Surveys

Baseline Alligator Nesting Data in Arthur R. Marshall Loxahatchee National Wildlife Refuge to Inform Monitoring

Laura A. Brandt*

U.S. Fish and Wildlife Service, 3205 College Ave., Davie, Florida 33314

Abstract

Monitoring key ecological attributes helps land managers understand the current state of the resource and decide if management action is necessary. Baseline data on spatial and temporal variability of attributes to be monitored is important for development of successful monitoring programs. In this study, I collected data from 2000 to 2004 on American alligator Alligator mississippiensis nesting in the Arthur R. Marshall Loxahatchee National Wildlife Refuge to determine feasibility of conducting alligator nest surveys and collect baseline data on alligator nesting status and variability. I used nest data to provide examples of potential monitoring strategies for tracking trends over time or understanding the effects of different hydrologic conditions on alligator nesting. Conducting ground surveys with airboats in Arthur R. Marshall Loxahatchee National Wildlife Refuge proved to be an effective method of finding alligator nests. Number of nests per 1.6 km $^3$ 1.6 km (256-ha) plot ranged from 1 to 12, and by year from 28 to 53. Overall, average number of nests per hour ranged from 1.8 ± 0.26 (SE) in 2000 to a low of 0.84 ± 0.08 in 2004. Using data from this study for the six plots sampled each year, and assuming no change in variability, power analysis shows that 10 y of sampling would allow for detection of an annual 10% change in number of nests per hour, with power and level of certainty set equal at 90% ($\beta$ and $\alpha$ both 0.10). Additionally, 15 y of data would allow for a detection of a 5% change per year. Thirty-seven plots per area would be necessary to assess a 40% difference in number of alligator nests per hour in areas with different hydrologic conditions with power and level of certainty at 90%. Land managers can use these data and analyses, along with examples of monitoring strategies, to guide development of more specific monitoring protocols that address restoration objectives and management actions throughout the Florida Everglades.

Keywords: Everglades; sampling design; protocols

Introduction

Monitoring is a critical component of successful natural resource management. Carefully designed monitoring programs can help land managers understand the current state of the resource, decide if management action is needed, and inform them if management actions have had the desired effect (Nichols and Williams 2006; Lyons et al. 2008; Lindenmayer and Likens 2010; Reynolds et al. 2016). Monitoring is important for both large-scale restoration projects such as the Florida Everglades and for site-specific management such as on individual units of the National Wildlife Refuge System (hereafter Refuges), a system of public lands and waters set aside to conserve America’s fish, wildlife, and plants and managed by the U.S. Fish and Wildlife Service (USFWS; https://www.fws.gov/refuges/). The 1997 Refuge Improvement Act, which provides a mission for the National Wildlife Refuge System (hereafter Refuge System) and clear standards for Refuge management,
use, planning, and growth (USFWS 1999) guides management of the Refuge System. The Refuge System’s inventory and monitoring policy requires that Refuges develop and follow an inventory and monitoring plan that is consistent with objectives described in the Refuge’s Comprehensive Conservation Plan, the 15-year vision for the Refuge. In addition to clearly addressing management needs and objectives, monitoring should have a rigorous sampling design that defines what will be sampled (indicator), where it will be sampled, what will be measured (attribute), and target responses from management. The sampling design should also define amount of change in the attribute, when managers can expect a change to be observed, the desired accuracy of estimates, magnitude of change one wants to detect, chance of error one is willing to accept, and the power to detect change of a specified magnitude (USFWS 2013).

The Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR) is an approximately 57,000-ha wetland that is part of the Florida Everglades, and thus a part of efforts to restore that ecosystem. A primary component of Everglades restoration is the Comprehensive Everglades Restoration Plan (U.S. Army Corps of Engineers and South Florida Water Management District 1999). Implementation of the Comprehensive Everglades Restoration Plan is being guided by an applied science strategy which includes identification of indicators that are used to both evaluate suitability of projects (through modeling) and monitor and assess effects of projects (Ogden et al. 2003). The American alligator *Alligator mississippiensis* is one of the indicators managers are using to monitor ecosystem responses to Everglades restoration (RECOVER 2009) and the LNWR Comprehensive Conservation Plan has identified it as a key species in LNWR (USFWS 2000). Scientists and managers selected alligators as an indicator because they are an important component of wetland ecosystems in the southeastern United States both ecologically and culturally (Mazzotti et al. 2009). Alligators play a pivotal role in the food chain as both prey and top predator (Mazzotti and Brandt 1994). They are also ecological engineers, creating high ground (nests) and depressions (trails and holes) in the landscape, which can influence the availability of resources and presence of other species (Palm and Mazzotti 2004). Culturally, they are valuable to tourists and hunters.

Alligator ecology is tightly linked to hydrologic conditions (Mazzotti and Brandt 1994) with documented clear linkages between hydrology and alligator nesting (TIEM 2003; Palmer et al. 2004; Rice et al. 2004; Ugarte et al. 2012; Shinde et al. 2014). Managers expect alligator nesting to respond to hydrologic management; they have used nesting in modeling to evaluate the Comprehensive Everglades Restoration Plan, and the Florida Fish and Wildlife Conservation Commission and National Park Service have monitored nesting elsewhere in the Everglades ecosystem (Dalrymple 2001; Ugarte et al. 2013). Therefore, I have selected alligator nesting, and specifically nest effort as measured by number of alligator nests laid, as the measurement attribute for this study. However, because only one study of alligator nesting had been conducted at LNWR (Brandt and Mazzotti 2000) prior to this one, little information was available to address the key components needed for an effective monitoring plan. Therefore, I conducted this study to assess feasibility of conducting systematic surveys for alligator nests (including costs) and collect baseline data on spatial and temporal variability in number of nests. I then used these data to create a range of options for monitoring strategies to address assessing trends over time in number of alligator nests and to assess effects of different hydrologic conditions on number of alligator nests.

## Study Site

Arthur R. Marshall Loxahatchee National Wildlife Refuge is an approximately 57,000 ha of northern Everglades ridge-and-sloough wetland. Canals and levees surround the majority of LNWR (Water Conservation Area 1), and local rainfall and water management determine hydrologic conditions. The U.S. Army Corps of Engineers regulates water levels following a water regulation schedule (U.S. Army Corps of Engineers 1994) designed to keep water level between 4.3 and 5.2 m (14.0 and 17.5 ft) National Vertical Geodetic Datum, depending on season. This results in water depths ranging from approximately 0.0 to 3.1 m depending on location and season. The U.S. Army Corps of Engineers makes decisions on and implements water management actions in coordination with LNWR to the extent possible. Unlike many areas of the Everglades, where there is little substrate overlaying the bedrock, LNWR has a relatively deep peat base ranging from 1.25 m to over 4.5 m in depth (Stephens 1984). Peat surface topography influences the distribution of vegetation communities (Pope 1991), which include a mosaic of sawgrass *Cladium jamaicense* marsh, wet prairie, slough, and tree islands. This mosaic of habitats results in a marsh that contains high densities of potential alligator food items such as invertebrates, small and large fish, amphibians, and turtles. Additionally, there are numerous habitat options for alligators. These range from areas with high densities of tree islands that provide high ground for nesting to sloughs and alligator holes that provide refugia during droughts. There are three general hydrologic areas in LNWR: the northern drier area, the central slough, and the southern wetter area (Richardson et al. 1990).

Restoration planners designated parts of these areas as indicator regions and used them for evaluation of alternative Everglades restoration plans during development of the Comprehensive Everglades Restoration Plan (U.S. Army Corps of Engineers and South Florida Water Management District 1999).

## Methods

Because there were known differences in hydrologic conditions from north to south in LNWR, I used a stratified approach for selecting sample plots. I used the 3.2 × 3.2 km grid cells of the South Florida Water Management District Water Management Model (Fenne-
ma et al. 1994) along with the indicator regions developed for the Comprehensive Everglades Restoration Plan (U.S. Army Corps of Engineers and South Florida Water Management District 1999) as the basis for plot selection. This was to ensure the information could be used in the context of Everglades restoration. The three indicator regions in LNWR have 3, 11, and 6 cells of 3.2 × 3.2 km respectively (Figure 1). I randomly selected one-third of the cells within each indicator region for sampling. I further divided selected cells into four 1.6 × 1.6 km (256-ha) plots and randomly selected one plot for sampling. Sampling in 2000 and 2001 focused on cells in the central region, where sampling occurred as part of another study on alligator nest production (Chopp 2003). It was also more practical for that study to have nests in close proximity to each other. To maintain a total of seven plots, I selected two additional central indicator region cells as described above. I used these in place of one of the northern cells and one of the southern cells. In 2002, I added three plots to bring the total number of plots to 10 and increase spatial coverage (Figure 1).

Observers located nests from the ground using airboats in July and August 2000 to 2004. Rather than the alternative method of aerial surveys, I selected airboat surveys because the canopy cover on tree islands often obscures nests (L.A.B., personal observation). Observers searched the ten 1.6 × 1.6 km (256-ha) plots for alligator nests by driving transects up and down sloughs (north to south) approximately 0.2 km apart. Observers used a global positioning system (GPS) to record transect location (track). Effective width of transects were 5 m on each side of the boat as that reflects the distance easily seen from the airboat. Along each transect, observers surveyed the marsh and circled tree islands when possible to locate alligator trails and nests. Observers searched trails leading onto tree islands on foot. They noted location (GPS coordinate), physical description of the area, and nest, as well as presence of female, when a nest was located. They documented presence and location of nests from previous years when such nests were observed. The observers also recorded amount of time spent searching by boat and by foot. I expressed number of nests found in each plot as number of nests per hour of search (boat only). I used number of nests per hour in analysis because it was directly measured during the surveys, had a high correlation with number of nests per hectare searched, and was not affected by missing GPS track information. I used number of nests per hectare searched only for comparison with other studies.

I used nest locations from previous years of the study to help assess what proportion of nests observers might have missed. In addition, a preliminary double sampling effort was conducted on 26 transects in 3 plots (54NW, 54SW, 54SE) in 2004 to determine an appropriate and feasible protocol for better quantifying nest detectability (Graham 2004). Three experienced individuals participated in the sampling. They conducted two surveys along each transect within 7 d of each other. Each participant sampled a portion of the transects on the first survey and another portion on the second survey, but never conducted both the first and second survey. Results were analyzed using an independent survey method (Magnusson et al. 1978). This method assumes sighting probability of each nest is equal on both occasions (e.g., during first and second surveys, a nest does not move or change color like an animal could), and that the population is closed (e.g., invariable—no nests can possibly move in or out of the area).

Nests observed on both surveys were compared with nests observed only on the first survey and nests that were only observed on the second survey. Following formulas used by Magnusson et al. (1978) and Rice et al. (2000), an estimate of detection probabilities, total nests, variance in the estimate of total nests, and standard error of detection probabilities were calculated.

\[ \hat{p}_1 = \frac{B}{B + S_2} \]
\[ \hat{p}_2 = \frac{B}{B + S_1} \]
\[ \hat{N} = \frac{(B + S_1)(B + S_2)}{B} \]
\[ \text{SE}(\hat{p}_i) = \sqrt{\frac{n_i^2}{\hat{N}^2} \frac{\text{Var} \hat{N}}{\hat{N}} + \frac{\hat{p}_i(1 - \hat{p}_i)}{\hat{N}}} \]

where \( p_i \) is the probability of observer \( i \) finding a nest, \( \hat{p}_1 \) is the probability of finding a nest on the first survey, \( \hat{p}_2 \) is the probability of finding a nest on the second survey, \( S_1 \) is the number of nests found on the first survey, \( S_2 \) is the number of nests found on the second survey, \( B \) is the number of nests found on both surveys, \( N \) is the total number of nests estimated, \( \text{Var} \hat{N} \) is the variance of the number of nests estimated, and \( n_i \) is the count made on survey \( i \).

Statistical power is the probability that a given procedure will reject the null hypothesis when it is false (Hatch 2003). Power analysis is important for developing robust monitoring programs that ensure sampling can detect the level of change desired. There are five parameters in power analysis: 1) number of samples needed to detect a response; 2) variation—a measure of precision expressed as standard deviation (SD) or coefficient of variation (CV); 3) effect size—the degree to which the observed phenomena or response varies from the null hypothesis (for trend analysis this is the slope of the line); 4) significance criterion—the \( \alpha \) level—the probability of rejecting the null hypothesis when it is true (Type I error); and 5) \( \beta \) level—the probability of failing to reject the null hypothesis when it is false (Type II error). Mathematically, power is \( 1-\beta \).

I performed power analysis using data from the six plots surveyed in all 5 y (38SE, 45SW, 54NW, 54SE, 54SW, 61NE) to address two potential objectives for sampling. The first was the ability to detect trends in number of nests per hour. The second was to determine number of plots necessary to detect differences in number of nests per hour between areas with different hydrologic conditions, such as the indicator regions, or to detect differences in nests per hour after a hydrologic change.
Figure 1. American alligator *Alligator mississippiensis* nests located during ground surveys in Arthur R. Marshall Loxahatchee National Wildlife Refuge, Florida, 2000 to 2004. Small plots are sample plots. Larger grey areas are the indicator regions. I substituted plot 28SE for a plot in north indicator region because vegetation and water depth made it impossible to survey plots north of there. I used only nests within 50 m of plot boundaries in analysis.
Results

Number of nests per plot ranged from 1 to 12, and by year from 28 to 53 (Table S1, Supplemental Material).
plots (assuming 1.6 × 1.6 km plots), thus 88 plots per area are available for comparisons between two areas with different hydrology.

### Discussion

Systematic ground surveys from airboats as described here are an effective and relatively inexpensive (surveys of each plot generally took 2 d, so cost per plot ranged from $500 to $1,000 depending on survey personnel salary and airboat costs) method for locating alligator nests. Land managers can use airboat surveys to look at number of nests from year to year and from area to area. My results provide context for how the number of alligator nests in LNWR compare to other wetlands and describe variability over time and space, both of which managers can use to identify the amount and magnitude of change expected in response to management actions. Data collected in this study provide baseline information on alligator nesting in LNWR necessary for developing robust sampling designs for tracking trends or evaluating effects of management.

Number of alligator nests per hectare searched in LNWR (yearly range 0.11 to 0.30 nests/ha; Table S1, Supplemental Material) was higher than that reported in other studies from Florida (0.01 to 0.05 nests/ha; Woodward et al. 1984), and Louisiana (0.04 to 0.07 nests/ha; Regan 2000; 0.005 to 0.19 nests/ha; Joanen and McNease 1989). Variability in nesting in relation to wetter and drier years followed what researchers have observed in both Florida and Louisiana. I observed the greatest differences in number of nests per hour from year to year and from area to area. My results provide context for how the number of alligator nests in LNWR compare to other wetlands and describe variability over time and space, both of which managers can use to identify the amount and magnitude of change expected in response to management actions. Data collected in this study provide baseline information on alligator nesting in LNWR necessary for developing robust sampling designs for tracking trends or evaluating effects of management.

Number of alligator nests per hectare searched in LNWR (yearly range 0.11 to 0.30 nests/ha; Table S1, Supplemental Material) was higher than that reported in other studies from Florida (0.01 to 0.05 nests/ha; Woodward et al. 1984), and Louisiana (0.04 to 0.07 nests/ha; Regan 2000; 0.005 to 0.19 nests/ha; Joanen and McNease 1989). Variability in nesting in relation to wetter and drier years followed what researchers have observed in both Florida and Louisiana. I observed the greatest differences in number of nests per hour from year to year and from area to area. My results provide context for how the number of alligator nests in LNWR compare to other wetlands and describe variability over time and space, both of which managers can use to identify the amount and magnitude of change expected in response to management actions. Data collected in this study provide baseline information on alligator nesting in LNWR necessary for developing robust sampling designs for tracking trends or evaluating effects of management.

### Table 2. Number of continuous years of sampling necessary to detect a 10 or 5% change per year in the number of American alligator *Alligator mississippiensis* nests per hour in the Arthur R. Marshall Loxahatchee National Wildlife Refuge. Results are based on the variability from data in the six plots sampled all 5 y (2000 to 2004) of this study. Results are based on log-transformed nests per hour data.

| Level of certainty | % Change per year | 90% power | 80% power | 75% power |
|-------------------|-----------------|-----------|-----------|-----------|
| 95%               | 10%             | 11        | 10        | 8         |
| 95%               | 5%              | 16        | 15        | 12        |
| 90%               | 10%             | 10        | 9         | 8         |
| 90%               | 5%              | 15        | 13        | 11        |
| 80%               | 10%             | 9         | 8         | 7         |
| 80%               | 5%              | 13        | 12        | 10        |
| 75%               | 10%             | 8         | 7         | 6         |
| 75%               | 5%              | 13        | 11        | 9         |

| Level of certainty | 90% power | 80% power | 75% power |
|-------------------|-----------|-----------|-----------|
| 90%               | 32%       | 27%       | 25%       |
| 90%               | 25%       | 21%       | 20%       |
| 80%               | 19%       | 16%       | 15%       |
| 75%               | 18%       | 15%       | 13%       |

McNease 1989). Joanen and McNease (1989) attributed the year-to-year differences to differences in hydrologic conditions with the greatest increases occurring in wetter years and the greatest decreases occurring in drought years. The rate of increase was approximately 5% per year across the 18 years of their study, despite the wide range in values from year to year.

I was able to quantify variation in alligator nesting across LNWR as well as quantifying variation over time. There appear to be spatial patterns in nest densities related to hydrologic conditions, although I did not test this statistically. Nest densities in the northern and south-central parts of LNWR, where hydrologic conditions are drier and wetter, respectively, appear to be lower than in the central part of LNWR. The rates of change in number of nests per hour of 5 and 10% for trend analysis seem reasonable given the similarity in variability observed in this study to what is known about yearly fluctuations in alligator nesting (Joanen and McNease 1989; Dalrymple 2001). Similarly, testing for 20, 40, and 60% differences in number of nests per hour between areas with different hydrologic conditions, such as the indicator regions, or to detect differences in nests per hour after a hydrologic change falls within what is biologically relevant.

Researchers can develop sampling designs to detect trends in number of nests per hour using data from this study. Assessing trends will allow us to address this question: As Everglades restoration proceeds, are ecological conditions across the whole of LNWR moving toward or away from what is desired as measured by alligator nesting effort (nests per hour)? The net expectation with restoration across all LNWR is that number of alligator nests per hour will remain stable or increase because some areas are wetter and others are drier than desired. Sampling six plots for 10 consecutive years would allow for detection of an annual 10% change in number of nests per hour with 95% certainty and 80% power assuming the variability in alligator nests per hour from this study remains the same. Using this conventional combination of level of certainty and power assumes that committing a Type I error (falsely identifying a trend of 10% per year) is four times more serious than committing a Type II error (not identifying a trend when there is one). If there is potential for negative ecological effects, this may not be good practice as the consequences of not determining a trend when there is one may be more costly than determining a trend when there is not one. If for example, the desire is to catch a negative trend as quickly as possible, then it might be
Table 4. Number of plots necessary to detect differences in the number of American alligator Alligator mississippiensis nests per hour in different areas of the Arthur R. Marshall Loxahatchee National Wildlife Refuge using different levels of power assuming the same variability of data from 2000 to 2004 surveys. Standard deviations were based on the year with the most variability, least variability, and for all years combined. If the indicator regions are used to delineate the spatial boundary of areas, only results with ≤20 plots would be possible since there are only 20 plots in the north indicator region. If we extended the sample frame to include the entirety of Arthur R. Marshall Loxahatchee National Wildlife Refuge, 88 plots would be available for comparison of two areas. Combinations of power and variability that result in greater than 88 plots per area are not included in the table.

| Year       | SD  | Power | % Level of certainty | % Difference | % Level of certainty | Number of plots per area |
|------------|-----|-------|----------------------|--------------|----------------------|--------------------------|
| Least variable | 0.24 | 80   | 90                   | 60           | 3                    |                          |
| Least variable | 0.24 | 80   | 95                   | 60           | 4                    |                          |
| Least variable | 0.24 | 90   | 90                   | 60           | 4                    |                          |
| Least variable | 0.24 | 90   | 95                   | 60           | 4                    |                          |
| Least variable | 0.24 | 95   | 90                   | 60           | 4                    |                          |
| Least variable | 0.24 | 80   | 90                   | 40           | 5                    |                          |
| Least variable | 0.24 | 95   | 95                   | 60           | 5                    |                          |
| Least variable | 0.24 | 90   | 95                   | 40           | 6                    |                          |
| Least variable | 0.24 | 90   | 90                   | 40           | 6                    |                          |
| Least variable | 0.24 | 95   | 90                   | 40           | 9                    |                          |
| All         | 0.64 | 80   | 90                   | 60           | 13                   |                          |
| Least variable | 0.24 | 95   | 90                   | 60           | 16                   |                          |
| All         | 0.64 | 80   | 95                   | 60           | 16                   |                          |
| All         | 0.64 | 90   | 90                   | 60           | 17                   |                          |
| Most variable | 0.83 | 80   | 90                   | 60           | 20                   |                          |
| Least variable | 0.24 | 80   | 95                   | 20           | 20                   |                          |
| All         | 0.64 | 90   | 95                   | 60           | 21                   |                          |
| All         | 0.64 | 90   | 95                   | 60           | 21                   |                          |
| Least variable | 0.24 | 90   | 90                   | 20           | 22                   |                          |
| All         | 0.64 | 95   | 95                   | 60           | 25                   |                          |
| Most variable | 0.83 | 80   | 95                   | 60           | 26                   |                          |
| All         | 0.64 | 80   | 90                   | 40           | 27                   |                          |
| Most variable | 0.83 | 90   | 90                   | 60           | 27                   |                          |
| Least variable | 0.24 | 90   | 95                   | 20           | 27                   |                          |
| Least variable | 0.24 | 95   | 90                   | 20           | 27                   |                          |
| Least variable | 0.24 | 95   | 95                   | 20           | 27                   |                          |
| Most variable | 0.83 | 90   | 95                   | 60           | 34                   |                          |
| Most variable | 0.83 | 90   | 90                   | 60           | 34                   |                          |
| All         | 0.64 | 80   | 95                   | 40           | 35                   |                          |
| All         | 0.64 | 90   | 90                   | 40           | 37                   |                          |
| Most variable | 0.83 | 90   | 95                   | 60           | 41                   |                          |
| Most variable | 0.83 | 80   | 90                   | 40           | 45                   |                          |
| All         | 0.64 | 90   | 95                   | 40           | 46                   |                          |
| All         | 0.64 | 90   | 90                   | 40           | 47                   |                          |
| Most variable | 0.83 | 80   | 95                   | 40           | 56                   |                          |
| Most variable | 0.83 | 90   | 90                   | 40           | 62                   |                          |
| Most variable | 0.83 | 90   | 95                   | 40           | 76                   |                          |
| Most variable | 0.83 | 95   | 90                   | 40           | 78                   |                          |

prudent to have power and level of certainty equal, or power greater than level of certainty. For these data, if power and level of certainty are set equal at 90% (β and α both 0.10), then 10 y of data are necessary to detect a 10% change per year and 15 y of data to detect a 5% change per year. In this example, we are willing to be wrong 10% of the time for either type of error.

Decreasing the variability (CV) is another way to identify a negative trend more quickly. Standardized protocols and training of observers (such as those used in this study; Brandt 2005) are a part of that. Variability can also be decreased by explicitly accounting for detection probability and using that to estimate number of nests. In the first 4 y of this study, I put only a small effort into quantifying detection probability and factors, such as observer, that affect it. The limited double-count data suggest that nests located may be 60 to 64% of nests present and that the actual proportion varies spatially and temporally. These detection probabilities are lower than the sighting probabilities observed by Rice et al. 2000 (0.796 ± 0.024) for aerial surveys of lakes in north-central Florida and may reflect differences in habitats or ground vs. aerial surveys. Water levels may also influence nest detection, as it is easier to see alligator trails when water levels are lower. Collecting data on factors that affect detection such as water level, habitat, visible presence of female, and observer should be a part of the monitoring protocol regardless of the question being addressed. I used experienced observers and conducted presurvey training for new observers in this study to minimize observer bias. This is essential for reducing variability due to observer. The most desirable situation would be to have the same observer survey the same plots each year, as was done for four plots in this study.

The LNWR may also be interested in determining differences in number of nests per hour between areas with different hydrologic conditions, such as the indicator regions. Based on power analysis using the data collected in this study, testing for a 40% difference in nests per hour using a power of 90% and a level of certainty of 90% would require sampling 37 plots in each target area. If the current indicator regions were the target areas this design would not be logistically feasible because there are only 20 available plots in the northern indicator region. If a study expanded the sample frame to the entirety of LNWR, 176 sample plots (assuming the same size as used in this study) could be sampled so the above design would be feasible. Researchers could use existing hydrologic modeling tools to identify spatial bounds for areas with different hydrologic conditions so as not to be constrained by the boundaries of the indicator regions.

Researchers could set up a before-and-after study in areas where management targets improving hydrologic conditions. Hydrologic conditions (hydroperiods and depth) in the central portion of LNWR are the closest to hydrologic targets developed for Everglades restoration. Conditions in more northern areas are drier than desired and it has been suggested that ecological conditions would be improved if water stages in the northern indicator region remain greater than 15.24 cm (0.5 ft) for at least 4 wk at least 4 of 5 y (USFWS 2014). Alligator nesting should respond favorably (higher number of nests per hour) in areas where water...
management actions are implemented to achieve this goal and target depths and hydroporrids are achieved. Hydrologic models could be useful for spatially projecting the expected changes in hydrology with sampling occurring in the same 37 plots before and after changes occur.

The data and analysis in this study quantify the state of alligator nesting in LNWR, provide characterization of variability in number of nests per hour, and illustrate how this information can be used to develop monitoring plans for assessing trends over time, evaluating alligator nesting in areas with different hydrology, or assessing responses of alligator nesting to changes in hydrologic management. The decision on what monitoring strategy to implement will depend on which question is most important to address (trend or response to management), the level of certainty and power that is acceptable, and resources available. Using the information presented here to inform the sampling design will help to ensure that monitoring efforts are effective and efficient.

### 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.

**Table S1.** Number of American alligator *Alligator mississippiensis* nests, nests/h, and nests/ha surveyed found in 256-ha (1.6 × 1.6 km) plots surveyed in the Arthur R. Marshall Loxahatchee National Wildlife Refuge 2000–2004. See Figure 1 for plot locations.

Found at DOI: [https://doi.org/10.3996/092017-JFWM-078.S1](https://doi.org/10.3996/092017-JFWM-078.S1)

**Reference S1.** Brandt LA. 2005. Relative density of alligator nests in the Arthur R. Marshall Loxahatchee National Wildlife Refuge 2000–2004. Final Report to U.S. Fish and Wildlife Service Arthur R. Marshall Loxahatchee National Wildlife Refuge, Boynton Beach, Florida.

Found at DOI: [https://doi.org/10.3996/092017-JFWM-078.S2](https://doi.org/10.3996/092017-JFWM-078.S2)

**Reference S2.** Dalrymple GH. 2001. American alligator nesting and reproductive success in Everglades National Park. An analysis of the systematic reconnaissance flight data (SRF) from 1985–1998. Final report to Everglades National Park, University of Miami–Everglades National Park Cooperative Agreement CA528-03-9013, Homestead, Florida.

Found at DOI: [https://doi.org/10.3996/092017-JFWM-078.S3](https://doi.org/10.3996/092017-JFWM-078.S3)

**Reference S3.** Gerrodette T. 1993. Program TRENDS: users guide. Unpublished report to National Oceanic and Atmospheric Administration, Southwest Fisheries Science Center, La Jolla, California.

Found at DOI: [https://doi.org/10.3996/092017-JFWM-078.S4](https://doi.org/10.3996/092017-JFWM-078.S4)

**Reference S4.** Graham JA. 2004. Establishing a method to assess detectability of American alligator nests in the Arthur R. Marshall Loxahatchee National Wildlife Refuge. Report to U.S. Fish and Wildlife Service Arthur R. Marshall Loxahatchee National Wildlife Refuge, Boynton Beach, Florida.

Found at DOI: [https://doi.org/10.3996/092017-JFWM-078.S5](https://doi.org/10.3996/092017-JFWM-078.S5)

**Reference S5.** Nur N, Jones SL, Geupel GR. 1999. A statistical guide to data analysis of avian monitoring programs. Report BTP-R6001-1999 to U.S. Fish and Wildlife Service, Washington, D.C.

Found at DOI: [https://doi.org/10.3996/092017-JFWM-078.S6](https://doi.org/10.3996/092017-JFWM-078.S6)

**Reference S6.** Rice KG, Mazzotti FJ, Brandt LA, Tarboton KC. 2004. Alligator habitat suitability index. Pp. 93–110 in Tarboton KC, Irizzarry-Ortiz MM, Loucks DP, Davis SM, Obeysekera JT, editors. Habitat suitability indices for evaluating water management alternatives. Technical Report to South Florida Water Management District Office of Modeling, West Palm Beach, Florida.

Found at DOI: [https://doi.org/10.3996/092017-JFWM-078.S7](https://doi.org/10.3996/092017-JFWM-078.S7)

**Reference S7.** Richardson JR, Bryant WL, Kitchens WM, Mattson J, Pope KR. 1990. An evaluation of refuge habitats and relationships to water quality and hydroporrid. Final Report to Florida Cooperative Fish and Wildlife Research Unit, Gainesville, Florida.

Found at DOI: [https://doi.org/10.3996/092017-JFWM-078.S8](https://doi.org/10.3996/092017-JFWM-078.S8)

**Reference S8.** Shinde D, Pearlstine L, Brandt LA, Mazzotti FJ, Parry MW, Jeffery B, LoGalbo A. 2014. Alligator production suitability index model (GATOR–PSIM v. 2.0): ecological and design documentation. Ecological Model Report to National Park Service South Florida Natural Resources Center, Everglades National Park, SFNRC Technical Series 2014:1, Homestead, Florida.

Found at DOI: [https://doi.org/10.3996/092017-JFWM-078.S9](https://doi.org/10.3996/092017-JFWM-078.S9)

**Reference S9.** Stephens JC. 1984. Subsidence of organic soils in the Florida Everglades: a review and update. Pages 375–381 in Gleason PJ, editor. Environments of South Florida present and past II. Miami Geological Society, Coral Gables, Florida.

Found at DOI: [https://doi.org/10.3996/092017-JFWM-078.S10](https://doi.org/10.3996/092017-JFWM-078.S10)
Acknowledgments

Special thanks to everyone who assisted with alligator nest surveys especially M. Chopp, G. Cook, J. Graham, M. Parry, and K. Rice. F. Mazzotti and K. Rice provided logistical support. Partial support was provided by the U.S. Geological Survey Greater Everglades Priority Ecosystems Science program. D. Smith and two anonymous reviewers, and the Associate Editor provided detailed comments that improved an earlier version of this manuscript. J. Dalaba assisted with technical editing and J. Nestler assisted with the figures.

Any use of trade, product, website, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Brandt LA. 2005. Relative density of alligator nests in the Arthur R. Marshall Loxahatchee National Wildlife Refuge 2000–2004. Final Report to U.S. Fish and Wildlife Service Arthur R. Marshall Loxahatchee National Wildlife Refuge, Boynton Beach, Florida. (see Supplemental Material, Reference S1).

Brandt LA, Mazzotti FJ. 2000. Nesting of alligators at the Arthur R. Marshall Loxahatchee National Wildlife Refuge. Florida Field Naturalist. 28:122–126.

Chopp MD. 2003. Everglades alligator production and natural history in marsh interior and canal habitats at Arthur R. Marshall Loxahatchee National Wildlife Refuge. Master’s thesis. Gainesville, Florida: University of Florida.

Cohen J. 1988. Statistical power analysis for the behavioral sciences. 2nd edition. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Dalrymple GH. 2001. American alligator nesting and reproductive success in Everglades National Park. An analysis of the systematic reconnaissance flight data (SRF) from 1985–1998. Final report to Everglades National Park, University of Miami–Everglades National Park Cooperative Agreement CA528-03-9013, Homestead, Florida (see Supplemental Material, Reference S2).

Fennema RJ, Neidrauer CJ, Johnson RA, MacVicar TK, Perkins WA. 1994. A computer model to simulate natural Everglades hydrology. Pages 249–289 in Davis SM, Ogden JC, editors. Everglades: the ecosystem and its restoration. Delray Beach, Florida: St. Lucie Press.

Gerrodette T. 1987. A power analysis for detecting trends. Ecology 68:1364–1372.

Gerrodette T. 1993. Program TRENDS: users guide. Unpublished report to National Oceanic and Atmospheric Administration, Southwest Fisheries Science Center, La Jolla California (see Supplemental Material, Reference S3).

Graham JA. 2004. Establishing a method to assess detectability of American alligator nests in the Arthur R. Marshall Loxahatchee National Wildlife Refuge. Report to U.S. Fish and Wildlife Service Arthur R. Marshall Loxahatchee National Wildlife Refuge, Boynton Beach, Florida (see Supplemental Material, Reference S4).

Hatch SA. 2003. Statistical power for detecting trends with applications to seabird monitoring. Biological Conservation 111:317–329.
Joanen T, McNease LL. 1989. Ecology and physiology of nesting and early development of the American alligator. American Zoologist 29:987–998.

Kushlan JA, Jacobsen T. 1990. Environmental variability and the reproductive success of Everglades alligators. Journal of Herpetology 24:176–184.

Lindenmayer DB, Likens GE. 2010. The science and application of ecological monitoring. Biological Conservation 143:1317–1328.

Lyons JE, Runge MC, Laskowski HP, Kendall WL. 2008. Monitoring in the context of structured decision-making and adaptive management. Journal of Wildlife Management 72:1683–1692.

Magnusson WE, Caughley GJ, Grigg GC. 1978. A double-survey estimate of population size from incomplete counts. Journal of Wildlife Management 42:174–176.

Mazzotti FJ, Best GR, Brandt LA, Cherkiss MS, Jeffery BM, Rice KG. 2009. Alligators and crocodiles as indicators for restoration of Everglades ecosystems. Ecological Indicators 9S:S137–S149.

Mazzotti FJ, Brandt LA. 1994. Ecology of the American alligator in a seasonally fluctuating environment. Pages 485–505 in Davis SM, Ogden JC, editors. Everglades: the ecosystem and its restoration. Delray Beach, Florida: St. Lucie Press.

Nichols JD, Williams BK. 2006. Monitoring for conservation. Trends in Ecology and Evolution 21:668–673.

Nur N, Jones SL, Geupel GR. 1999. A statistical guide to data analysis of avian monitoring programs. Report BTP-R6001-1999 to U.S. Fish and Wildlife Service, Washington, D.C. (see Supplemental Material, Reference S5).

Ogden, JC, Davis, SM, Brandt LA. 2003. Science strategy for a regional ecosystem monitoring and assessment program: the Florida Everglades example. Pages 135–163 in Busch D, Trexler J, editors. Monitoring ecosystems: interdisciplinary approaches for evaluating ecoregional initiatives. Washington, D.C.: Island Press.

Palmer ML, Mazzotti FJ. 2004. Structure of Everglades alligator holes. Wetlands 24:115–122.

Palmer MR, Gross L, Rice KG. 2004. ATLSS American alligator production index model basic model description. Available: http://atlss.org/gator_mod.html. (July 2018). Archived by WebCite: http://www.webcitation.org/71KRGhsdK.

Pope KR. 1991. The relationship of vegetation to sediment chemistry and water level variance on the Arthur R. Marshall Loxahatchee National Wildlife Refuge. Master’s thesis. Gainesville, Florida: University of Florida.

R Core Team. 2014. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available: http://www.R-project.org/ (November 2016). Archived by WebCite: http://www.webcitation.org/76hUydVIL.

RECOVER. 2009. CERP monitoring and assessment plan. Revised December 2009. Jacksonville and West Palm Beach, Florida: U.S. Army Corps of Engineers and South Florida Water Management District. Available: http://141.232.10.32/pm/recover/recover_map_2009.aspx (July 2018). Archived by WebCite: http://www.webcitation.org/71QkbUxt.

Regan SR. 2000. American alligator nesting ecology in impounded marsh habitat, Louisiana. Doctoral dissertation. Baton Rouge, Louisiana: Louisiana State University.

Reynolds JH, Knutson MG, Newman KB, Silverman ED, Thompson WL. 2016. A road map for designing and implementing a biological monitoring program. Environmental Monitoring and Assessment 188:1–25.

Rice KG, Mazzotti FJ, Brandt LA, Tarboton KC. 2004. Alligator habitat suitability index. Pages 93–110 in Tarboton KC, Izrrarry-Ortiz MM, Loucks DP, Davis SM, Obeyskera JT, editors. Habitat suitability indices for evaluating water management alternatives. Technical Report to South Florida Water Management District Office of Modeling, West Palm Beach, Florida (see Supplemental Material, Reference S6).

Rice KG, Percival HF, Woodward AR. 2000. Estimating sighting proportions of American alligator nests during helicopter survey. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies 54:314–321.

Richardson JR, Bryant WL, Kitchens WM, Mattson J, Pope KR. 1990. An evaluation of refuge habitats and relationships to water quality and hydroperiod. Final Report to Florida Cooperative Fish and Wildlife Research Unit, Gainesville, Florida (see Supplemental Material, Reference S7).

Shinde D, Pearlstine LG, Brandt LA, Mazzotti FJ, Parry MW, Jeffery B, LoGalbo A. 2014. Alligator production suitability index model (GATOR–PSIM v. 2.0): ecological and design documentation. Ecological Model Report to National Park Service South Florida Natural Resources Center, Everglades National Park, SFNRC Technical Series 2014:1, Homestead, Florida (see Supplemental Material, Reference S8).

Stephens JC. 1984. Subsidiary of organic soils in the Florida Everglades: a review and update. Pages 375–381 in Gleason PJ, editor. Environments of South Florida present and past II. Miami Geological Society, Coral Gables, Florida (see Supplemental Material, Reference S9).

[TIEM] The Institute for Environmental Modeling. 2003. American alligator version 1.1—CERP target sheet, textual description, flowcharts, and presentation. Knoxville, Tennessee. The Institute for Environmental Modeling, University of Tennessee. Available: http://atlss.org/erq_runs/mod_info (July 2018). Archived by WebCite: http://www.webcitation.org/71KR5EINX.

Ugarte CA, Bass OL, Nuttle W, Mazzotti FJ, Rice KG, Fujisaki I, Whelan KRT. 2013. The influence of regional hydrology on nesting behavior and nest fate of the American alligator. The Journal of Wildlife Management 77:192–199. https://doi.org/10.1002/jwmg.463.
U.S. Army Corps of Engineers. 1994. Preliminary finding of no significant impact (FONSI) and environmental assessment Water Conservation Area No. 1 regulation schedule modification. U.S. Army Corps of Engineers, Jacksonville, Florida (see Supplemental Material, Reference S10).

U.S. Army Corps of Engineers and South Florida Water Management District. 1999. Central and southern Florida project comprehensive review study final integrated feasibility report and programmatic Environmental Impact Statement. U.S. Army Corps of Engineers, Jacksonville, Florida (see Supplemental Material, Reference S11).

[USFWS] U.S. Fish and Wildlife Service. 1999. Fulfilling the promise. The National Wildlife Refuge System. Visions for wildlife, habitat, people, and leadership. U.S. Fish and Wildlife Service, Washington, D.C. (see Supplemental Material, Reference S12).

[USFWS] U.S. Fish and Wildlife Service. 2000. Arthur R. Marshall Loxahatchee National Wildlife Refuge comprehensive conservation plan. U.S. Fish and Wildlife Service, Atlanta, Georgia (see Supplemental Material, Reference S13).

[USFWS] U.S. Fish and Wildlife Service. 2013. How to develop survey protocols, a handbook (version 1.0). Report to U.S. Department of Interior, Fish and Wildlife Service, National Wildlife Refuge System, Natural Resource Program Center, Fort Collins, Colorado (see Supplemental Material, Reference S14).

[USFWS] U.S. Fish and Wildlife Service. 2014. A.R.M. Loxahatchee National Wildlife Refuge—enhanced water quality program—10th annual report for calendar year 2013–June 2014. LOXA14—002. U.S. Fish and Wildlife Service, Boynton Beach, Florida (see Supplemental Material, Reference S15).