Mattamuskeet National Wildlife Refuge (NC).

| Year          | Selective sample (uncorrected) | Selective sample (correction: quarter) | Selective sample (correction: half) | Survey effort           |
|---------------|--------------------------------|----------------------------------------|-------------------------------------|-------------------------|
| 2015–2016     | -2%                            | 0%                                     | 2%                                  | 2/3 of all units        |
| 2016–2017     | -1%                            | 1%                                     | 3%                                  | 2/3 of all units        |
| 2018–2019     | -1%                            | 1%                                     | 3%                                  | 2/3 of all units        |

**Table 8.** Deviation from true yearly abundance of waterfowl resulting from selectively sampling survey units with the highest abundances at Two Rivers National Wildlife Refuge (IL).

| Year          | Selective sample (uncorrected) | Selective sample (correction: quarter) | Selective sample (correction: half) | Survey effort           |
|---------------|--------------------------------|----------------------------------------|-------------------------------------|-------------------------|
| 2016–2017     | 0%                             | 1%                                     | 2%                                  | 2/3 of all units        |
| 2017–2018     | 0%                             | 1%                                     | 2%                                  | 2/3 of all units        |
| 2018–2019     | 0%                             | 1%                                     | 2%                                  | 2/3 of all units        |
| 2016–2017     | -3%                            | -1%                                    | 1%                                  | 75% of total area       |
| 2017–2018     | -1%                            | 2%                                     | 4%                                  | 75% of total area       |
| 2018–2019     | -1%                            | -1%                                    | -1%                                 | 75% of total area       |

**Table 9.** Deviation from true yearly abundance of waterfowl resulting from selectively sampling survey units with the highest abundances at Tishomingo National Wildlife Refuge (OK).

| Year          | Selective sample (uncorrected) | Selective sample (correction: quarter) | Selective sample (correction: half) | Survey effort           |
|---------------|--------------------------------|----------------------------------------|-------------------------------------|-------------------------|
| 2017–2018     | 0%                             | 2%                                     | 5%                                  | 2/3 of all units        |
| 2018–2019     | 1%                             | 1%                                     | 2%                                  | 2/3 of all units        |
| 2017–2018     | 0%                             | 2%                                     | 3%                                  | 75% of total area       |
| 2018–2019     | -1%                            | 1%                                     | 2%                                  | 75% of total area       |

**Table 10.** Deviation from true yearly abundance of waterfowl resulting from selectively sampling survey units with the highest abundances at Shiawassee National Wildlife Refuge (MI).

| Year          | Selective sample (uncorrected) | Selective sample (correction: quarter) | Selective sample (correction: half) | Survey effort           |
|---------------|--------------------------------|----------------------------------------|-------------------------------------|-------------------------|
| 2015–2016     | -4%                            | -1%                                    | 2%                                  | 2/3 of all units        |
| 2017–2018     | -1%                            | 2%                                     | 5%                                  | 2/3 of all units        |
| 2018–2019     | -3%                            | 0%                                     | 4%                                  | 2/3 of all units        |
| 2015–2016     | -10%                           | 3%                                     | 16%                                 | 75% of total area       |
| 2017–2018     | -8%                            | -4%                                    | 1%                                  | 75% of total area       |
| 2018–2019     | -8%                            | -4%                                    | 0%                                  | 75% of total area       |
pling still performed far better (Text S4, Supplemental Material).

Selective sampling with no correction for area unsurveyed performed quite well. This method consistently resulted in biased-low estimates unless there were no birds on any of the unsurveyed units (which was almost never the case). Despite this bias, this method performed well, likely because units with greater abundances were disproportionately influencing the final estimate. Therefore, as long as all units with high abundances were included it was not always necessary to correct for the unsurveyed units with low abundance.

Our generalization that sampling at least two-thirds of the units or three-quarters of the total unit area and applying the quarter area correction consistently produced accurate estimates is likely conservative. The potential number of units to not sample and still get accurate estimates was constrained by Prime Hook and Wallkill River, which only had six and eight units, respectively. For the other three Refuges that had 16–25 units, a minimum of 16–44% of units needed to be surveyed to obtain accurate estimates. Thus, our recommendation of two-thirds of units is likely conservative, especially for Refuges that have a lot of units. For the three-quarter area recommendation, once Wallkill is excluded, a minimum of 52–67% of the area needed to be surveyed to obtain accurate estimates. Therefore, as long as all units with greater abundances were disproportionately influenced by management action) in essence, managers using probabilistic sampling would likely have to undergo the inefficient process of collecting separate data to estimate Refuge-wide abundance and quantify the effects of management actions. However, despite the advantages of selective sampling, it does have a few drawbacks. With selective sampling, there is no method to assess the uncertainty in the estimate of abundance (Link and Nichols 1994; Anderson 2001; Yoccoz et al. 2001) and inference strictly applies only to the units sampled coupled with the quarter area correction always produced estimates within 10% of true relative abundance for that Refuge. Although site-specific protocols are useful, we were most interested in establishing a consistent national methodology and providing general recommendations to additional Refuges that lack data necessary for site-specific protocols.

We validated our generalization that selectively sampling at least two-thirds of the units or three-quarters of the area and applying a quarter correction consistently produced estimates within 10% of true abundance using data from four different Refuges. Testing our results with independent data is vital to ensure their applicability beyond sites included in the analyses used in their formation. It is encouraging that all estimators made from selective sampling were within 5% of true abundance for the validation at four Refuge sites using the two-thirds-units recommendation and within 4% for estimates made using the quarter correction and three-quarters-area recommendation. Nonetheless, it is important to note that many of the Refuges used for validation were in the same states as the original Refuges. Accordingly, we were careful to include Shiawassee for validation because this Refuge is not only in a different state, Michigan, but also in a different region of North America, the upper Midwest. We are hopeful that as more Refuges provide data, we will be able to test this method in other regions across the United States.

In addition to providing the most accurate estimates, selective sampling has additional advantages as well as a few drawbacks. Selective sampling is the easiest sampling method for Refuges to implement because it is most similar to their previous methodology (IWMM, unpublished data). More importantly, a selective sampling framework is most amenable to understanding the effects of management actions on waterbird abundance, a goal of IWMM (Loges et al. 2021). Typically, management actions occur at the unit level. Consistent monitoring of the same unit over time is imperative to understanding the effects of management actions. Selective sampling consistently monitors all the units with the greatest waterbird abundances and provides an ideal framework to incorporate additional units into the monitoring, in case management is applied to low abundance units. In contrast, probabilistic sampling does not allow for inclusion of additional units. If any unit subjected to management was not included in the probabilistic sample, data from that unit would not contribute information toward Refuge-wide abundance. Although there are potential workarounds (e.g., stratifying by management action) in essence, managers using probabilistic sampling would likely have to undergo the inefficient process of collecting separate data to estimate Refuge-wide abundance and quantify the effects of management actions. However, despite the advantages of selective sampling, it does have a few drawbacks. With selective sampling, there is no method to assess the uncertainty in the estimate of abundance (Link and Nichols 1994; Anderson 2001; Yoccoz et al. 2001) and inference strictly applies only to the units sampled (Hulbert 1984; Anderson 2001). Despite these limitations, selective sampling consistently yields estimates closest to truth, is easily implemented, and allows for straightforward integration of additional units important for management, making it useful for managers seeking to minimize sampling effort.

We found strong support for an effect of unit size on waterfowl abundance with larger units having greater abundances. This finding is intuitive because these units provide more area to support more birds and possibly more varied habitats (Blake and Karr 1987; Riffell et al. 2001). However, we found the opposite relationship at Prime Hook with larger units having smaller abundances. Prime Hook had the smallest number of units (6). In addition, this relationship is probably driven by the fact that the two largest units had the lowest abundances. These largest units had lower diversity of food resources and more open water (A. Larsen, personal communication). These factors may result in differing species-level habitat selection (Riffell et al. 2001). Prime Hook aside, the strong relationship between abundance and unit size did not always yield strong inference from selective sampling by unit size. This is likely due to other factors in
addition to unit size influencing abundance, wetland habitat type likely being chief among them. For example, a small deep lake will likely have many more diving ducks than a large agriculture field. Thus, although selective sampling by unit size can work in some Refuges, it may be problematic to use in others.

Management Implications

Ideally, managers would survey all units every year with a consistent sampling design. Logistical and financial challenges render that prodigious for many survey efforts. Therefore, a sampling framework that allows some units to be unsurveyed is an important tool to develop. Our sampling recommendations require abundance information on each unit, which can only be obtained by sampling every unit the first year. We also recommend periodic resampling of all units at least every 5 y to ensure that unit-level abundance has not changed (Text S5, Supplemental Material). If sampling all units is impossible, we recommend considering both unit size and unit abundance when determining which units to survey and which ones to skip. Larger units and units thought to have greater abundances should be surveyed, whereas smaller units and units thought to have low abundance should be skipped. Importantly, if units are chosen without having abundance information for all units, the inference is limited to the units surveyed. However, consistent sampling of the same units through time still produces valuable trend information.

An important consideration for selective sampling is that it biases sampling toward habitats preferred by the most abundant species. If a species of management interest is not very abundant and selects different habitat compared with the most abundant species, then sampling the units with the greatest abundances will result in an underrepresentation of the species of management interest. In this situation, random sampling may be a better alternative.

Our recommendations only pertain to estimating abundance across all survey units. If the survey units encompass the entire Refuge, then our abundance estimate applies to the Refuge. However, if certain parts of the Refuge are not surveyed, then the abundance estimate only applies to the area surveyed but not the entire Refuge. Also, some Refuges might have additional objectives in addition to quantifying total abundance. For instance, they might be interested in assessing bird responses across units with differing management histories, necessitating sampling of all units with management histories of interest. Unit areas vary, so density rather than abundance is the appropriate metric to use when comparing bird counts among units.

Supplemental Material

Please note: The Journal of Fish and Wildlife Management is not responsible for the content or functionality of any supplemental material. Queries should be directed to the corresponding author for the article.

Text S1. Examples of area corrections used to estimate waterfowl abundance using random sampling and selective sampling with both half and quarter corrections. Corrections were used to adjust waterfowl abundances from nine National Wildlife Refuges spanning 2015–2019.

Available: https://doi.org/10.3996/JFWM-20-037.S1 (21 KB DOCX)

Text S2. Results from subsampling various metrics of waterfowl abundance based on unit-level abundance from five pilot Refuges: Alligator River National Wildlife Refuge (NC), Loess Bluffs National Wildlife Refuge (MO), Prime Hook National Wildlife Refuge (DE), Salt Plains National Wildlife Refuge (OK), and Wallkill River National Wildlife Refuge (NJ). The abundance metrics included daily counts, yearly counts and yearly use-days for waterfowl, dabbling duck, and shorebird abundance from 2015 to 2019.

Available: https://doi.org/10.3996/JFWM-20-037.S2 (71 KB DOCX)

Text S3. Results from subsampling various metrics of waterfowl abundance based on unit size from five pilot Refuges: Alligator River National Wildlife Refuge (NC), Loess Bluffs National Wildlife Refuge (MO), Prime Hook National Wildlife Refuge (DE), Salt Plains National Wildlife Refuge (OK), and Wallkill River National Wildlife Refuge (NJ), and four refuges used for validation: Mattamuskeet National Wildlife Refuge (NC), Shiuwassee National Wildlife Refuge (MI), Tishomingo National Wildlife Refuge (OK), and Two Rivers National Wildlife Refuge (IL) from 2015 to 2019.

Available: https://doi.org/10.3996/JFWM-20-037.S3 (27 KB DOCX)

Text S4. Results from subsampling of waterfowl abundance from Salt Plains National Wildlife Refuge, Alfalfa County, Oklahoma (2017–2019) based on various stratified subsampling schemes. Strata were determined by waterfowl abundance and by waterfowl density. In addition, the number of strata were varied.

Available: https://doi.org/10.3996/JFWM-20-037.S4 (40 KB DOCX)

Text S5. Methodology used to determine the recommended frequency of sampling all units within a Refuge. We used 2015–2019 data from the five pilot Refuges to determine the recommendations.

Available: https://doi.org/10.3996/JFWM-20-037.S5 (19 KB DOCX)

Data S1. Microsoft Excel file of bird counts at Alligator River National Wildlife Refuge (NC) from 2016 to 2019. The bird count and bird codes columns provided the data used in the analyses.

Available: https://doi.org/10.3996/JFWM-20-037.S6 (442 KB XLSX)
Data S2. Microsoft Excel file of bird counts at Loess Bluffs National Wildlife Refuge (MO) from 2015 to 2019. The bird count and bird codes columns provided the data used in the analyses.
Available: https://doi.org/10.3996/JFWM-20-037.S7 (2.08 MB XLSX)

Data S3. Microsoft Excel file of bird counts at Mattamuskeet National Wildlife Refuge (NC) from 2015 to 2019. The bird count and bird codes columns provided the data used in the analyses.
Available: https://doi.org/10.3996/JFWM-20-037.S8 (930 KB XLSX)

Data S4. Microsoft Excel file of bird counts at Prime Hook National Wildlife Refuge (DE) from 2015 to 2019. The bird count and bird codes columns provided the data used in the analyses.
Available: https://doi.org/10.3996/JFWM-20-037.S9 (2.25 MB XLSX)

Data S5. Microsoft Excel file of bird counts at Salt Plains National Wildlife Refuge (OK) from 2017 to 2019. The bird count and bird codes columns provided the data used in the analyses.
Available: https://doi.org/10.3996/JFWM-20-037.S10 (306 KB XLSX)

Data S6. Microsoft Excel file of bird counts at Shiawassee National Wildlife Refuge (MI) from 2015 to 2019. The bird count and bird codes columns provided the data used in the analyses.
Available: https://doi.org/10.3996/JFWM-20-037.S11 (2.7 MB XLSX)

Data S7. Microsoft Excel file of bird counts at Tishomingo National Wildlife Refuge (OK) from 2017 to 2019. The bird count and bird codes columns provided the data used in the analyses.
Available: https://doi.org/10.3996/JFWM-20-037.S12 (602 KB XLSX)

Data S8. Microsoft Excel file of bird counts at Two Rivers National Wildlife Refuge (IL) from 2016 to 2019. The bird count and bird codes columns provided the data used in the analyses.
Available: https://doi.org/10.3996/JFWM-20-037.S13 (426 KB XLSX)

Data S9. Microsoft Excel file of bird counts at Wallkill River National Wildlife Refuge (NJ) from 2015 to 2019. The bird count and bird codes columns provided the data used in the analyses.
Available: https://doi.org/10.3996/JFWM-20-037.S14 (516 KB XLSX)

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Available: https://doi.org/10.3996/JFWM-20-037.S17 (10.73 MB PDF) and https://ecos.fws.gov/ServCat/ Reference/Profile/135419

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Available: https://doi.org/10.3996/JFWM-20-037.S18 (8.49 MB PDF) and https://www.iwmmprogram.org/ documents/IWMM_NationalProtocolFW_V2.pdf

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Available: https://doi.org/10.3996/JFWM-20-037.S19 (10.23 MB PDF) and https://pubs.usgs.gov/of/2017/ 1052/ofr20171052.pdf

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Available: https://doi.org/10.3996/JFWM-20-037.S20 (2.73 MB PDF) and https://www.fws.gov/migratorybirds/ pdf/management/NAWMP/2012NAWMP.pdf

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