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RESEARCH ARTICLE

Influence of sanctuary disturbance, weather, and landscape characteristics on waterfowl harvest opportunity in western Tennessee

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Abstract

The North American Waterfowl Management Plan (NAWMP) recognizes waterfowl hunters and non-consumptive users as important stakeholders to sustain waterfowl populations through economic and political support for habitat conservation initiatives. Opportunities to shoot at and harvest ducks are key determinants of achievement-oriented hunt satisfaction and quality. Therefore, identifying factors influencing harvest opportunity would help hunters and wildlife managers identify optimal days afield and promote hunter recruitment, retention, and reactivation (R3) efforts in support of NAWMP. Waterfowl extensively use spatial sanctuaries during hunting seasons, especially diurnally, which could limit their perceived availability to hunters. Thus, a possible management action to support R3 is allowing limited public access on sanctuaries, which could offer diverse recreational opportunities for non-consumptive users and potentially increase harvest opportunities for hunters in traditional hunting areas if the limited disturbance caused waterfowl to leave sanctuaries. Therefore, we evaluated to what extent experimental sanctuary disturbance, landscape characteristics, and weather influenced local harvest opportunities. We conducted disturbance treatments including travel by a covered truck (i.e., truck with enclosed cab), a pedestrian on foot, and an uncovered vehicle (e.g., motor boat or all-terrain vehicle [ATV]). To measure harvest opportunity, we used autonomous recording units (ARU) to enumerate daily shotgun volleys at a landscape-scale across western

Tennessee, USA, during 2019–2021 waterfowl hunting seasons. We identified 339,391 distinct shotgun volleys ($\bar{x}$ = 73 shotgun volleys/day/ARU). Shotgun volleys decreased 50% within 2 weeks of opening day and did not notably increase for the remainder of the hunting season. Contrary to our predictions, sanctuary disturbance decreased harvest opportunity. Specifically, the pedestrian disturbance and covered vehicle disturbance decreased daily shotgun volleys by 32% and 31%, respectively. Additionally, harvest opportunity decreased 20% with every 5-km increase in distance from a sanctuary. Harvest opportunity increased 2% for every 1°C decrease from mean low temperatures and 9% with every 10-hPa increase in barometric pressure from the previous day. Conversely, harvest opportunity was unaffected by changes in cloud cover, daily precipitation, waterfowl abundance, or surface water inundation. Our results suggest disturbing sanctuaries decreases harvest opportunity and, in turn, may reduce hunt quality and satisfaction. If increasing harvest opportunity is a primary management objective, we recommend limiting sanctuary disturbance to maximize local harvest opportunities. Furthermore, greater harvest opportunity nearer sanctuaries indicates that additional disturbance-free areas may increase local harvest opportunities and hunter satisfaction.

KEYWORDS

anthropogenic disturbance, autonomous recording units, harvest opportunity, hunting, Mississippi Flyway, sanctuary, wintering waterfowl

Hunting generates billions of dollars each year and provides economic benefits to many rural communities and conservation dollars to state and federal governments for habitat conservation (U.S. Department of the Interior [USDOI] 2016, Frew et al. 2018); however, hunter numbers are declining across the United States, with estimated decreases of 16% from 2011 to 2016 (USDOI 2016). Consequently, total expenditures by hunters also declined 29%, from $36.3 billion to $25.6 billion between 2011 and 2016 (USDOI 2016). Reduced participation in hunting decreases revenue for conservation (Serfass et al. 2018) and affects state and federal abilities to achieve wildlife management goals (Heffelfinger et al. 2013). A primary goal of the North American Waterfowl Management Plan (NAWMP) is to increase the numbers of waterfowl hunters and other conservationists to promote waterfowl and wetland conservation in North America (Humburg et al. 2018, NAWMP 2018). Recruitment, retention, and reactivation efforts (R3) of hunters often focuses on improving hunting experiences (Humburg et al. 2018, Schummer et al. 2020). Social science researchers suggest viewing and having the potential to harvest game enhances hunt quality and satisfaction (Fulton et al. 2017, Bradshaw et al. 2019, Schroeder et al. 2019, Schummer et al. 2020). Thus, identifying factors associated with seeing, shooting at, and harvesting more game may yield important insights to promote hunter satisfaction and engagement (Ringelman and Rubec 1997).

Achievement-oriented motivations, such as harvest opportunity (i.e., seeing and shooting) or harvest success (i.e., harvesting game), are key determinants of hunt quality for waterfowl hunters (Bradshaw et al. 2019, Schummer et al. 2020). For instance, attracting and harvesting ducks was crucial for waterfowl hunter satisfaction in Minnesota, USA, and hunt quality scores from surveys collected on Wildlife Management Areas in Mississippi and Missouri, USA, were strongly correlated with the number of ducks harvested (Schummer et al. 2019; A. Raedeke, Missouri Department of Conservation, unpublished data). Biotic and abiotic factors influence harvest opportunity and success at varying scales. Environmental factors including weather conditions may increase or decrease hunter success by altering animal activity, the efficacy of hunting techniques, or both (Walters et al. 1973, Miller et al. 1988, Stafford et al. 2010, Wellendorf et al. 2012). In particular, increased movement during diurnal times may make individuals more susceptible to harvest. For instance, mallards (*Anas platyrhynchos*) made more diurnal flights when temperature decreased (Highway 2022), and Gammonley and Runge (2022) reported the number of waterfowl harvested increased as temperatures dropped. Cloud cover may also influence hunter success by affecting hunters' or animals' ability to hide or see, whereas dropping barometric pressure and precipitation, indicative of impending storms and frontal shifts, further alter animal behaviors, which may modify their susceptibility to harvest (Wellendorf et al. 2012, Leorna et al. 2020, Highway 2022). Additionally, shifts in wetland and surface water inundation (i.e., habitat availability) may influence waterfowl behavior and harvest at local and regional scales (Trost 1987, Raveling and Heitmeyer 1989, Stafford et al. 2010). Greater waterfowl abundance within sanctuary areas is believed to positively correlate with harvest opportunities locally, although empirical evidence is generally lacking.

Waterfowl sanctuaries (synonymous with refuges or rest areas) are geographic areas containing resources required by waterfowl (i.e., safety, water, and vegetation cover) that are free from hunting and most other anthropogenic disturbance (Hockin et al. 1992, Fox and Madsen 1997, Hagy et al. 2017). Waterfowl sanctuaries are managed by various entities (e.g., U.S. Fish and Wildlife Service, state wildlife agencies, private landowners, private hunt clubs); therefore, the authorized purpose of implementing waterfowl sanctuaries are multi-faceted (Bellrose 1954, Moser 2005, Sedgwick and Kroll 2010). Conservation planners assume that waterfowl are food-limited in some regions during the non-breeding period (Reinecke et al. 1989, Lower Mississippi Valley Join Venture 2015, Soulliere et al. 2017). Thus, a potential purpose of waterfowl sanctuaries is to provide rest areas to reduce energetic expenditure during non-breeding periods and ultimately ensure population persistence (Salyer 1945, Jorgensen et al. 1964). Additionally, waterfowl sanctuaries are management tools to maintain or increase local waterfowl abundance with the notion that some waterfowl will leave sanctuaries and provide hunting opportunities (Salyer 1945, Bellrose 1954, Evans and Day 2002, Guillemain et al. 2008). There is some limited evidence that waterfowl harvest in areas adjacent to sanctuaries is often greater than in areas farther from sanctuaries (Bellrose 1954, Guillemain et al. 2008); however, some hunters blame sanctuaries for attracting and holding waterfowl that are perceptively not available for harvest (Central Valley Habitat Joint Venture Technical Committee 1996). Ultimately, it remains unclear to what extent sanctuaries detract from or enhance harvest.

While some stakeholders view sanctuaries as an important component of conservation planning that increases opportunities to see and harvest more waterfowl (Salyer 1945), others believe sanctuaries unnecessarily limit hunter access and attract waterfowl that might otherwise use areas accessible to hunters (Central Valley Habitat Joint Venture Technical Committee 1996). Waterfowl increase the use of sanctuaries diurnally, when they are largely inaccessible by hunters or viewers (Evans and Day 2002, Casazza et al. 2012, Shirkey et al. 2020, McDuie et al. 2021). Consequently, there is intense sociopolitical pressure to alter sanctuary management and allow various activities and access (Devers et al. 2017, Responsive Management and National Shooting Sports Foundation 2017, USDOI 2017). Allowing limited public access on sanctuaries could offer diverse recreational opportunities (e.g., hiking, birding, wildlife photography) and potentially increase local harvest opportunity by displacing waterfowl from sanctuaries. If additional access is permitted, trade-offs between direct and indirect effects of anthropogenic disturbances on waterfowl and benefits obtained by people and wildlife management agencies must be evaluated (Hagy et al. 2017). If sanctuary disturbance has limited impacts (e.g., negligible changes in behavior or individual condition) on wintering waterfowl and simultaneously increases harvest and recreational opportunities, natural resource management agencies may consider additional access and subsequent sanctuary disturbance as a management tool to increase hunter satisfaction and non-consumptive stakeholder engagement during the waterfowl hunting season.

We evaluated the effects of anthropogenic disturbance on harvest opportunity outside of sanctuaries with respect to weather conditions, local waterfowl abundance, and landscape characteristics. We implemented a novel approach to index harvest opportunity using passive acoustic monitoring devices. These autonomous recording units (ARUs) enabled continuous monitoring and enumeration of daily shotgun volleys—our metric of harvest opportunity—throughout the waterfowl hunting season. We hypothesized waterfowl vulnerability to harvest (i.e., harvest opportunity) is influenced by landscape characteristics, weather conditions, and if sanctuaries were disturbed. Consequently, we predicted harvest opportunity would be greatest near sanctuaries, increase as local waterfowl abundance on sanctuaries increased, and increase as rivers exceeded their banks (i.e., increased habitat availability). We further predicted cloud cover, deviation from normal low temperature, and barometric pressure would be negatively correlated with harvest opportunity, whereas daily precipitation would be positively correlated to harvest opportunity. Lastly, we predicted that harvest opportunity would increase on days when sanctuaries were disturbed (Table 1).

TABLE 1 Hypotheses, variable name, and variable descriptions of factors we predicted influence daily harvest opportunity in western Tennessee, USA, during the general waterfowl hunting season November–January, 2019–2022. We derived the 20-km buffer for the waterfowl abundance and sanctuary disturbance variables from the maximum relocation distance of global positioning system-marked mallards in our study area, 2019–2022.

Hypothesis	Variable	Description	Predicted relationship
Landscape	Distance to sanctuary	Distance (km) from the nearest sanctuary boundary	–
	Waterfowl abundance	Waterfowl counts summed for sanctuaries within 20 km of each autonomous recording unit	+
	River stage	Index of habitat availability measured at the Obion River gauge at Bogota (National Oceanic and Atmospheric Administration 2022) and estimated as difference between river height and bank full (m)	+
Disturbance	Disturbance type	Factor variable representing whether a sanctuary within 20 km was disturbed (none, covered vehicle, pedestrian, all-terrain vehicle or boat)	+
Weather	Average cloud cover	Daily cloud cover from an hourly estimate of sky cover ranging from 0 to 4 averaged for the diurnal period (National Oceanic and Atmospheric Administration 2018): 0 = clear sky, 1 = few clouds, 2 = scattered clouds, 3 = broken clouds, and 4 = overcast	–
	Barometric pressure	Change in daily barometric pressure (hPa) from the previous day	–
	Daily precipitation	Total daily precipitation (cm)	+
	Deviation from historical low temperature	Deviation from historical mean low temperature (°C)	–

STUDY AREA

Our study took place in western Tennessee, USA, within a portion of the Lower Mississippi Alluvial Valley and the Obion and Forked Deer river floodplains (~6,000 km^2; ~150 m ASL; Figure 1). The topography of the landscape was mostly flat (~123 m); however, some hilly terrain existed along the Chickasaw Bluffs, which were ridges of loess rising 15–61 m above the Mississippi River floodplain. Areas within river floodplains contained wetlands, and river corridors were dominated by willow (*Salix* spp.), maple (*Acer* spp.), and ash (*Fraxinus* spp.). Hilly land and river corridors were forested; otherwise, agriculture was the dominant land use, typified by cotton, corn, wheat, and soybeans. Most agriculture fields were harvested in late summer and autumn, but some were left to serve as food plots for waterfowl (Highway 2022). Western Tennessee is characterized by sandy soils, warm humid summers (mean July temperatures = 28°C), and wet mild winters (mean January temperatures = 4°C). Annual precipitation averaged 140 cm (U.S. Fish and Wildlife Service [USFWS] 2006). Winter and early spring are the wettest times of year, with summer and early fall being the driest (Brown et al. 1973). River channelization occurred in the 1960s–early 1980s, resulting in bank erosion and sedimentation into river channels and flashy and severe flooding of adjacent agricultural fields and woodlots during winter (Johnson 2007). The study area contained 3 federal waterfowl sanctuaries and 7 state-owned sanctuaries including Chickasaw National Wildlife Refuge, Lake Isom National Wildlife Refuge, Reelfoot National Wildlife Refuge, Bean Switch Refuge, Black Bayou Refuge, Hop-In

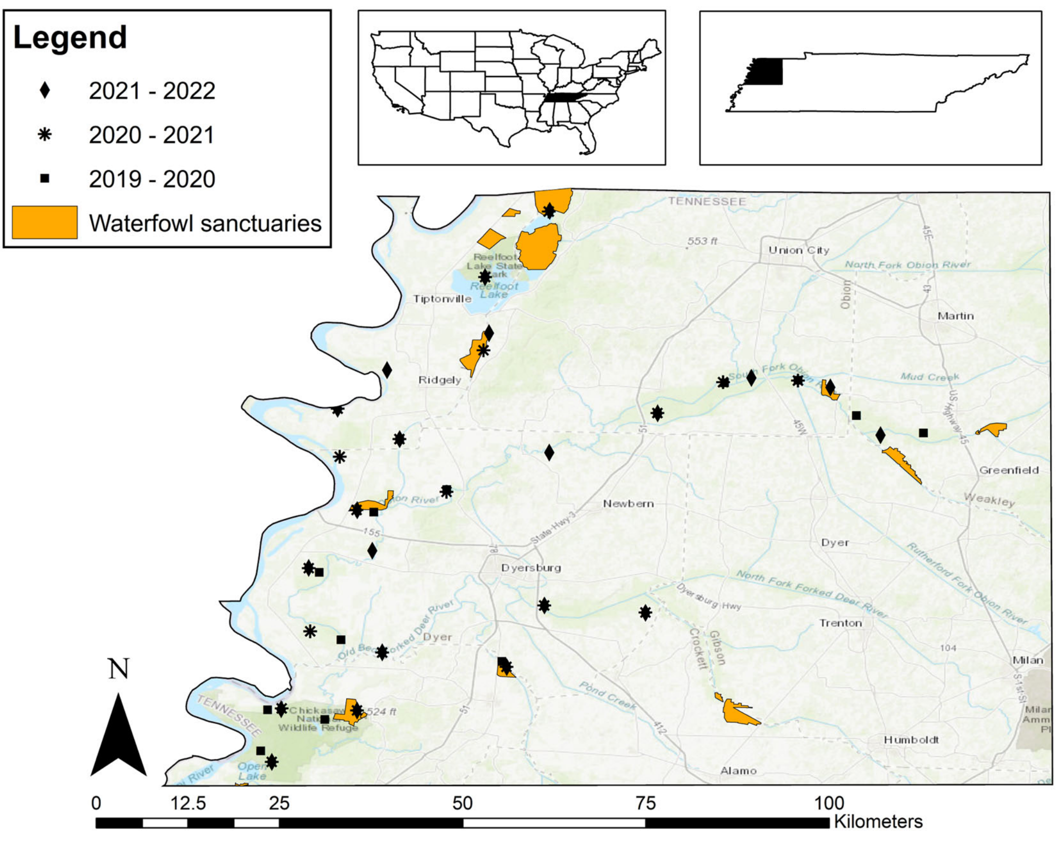

FIGURE 1 Locations of autonomous recording units (ARUs) and sanctuary boundaries in the northwestern corner of Tennessee, USA, during the general waterfowl hunting season November–January, 2019–2022. The ARUs were placed on state or federal lands and separated by >8 km to prevent duplicate detections. Most ARUs were placed in the same location annually.

Refuge, Horns Bluff Refuge, Lake Lauderdale Refuge, Maness Swamp Refuge, and White Lake Refuge. Sanctuaries varied in size (median = 494 ha, range = 260–3,384 ha) and distances apart (median = 8.5 km, range = 1–22 km), and were often located in low-lying areas along the Mississippi, Obion, and Forked Deer river systems. Sanctuaries contained various food resources including moist-soil management and planted crops (e.g., corn, millet, and rice) while simultaneously prohibiting hunting and other public access (i.e., vehicular and foot traffic) on or before 15 November and until 1 March each year (Figure 1). Therefore, spatial sanctuaries in our study prohibited almost all human access during the wintering period, except infrequent maintenance checks by agency staff. These sanctuaries hosted abundant waterfowl throughout the hunting season (Hagy et al. 2022, Tennessee Wildlife Resources Agency [TWRA] 2023).

The waterfowl hunting season lasted 60 days with an opening weekend in mid-November for Reelfoot Lake and late-November for the remainder of the study area. The season then closed until early December when it reopened and remained open until the end of January each year. Within our study area, waterfowl hunters hunt almost exclusively out of stationary blinds (Poudyal and Shrestha 2020). During the hunting season, most of the blinds in our study area were occupied by waterfowl hunters, indicating relatively stable hunter density over time (Masto et al. 2021).

METHODS

Autonomous recording units

To measure waterfowl harvest opportunity, we deployed ARUs across our study area (12 units in 2019–2020, 20 units in 2020–2021, 22 units in 2021–2022). We placed ARUs on federal and state-owned properties where they were accessible for maintenance. We used Song Meter SM4 and Song Meter Mini units, which have comparable recording quality (Wildlife Acoustics, Maynard, MA, USA). To reduce wind interference on recording quality, we added 2 additional interlocking windscreens (Extra Large Windscreen Wildlife Acoustics and YOUSHARES Furry Outdoor Windscreen Muff [outermost windscreen]; Figure S1, available in Supporting Information). We placed ARUs ≥8 km apart to avoid detection overlap. We secured ARUs to trees using wood-decking screws 6 m above the ground (Figure S1). We chose locations >20 m from trails or roads to limit possibility of theft and reduce wind influence.

We deployed ARUs 1 week prior to the waterfowl hunting season, programmed them to begin recording on opening day, and collected acoustic data throughout the 60-day waterfowl hunting seasons: ~27–29 November through ~29–31 January 2019–2022. We scheduled ARUs to record during legal shooting hours (a half hour before sunrise to sunset) and maintained manufacturer gain and amplifier settings on the device hardware panel. We replaced batteries and memory cards every 4–6 weeks depending on battery usage and storage. All recordings were saved as hourly.WAV files onto 64–256 GB memory cards inserted into the units.

Acoustic recording processing

We used RavenPro version 1.6 (Charif et al. 2010) to process acoustic files. To create an automated detection file, we first conducted field tests to estimate sensitivity and maximum distance shotgun blasts were able to be detected by ARUs. Within our study area, we placed 4 ARUs, programmed them to record simultaneously, and shot typical waterfowl hunting shotguns (i.e., 12 gauge) with steel waterfowl loads (i.e., size 2 shot) 110 times at varying distances (0.1–4.5 km) and land cover types (e.g., open fields, timber stands). Observers recorded a global positioning system (GPS) location to document the location and time of each shot. We conducted field tests during moderate wind conditions (12–16 km/hr), which reflected conditions during the waterfowl hunting season.

We then used acoustic files from field testing to develop an automated detector. The band-limited energy detector estimates background sound pressure levels (i.e., noise) of a signal and uses it to find sections of signal that exceed a user-specified signal-to-noise ratio threshold in a specific frequency band at specific times (Charif et al. 2010). To draft the detector, we examined a shotgun blast spectrogram, which consisted of an initial sharp increase in frequency (kHz) lasting approximately 1 second then decaying rapidly beyond detection (Figure S2, available in Supporting Information). We focused the automated detector on the first 1 second of the shotgun spectrogram to represent the most unique aspect of a shotgun acoustic signature compared to non-target noises (e.g., gusting wind, vehicle noise). We set a minimum and maximum frequency detection range of 200–2,000 Hz and minimum and maximum duration of 2 frames (0.02 sec) and 62 frames (0.67 sec), respectively, based on the acoustic signatures of shotgun blasts. Although shotgun signatures ranged from 1–8,000 Hz, reducing the maximum frequency to 2,000 Hz eliminated numerous non-target sounds (Dobbins et al. 2020). Furthermore, because of the rapid succession of shotgun blasts encountered in field settings (i.e., volleys), we set minimum separation to 9 frames (0.10 sec). We set minimum occupancy to 60% and increased the signal-to-noise ratio threshold to 16.5 decibels. To adjust the moving window of the detector, we specified block size to 59 frames (0.63 sec), hop size to 13 frames (0.14 sec), and percentile to 14. We determined American crow (*Corvus brachyrhynchos*) calls were often misclassified as shotgun detections; therefore, we added an exclusion band to our automated detector to reduce false positives of crow calls with minimum frequency of 1,250 Hz, maximum frequency of 1,650, and signal-to-noise ratio threshold of 23 decibels.

We evaluated our automated detector's performance by manually processing sound files and comparing whether the detector correctly classified target sounds. After tabulating the number of true positives (TP; shotgun volley correctly detected), false positives (FP; non-target sound incorrectly classified as a shotgun volley detection), and false negatives (FN; shotgun volley not detected), we calculated precision (TP/[TP + FP]) and sensitivity (TP/[TP + FN]). We then determined how detection probability of shotgun blasts changed with increasing distance from an ARU using a logistic regression where TPs were 1 s, FNs were 0 s, and distance was our covariate of interest. Background noise may influence detection probability of target sounds (Wilhite et al. 2020). Therefore, we manually searched 200 random files from our 2019–2020 field season and estimated average background noise (mean = 0.4 kHz; range = 0.1–2.5 kHz). Background noise was primarily influenced by wind; accordingly, we removed days with average wind speed ≥25 km/hr (mean = 0.9 kHz) from future analyses.

We retrieved acoustic recordings and observers processed the files using the automated detector. We trained observers using files of known shotgun blasts, and observers confirmed whether detections were true (i.e., shotgun blasts) or false (e.g., wind, crow calls). After we processed acoustic files from Tennessee waterfowl hunting seasons, we summed the number of true positive detections and enumerated volleys/ARU/day (i.e., daily harvest opportunity). We defined a shotgun volley as a single shot or multiple shots separated by <10 seconds. This accounted for differences between sizes of hunting parties. Furthermore, because of an estimated 15–20% crippling rate in waterfowl hunting, this approach also accounted for delayed shots to kill crippled birds common in waterfowl hunting (Schulz et al. 2009).

Explanatory variables

To assess factors that influenced harvest opportunity (i.e., shotgun volleys), we collected data on variables that formed our *a priori* hypotheses at a daily scale (Table 1). We conducted all data extraction, manipulation, and statistical analyses in program R version 4.0.2 (R Core Team 2020).

To evaluate how anthropogenic disturbance on waterfowl sanctuaries affected harvest opportunity, we conducted 3 distinct disturbance treatments along a gradient of increasing anthropogenic disturbance intensities (Figure 2). We separated disturbance treatments by ≥5 days to isolate disturbance events and allow birds to resume normal activities (Dooley et al. 2010*a*). Disturbance treatments lasted approximately 1 hour and occurred primarily between 0800 and 1100. The lowest intensity of disturbance was a waterfowl survey conducted from a covered

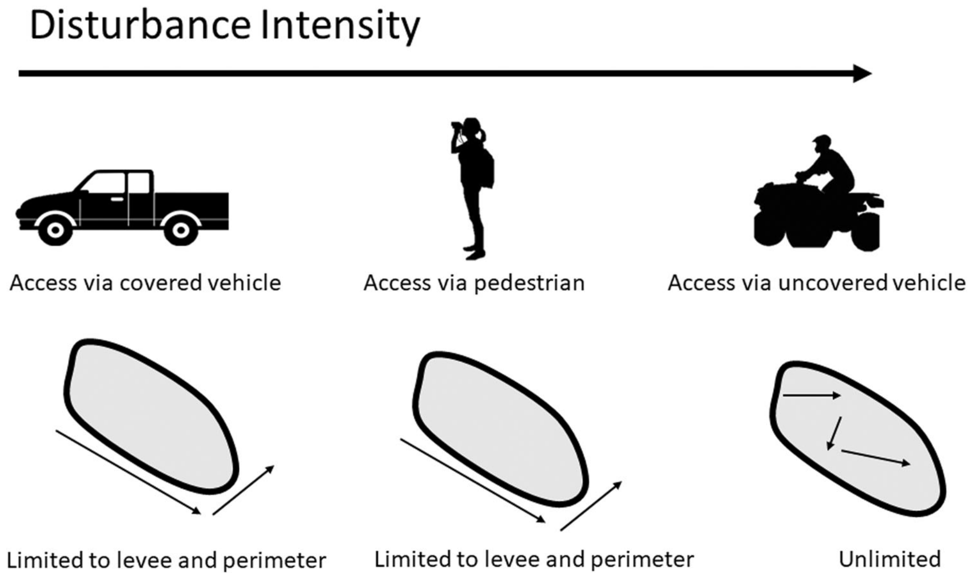

FIGURE 2 Schematic representation of experimental disturbance treatments ordered by predicted increasing intensity (low, medium, and high) and general access to wetland units. Disturbance treatments occurred weekly on waterfowl sanctuaries in western Tennessee, USA, during 2019–2022 and lasted approximately 1 hour each.

truck (i.e., truck with enclosed cab; Klein 1993, Pease et al. 2005; Figure 2). Observers drove predetermined routes along roads or levees with vantage points to estimate waterfowl abundance. The length of routes differed among sanctuaries based on their size and vegetative cover (e.g., forested vs. open water wetlands). An intermediate intensity disturbance treatment mimicked disturbance from a pedestrian (Bregnballe et al. 2009, McLeod et al. 2013, Guay et al. 2019; Figure 2). Two observers walked separate routes along levees at normal walking speed (i.e., 4.8 km/hr) and walked the same routes at each visit unless a route during a given visit was inaccessible (e.g., flooding events). The highest intensity disturbance treatment was driving an uncovered vehicle, either an all-terrain vehicle (ATV) or an outboard motorboat, into wetlands (Havera et al. 1992, Madsen and Fox 1995, Knapton et al. 2000; Figure 2). We maintained speed of motorized vehicles to approximately 16 km/hr for 10 minutes, stopped for 5 minutes, and repeated until 1 hour elapsed.

For each day of our study, we assigned each ARU a categorical disturbance variable of none, covered vehicle, pedestrian, or uncovered vehicle (ATV/boat). We considered an ARU to receive a disturbance treatment if a disturbed sanctuary was within 20 km. We selected a 20-km buffer because this corresponded to the maximum flight distance associated with relocation events based on the empirical step-length distribution of GPS-marked mallards (Highway 2022; A. G. Blake-Bradshaw, Tennessee Tech University, unpublished data). If multiple sanctuaries within 20 km were disturbed on a given day, we included the categorical variable for the disturbance type from the nearest sanctuary for that day. All ARUs were <20 km from the nearest sanctuary; therefore, an ARU was always assigned a disturbance treatment indicator.

We indexed wetland and surface water inundation availability by quantifying the differences in river level to bank full water levels at the Obion River gauge in Bogota, Tennessee, which was the approximate centroid of our study region (Highway 2022). We considered all rivers and tributaries to be at bank full water level when the Obion River level was >3 m at the United States Geological Survey river gauge in Bogota (National Oceanic and Atmospheric Administration [NOAA] 2022). Therefore, we scaled river gauge readings to 0 when water levels were ≤3 m and calculated the difference in river height and 3 m when the river gauge exceeded 3 m. We also included a predictor variable representing relative waterfowl abundance, which we obtained from bi-weekly waterfowl counts on sanctuaries by TWRA and USFWS personnel within 20 km of an ARU (Table 1). In cases of missed waterfowl surveys, we imputed the previous waterfowl counts forward until the next waterfowl survey date. Lastly, to evaluate how proximity to sanctuary influenced harvest opportunity, we calculated distance (km) to nearest sanctuary edge from each ARU in the rgeos package in program R (Bivand and Rundel 2020; Table 1).

To evaluate how weather characteristics influenced harvest opportunity, we retrieved daily weather variables from NOAA data using the rnoaa package in R (Chamberlain 2021). We extracted hourly measures for barometric pressure (hPa), precipitation (cm), and cloud cover and summed total daily precipitation (cm; Minnis et al. 2015, NOAA 2018; Table 1). To evaluate changes in barometric pressure indicative of frontal shifts, we calculated the change in daily barometric pressure (hPa) from the previous day. We averaged hourly values for cloud cover by date and only included diurnal measurements that corresponded with legal hunting times (i.e., ≤30 minutes before sunrise until sunset). Lastly, for each day, we extracted minimum temperature and historical low temperatures (30-yr period 1991–2020; National Weather Service 2022) and calculated the deviation from historical low temperatures.

Statistical analyses

We fitted generalized linear mixed-effects models to infer how our explanatory variables affected harvest opportunity using the lme4 package (Bates et al. 2015). We used the performance package to test for overdispersion in daily shotgun volleys and subsequently selected the negative binomial distribution because overdispersion was evident (Lüdecke et al. 2021). We accounted for repeated measures and spatial and temporal variation using the following intercept-only additive random effects: ARU identifier, a categorical indicator of bi-weekly hunting period nested within hunting season, and nearest sanctuary to an ARU's location. The random effect of ARU accounted for repeated observations and unmeasured spatial variation associated with shotgun volleys (e.g., hunter density, bird behavior, habitat management).

The bi-weekly period nested within hunting season accounted for temporal variation (e.g., likely greater hunter density on opening day, naïve waterfowl earlier in season). Lastly, the nearest sanctuary to an ARU location accounted for expected differences in disturbance treatment effects relative to sanctuary size and other characteristics (e.g., openness, wetland composition).

We calculated Pearson correlations (r) between pairs of covariates prior to building candidate models because inclusion of highly correlated covariates in models can inflate estimates of variance and hinder effect size interpretation. If covariates were correlated ($|r| \geq 0.6$), we retained only 1 covariate that provided a simpler or more meaningful biological interpretation (Dormann et al. 2013). We standardized continuous variables and report scaled beta coefficients (Schielzeth 2010; Table S1, available in Supporting Information). We compared model performance using Akaike's Information Criterion corrected for small sample sizes (AIC_c; Burnham and Anderson 2002) using the AICcmodavg package (Mazerolle 2020). We considered the model with the lowest AIC_c score to be the top-performing model and models within 2 AIC_c as equally plausible. We used the MuMIn package to calculate marginal and conditional R^2 for the top model(s), which represents the variance explained by the fixed effects alone and the variance explained by the fixed and random effects, respectively (Nakagawa and Schielzeth 2013, Barton 2022). For the top model(s), we interpreted direction of beta coefficients and evaluated whether 95% confidence intervals overlapped zero to ascertain whether model parameters were informative. We present predictions for variables with confidence intervals not overlapping zero.

RESULTS

The automated detector correctly classified 79.2% of known shotgun volleys. The farthest distance a volley was detected was 2.1 km (median distance = 1.2 km). Precision, which quantifies true positive rate, was 70%; thus 30% of our automated detector's detections were false positives. The automated detector correctly classified 100% of shotgun volleys ≤1.0 km from an ARU. Detection accuracy then decreased rapidly when shots were >1.4 km from the ARU (Figure S3, available in Supporting Information). As distance of shotgun volleys from the ARU increased, probability of detecting shots decreased (β = −4.09; 95% CI = −6.06–−2.69). For example, model-predicted detection probability of shotgun volleys was 83% (95% CI = 68–92%) at 1.5 km from an ARU, 39% (95% CI = 23–58%) at 2.0 km, and 1% (95% CI = 0–8%) at 3.0 km.

We processed 28,711 hours of acoustic recordings and detected 339,391 distinct shotgun volleys during the 2019–2022 waterfowl hunting seasons. Shotgun volley detections fluctuated within waterfowl hunting seasons with greatest number of detections at the beginning of hunting season (Figure 3). We detected 73 shotgun volleys/day/ARU on average (SD = 94, range = 0–881). We did not detect shots for 3.7% of ARU-date combinations.

We did not remove any covariates because of collinearity. The top-performing model was the global model (Table 2). The fixed effects explained 7% of the variation in shotgun volleys per day, whereas fixed and random effects combined accounted for 50% of the variation ($R^2_{marginal} = 0.07$ and $R^2_{conditional} = 0.50$). The standard deviations for the random effects ($SD_{ARU} = 0.38$, $SD_{TwoWeeks:Season} = 0.38$, $SD_{Season} = 0.13$, $SD_{NearestSanctuary} = 0.52$) indicated considerable spatial and some temporal variation in harvest opportunity. Two disturbances treatments decreased daily shotgun volleys within 20 km of sanctuaries. Specifically, daily shotgun volleys decreased by 30.6% and 32.0% for the covered vehicle and pedestrian disturbance, respectively (Figure 4A; Table 3). We did not find an effect of the uncovered vehicle (e.g., motor boat, ATV) disturbance on daily shotgun volleys (Table 3). Daily shotgun volleys were greater closer to sanctuaries with a 4.0% decrease in volleys for every 1.0 km farther from sanctuary (Figure 4B; Table 3). We did not find an effect of waterfowl abundance or an effect of river stage (e.g., changes in habitat availability) on daily shotgun volleys (Table 3). Lastly, daily shotgun volleys increased 2.8% for every 1°C decrease in temperature from the normal low and increased by 9.0% when barometric pressure increased by 10 hPa from the previous day (Figure 4C; Table 3); however, there was no effect of average cloud cover or precipitation on daily shotgun volleys (Table 3).

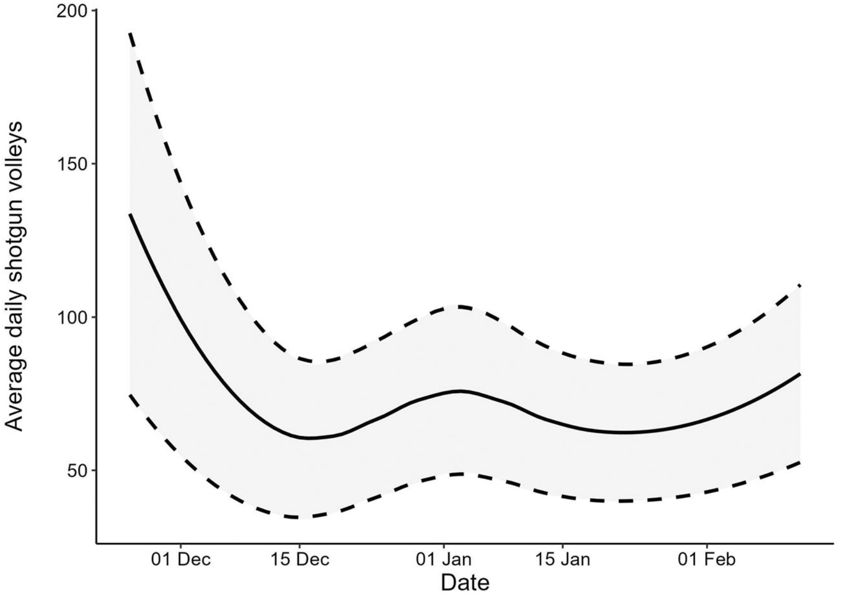

FIGURE 3 Mean daily shotgun volleys detected per autonomous recording unit (ARU) and pooled across 3 waterfowl hunting seasons. We collected data in western, Tennessee, USA, November–January during 2019–2022. The 95% confidence intervals are indicated by dashed lines and the data are fitted using locally estimated scatterplot smoothing regressions (LOESS) using the ggplot package in R (Cleveland 1979, Wickham 2016).

TABLE 2 Model name, formula, number of parameters (K), Akaike's Information Criterion adjusted for small sample size (AIC_c), ΔAIC_c, and negative log likelihoods (LL) for candidate generalized linear mixed models examining harvest opportunity, indexed by daily shotgun volleys per autonomous recording unit (ARU), in western, Tennessee, USA, during the November–January 2019–2022 general waterfowl hunting seasons. All continuous variables were standardized by subtracting the mean and dividing by one standard deviation.

Model name	Model formula	K	AIC_c	ΔAIC_c	LL
Global	~distance to sanctuary + river stage + waterfowl abundance + disturb + temperature deviation + average cloud + chg_baro[a] + precipitation + (1| season) + (1 | ARU ID) + (1| nearest sanctuary)	16	22,266	0	−11,117
Landscape	~distance to sanctuary + river stage + waterfowl abundance + (1| season) + (1 | ARU ID) + (1| nearest sanctuary)	10	22,317	51	−11,148
Weather	~temperature deviation + average cloud + chg_baro + precipitation + (1| season) + (1 | ARU ID) + (1| nearest sanctuary)	9	22,320	55	−11,151
Disturbance	~disturb + (1| season) + (1 | ARU ID) + (1| nearest sanctuary)	9	22,326	60	−11,154
Null	~(1| season) + (1 | ARU ID) + (1| nearest sanctuary)	6	22,347	82	−11,168

[a]Change in barometric pressure.

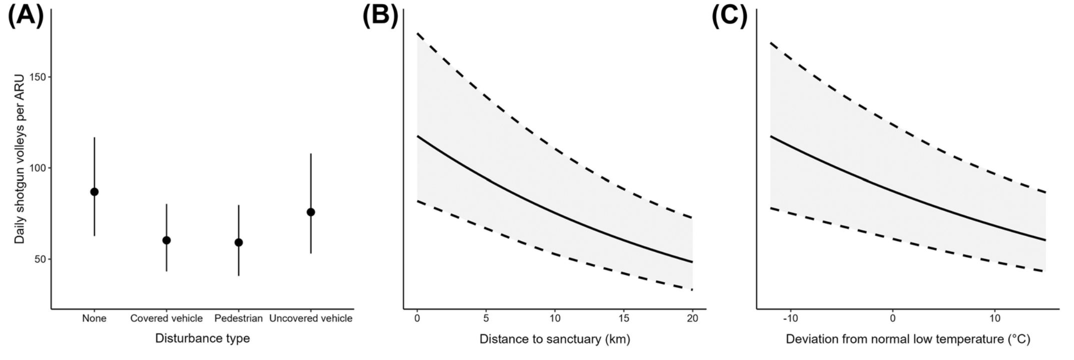

FIGURE 4 Model predicted daily shotgun volleys per autonomous recording unit (ARU) in relation to A) disturbance treatment ≤20 km from each ARU, B) distance from each ARU to the nearest sanctuary (km), and C) deviation from normal low daily temperature (°C) in western, Tennessee, USA, November–January during 2019–2022. The 95% confidence intervals are indicated by black bars in panel A and by dashed lines in panels B–C. All parameters were set at their mean value, and disturbance type = none for B–C.

DISCUSSION

We used a novel approach to index harvest opportunity by measuring daily shotgun volleys with passive acoustic monitoring at a landscape scale. Within 2 weeks of opening day, daily shotgun volleys decreased by 50% and roughly stabilized. Researchers suggest waterfowl are most susceptible to harvest at the onset of the waterfowl hunting season, particularly within the first 2 weeks (Fleskes et al. 2007, Dooley et al. 2010*b*, Davis et al. 2011, Palumbo et al. 2022). We hypothesize this initial spike in daily harvest opportunity was due to waterfowl naïveté to hunting pressure within the study area (Dooley et al. 2010*b*), although higher hunter densities on opening weekend may have played a role (Gammonley and Runge 2022). McDuie et al. (2021) demonstrated dabbling ducks (Anatini) doubled the time they spent flying during opening weekend in California, USA; presumably, increased movement between patches makes waterfowl more susceptible to hunters. Furthermore, waterfowl appear to adjust to hunting disturbance quickly, with many individuals using sanctuaries diurnally (Shirkey et al. 2020,

TABLE 3 Parameter estimates (β), standard errors, and 95% confidence intervals for all explanatory variables used to predict harvest opportunity with fitted generalized linear mixed effects models and a negative binomial distribution in western, Tennessee, USA, November–January during 2019–2022. Harvest opportunity was sampled via autonomous recording units (ARU) and was represented as the daily shotgun volleys per ARU. Scaled βs are reported on the log scale.

			95% CI	
Variable	**β**	**SE**	**Lower**	**Upper**
(Intercept)	4.466	0.232	4.011	4.921
Disturb, covered vehicle	−0.366	0.080	−0.523	−0.208
Disturb, pedestrian	−0.386	0.110	−0.600	−0.171
Disturb, all-terrain vehicle or boat	−0.137	0.103	−0.339	0.064
Distance to sanctuary[a]	−0.229	0.042	−0.310	−0.148
River stage[a]	0.049	0.029	−0.007	0.105
Waterfowl 20 km[a]	0.043	0.033	−0.023	0.108
Cloud cover	0.008	0.028	−0.046	0.063
Change in pressure (hPa)[a]	0.054	0.023	0.010	0.099
Deviation from normal low (°C)[a]	−0.133	0.025	−0.181	−0.084
Precipitation (cm)[a]	0.019	0.024	−0.027	0.066

[a]Continuous variables were z-scaled by subtracting the mean and dividing by 1 standard deviation.

McDuie et al. 2021) or reducing movement during legal shooting hours (McDuie et al. 2021). McDuie et al. (2021) documented diurnal use of sanctuary tripled during opening weekend and flights during legal shooting hours nearly ceased within 2 weeks following the opening day of the hunting season. Despite an initial spike in shotgun volleys, harvest data indicate waterfowl harvest is typically distributed throughout the hunting season in most areas (Vrtiska 2016, USFWS 2022), which may suggest harvest efficacy increases as hunters become more accurate shooters as the season progresses (Ellis et al. 2022). It is also possible that shotgun volleys are not directly correlated with harvest and this should be a subject of future research. Regardless, our results indicate daily pulses in harvest opportunity are likely influenced by local conditions.

When waterfowl sanctuaries were first established, protecting migratory birds from effects of continued human expansion and overexploitation was the primary emphasis (Salyer 1945, Moser 2005). Since 1935, however, the emphasis his shifted toward the creation and management of sanctuaries and public hunting areas. This is thought to benefit waterfowl populations and hunters by providing rest areas that hold waterfowl in an area longer (Salyer 1945, Jorgensen et al. 1964, Roy et al. 2013). Our results suggest hunters closer to waterfowl sanctuaries have greater harvest opportunity than those farther away. Guillemain et al. (2008) likewise supported this finding when they reported greater harvest near waterfowl sanctuaries in southern France. Additionally, others have correlated waterfowl abundance with harvest (Trost 1987, Raveling and Heitmeyer 1989, Stafford et al. 2010); however, local waterfowl abundance, indexed by bi-weekly counts, did not influence harvest opportunity in our study. Similarly, monthly indices of duck abundance did not influence hunter success or satisfaction in a recent study (Gammonley and Runge 2022). Perhaps monthly or even bi-weekly waterfowl abundance estimates are too coarse in scale to adequately explain variation in harvest opportunity. Furthermore, differences in detection probability among counts and between observers were unknown and may have masked effects of local waterfowl abundance on harvest opportunity. Regardless of waterfowl abundance, areas near sanctuaries had greater harvest opportunity; therefore, sanctuaries seemingly serve as a source of harvestable ducks, while simultaneously providing safety and food resources.

Contrary to our predictions, disturbance on waterfowl sanctuaries decreased harvest opportunity adjacent to sanctuaries. Other researchers reported disturbance decreased waterfowl abundance on sanctuaries and increased movement from disturbed areas (Madsen and Fox 1995, Evans and Day 2002, Dooley et al. 2010*a*). Although species respond differently to anthropogenic disturbance (Frid and Dill 2002, Tolon et al. 2009, Crosmary et al. 2012, Clinchy et al. 2016), these responses do not necessarily make them more vulnerable to hunters. For instance, willow ptarmigan (*Lagopus lagopus*) exposed to hunters did not increase movements but instead made greater use of dense cover (i.e., refugia), thus decreasing harvest exposure (Olsson et al. 1996, Brøseth and Pedersen 2010). Furthermore, changes in harvest opportunity differed across disturbance treatments with no effect of the uncovered vehicle disturbance. Observational studies demonstrate waterfowl show more exaggerated shifts away from pedestrians compared to vehicle disturbances; however, flight and shifts often occur within wetlands with waterfowl remaining at the location that was disturbed (Pease et al. 2005, Bregnballe et al. 2009, McLeod et al. 2013). Consequently, responses where individuals do not leave protected areas, or immediately return to them, would have no effect on harvest opportunity. It seems plausible waterfowl disturbed on sanctuaries in our study simply shifted to other parts of the sanctuary (A. G. Blake-Bradshaw, unpublished data), shifted habitat use to conceal themselves from hunters or observers (e.g., forested wetlands; Davis and Afton 2010), or relocated to other waterfowl sanctuaries.

Allowing limited access and recreation on sanctuaries would result in multiple tradeoffs between recreationists, hunters, and waterfowl. For instance, opening sanctuaries to non-consumptive forms of recreation may reach a more diverse set of stakeholders and could result in additional sources of funding (e.g., purchased passes, guided tours); however, our results suggest allowing access or disturbance, especially pedestrian disturbance, on sanctuaries would decrease harvest opportunity to the detriment of local hunters. Although increasing the number of non-consumptive users besides hunters is a primary goal of NAWMP (Humburg et al. 2018, NAWMP 2018), additional access on sanctuaries may dampen harvest opportunity and subsequent hunt quality (Grado et al. 2011, Vrtiska et al. 2013). We acknowledge that our inferences are limited by the duration of experimental disturbance (e.g., 1 hr/week). It is therefore possible that longer, more frequent, or more intense sanctuary disturbance could displace waterfowl (Madsen 1998, Evans and Day 2002, Dooley et al. 2010*a*), but effects on harvest opportunity are unknown and warrant further research.

Wintering waterfowl experience dynamic landscapes with rapid shifts in wetland availability, environmental conditions, and predation risk. Flood events were commonplace during our study and hypothesized to increase harvest opportunity; however, river stage was not related to harvest opportunity. Highway (2022) demonstrated mallards decreased diurnal flight frequency when areas were inundated by flooding, presumably as increased habitat availability allowed access to nonhunted areas and increased access to forage resources (Heitmeyer 2006, Dugger and Feddersen 2009). Although changes in water levels may shift habitat availability by making previous foraging areas unavailable and creating new foraging areas, reduced movements during flood events may have resulted in limited increase to harvest opportunity.

Colder than normal conditions increased harvest opportunity in our study. Stafford et al. (2010) similarly reported decreases in mean low temperatures with increased harvest in Illinois, USA, and Gammonley and Runge (2022) documented the same relationship using daily mean temperature in Colorado, USA. Colder temperatures may cause waterfowl to move to other areas to meet greater daily energy requirements (McKinney and McWilliams 2005) or to find available habitat as wetlands freeze or are covered in snow (Boos et al. 2007, Notaro et al. 2016, Masto et al. 2022) further exposing them to hunters. Likewise, precipitation alters access to food resources and may encourage waterfowl to explore and seek out newly inundated resources (McEvoy et al. 2015, Highway 2022) and increase individual exposure to hunters (Gammonley and Runge 2022); however, we did not find an effect of precipitation on harvest opportunity in our study. Rather, we found that increases in barometric pressure from the previous day, indicative of clear windy weather, was positively associated with harvest opportunity. Perhaps improved weather conditions elicited changes in waterfowl movements or behaviors making them more susceptible to hunters. Alternatively, increased effectiveness of decoying techniques during clear conditions could play a role. Lastly, few studies have evaluated the effect of cloud cover, and those that have indicated little to no effect on harvest success, paralleling our result of no effect (Caswell and Caswell 2004, Lebel et al. 2012).

We provide further empirical support that ARUs can be used to assess the prevalence of shooting in field settings (Hill et al. 2018, Hedley and Bayne 2022). Passive acoustic surveys offer advantages over traditional survey methods including increased sampling efforts with limited personnel and standardized data collection and subsequent analyses (Colbert et al. 2015). Although upfront costs may inhibit some from using this technology, prices of acoustic recording units are declining. Furthermore, while the ability to increase sampling effort is evident, post-processing of sound files is still a substantial undertaking. In this study, observers processed an average of 100 hours of sound files (range = 40–160 hr) in approximately 1 hour using automated detection. Despite 2 additional windscreens (Figure S1), windy conditions (≥25 km/hr) increased processing time, which necessitated the removal of 6% of acoustic files from analyses. We would expect increased shotgun volleys on windier days (Kazantzidis et al. 2020), but we were unable to evaluate this prediction given our methodology. Our automated detector had similar sensitivity and detection distances as those produced by other researchers using ARUs to detect gunshots (e.g., 1.2 km; Astaras et al. 2017; 1.25 km; Dobbins et al. 2020). Furthermore, ARUs can be used to detect spatial patterns of hunter activity. For example, Hedley and Bayne (2022) reported rates of gunshots declined with increasing distance from access points such as roads or parking lots. While our goal was to achieve even coverage of hunted areas within our study area (Astaras et al. 2020, Hedley and Bayne 2022), others have used a gridded design with units much closer together (i.e., 200 m), which could allow triangulation if shotgun blasts are detected by more than one ARU (Piña-Covarrubias et al. 2019). Given detector performance and ARU detection radius, we believe this approach can feasibly be applied at varying spatial scales such as a single wildlife management area or a greater complex (e.g., USFWS Refuge Complex) and possibly address other questions associated with hunter behavior and shot density across a landscape.

In light of declining waterfowl hunter numbers and decreased hunter satisfaction (Brunke and Hunt 2008, USDOI 2016, Bradshaw et al. 2019), research examining harvest opportunity and hunt quality is warranted. Our approach evaluates harvest opportunity, an important metric useful to hunter R3 objectives of recruiting, retaining, and reactivating hunters at a landscape scale (Schummer et al. 2020). To achieve R3 and other conservation goals, agencies recognize they must engage with hunters and other stakeholder groups (e.g., birders, outdoor enthusiasts; NAWMP 2018). Our study illustrates tradeoffs between additional access or forms of recreation on sanctuaries and harvest opportunity. Namely, harvest opportunity (number of shotgun volleys) decreased near sanctuaries on days when limited disturbance occurred on sanctuaries, suggesting disturbance reduced local hunt quality (Brunke and Hunt 2008, Fulton et al. 2017). We believe our results are applicable to other heavily hunted regions with well-distributed sanctuaries (≤25 km apart); however, areas with more variable hunter density or regions with fewer sanctuaries may yield disparate results. Ultimately, we were interested in how disturbance on sanctuaries and other factors influenced harvest opportunity; however, there was considerable spatial variation in our study. Therefore, we encourage replication of our study and methodology at different spatial scales and across other geographies with varying hunter densities and sanctuary restrictions. Additionally, future studies should incorporate individual responses to disturbance to complement quantitative evaluation of harvest opportunity. Monitoring movements of GPS-marked waterfowl in relation to disturbance on sanctuaries would elucidate the influence of disturbance on waterfowl behavior and the indirect effects of such behavior on harvest opportunity.

MANAGEMENT IMPLICATIONS

Duck hunter success, harvest, and satisfaction depends on numerous factors, and the assumption that allowing additional access on sanctuaries could increase recreational opportunities should be rigorously tested to weigh the potential costs and benefits to changes in management. Although displacing ducks from sanctuaries should theoretically make them more vulnerable to harvest, disturbing waterfowl on sanctuaries decreased nearby harvest opportunity in our study. Thus, if increasing local harvest opportunity is a goal, our results suggest managers should keep sanctuaries as disturbance-free as possible. Furthermore, pedestrian disturbance resulted in the greatest decrease in harvest opportunity, so out-of-vehicle activities must be considered in refuge design and management. The notion that disturbing waterfowl while in sanctuaries will increase harvest opportunity was not supported in our results and may represent a misalignment of public perception and the role of sanctuary management. Thus, public engagement and education should be a focus if sanctuary management were to change going forward. Because harvest opportunity was greatest near sanctuaries, the addition of disturbance-free spatial sanctuaries may increase harvest opportunity and hunt quality at local scales.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

No animals were collected or humans surveyed during this study.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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SUPPORTING INFORMATION

Additional supporting material may be found in the online version of this article at the publisher's website.

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