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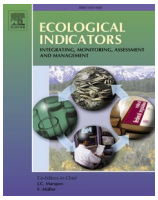

Multi-method biodiversity assessments from wetlands in Grand Teton National Park

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ABSTRACT

A cost-efficient approach to long-term monitoring is to focus on one species or group of organisms as indicators of ecological condition. Through the use of autonomous monitoring technologies, monitoring programs can efficiently expand the biological community surveyed and inferences made. Amphibians have been monitored in Yellowstone and Grand Teton national parks by the Greater Yellowstone Inventory and Monitoring Network (GRYN) since 2006, yet other taxa dependent on wetlands have not been systematically studied. Our main aim was to explore what additional insights we could gain about wetland biodiversity by combining GRYN's amphibian surveys with multiple autonomous technologies. We deployed wildlife cameras and acoustic recorders (for audible and ultrasonic sounds) at 4 permanent wetlands in Grand Teton National Park, WY during early and late summer 2017 and used descriptive metrics to summarize our findings. During GRYN's surveys, 3 of 4 native amphibians were detected. With autonomous monitoring tools, we also documented avian and mammalian communities and detected changes in the degree of activity over the summer. Combining multiple, complementary technologies with field-based surveys provides a more comprehensive picture of wetland biodiversity and enhances insights about ecological condition and change.

1. Introduction

Freshwater wetlands cover <8% of the Earth's land surface, yet they provide numerous ecosystem services, as well as habitat for diverse plants and animals (Keddy et al., 2009). Arguably, wetlands are keystone ecosystems because their area is disproportional to their influence on landscape processes (Calhoun et al., 2017). More than half of the wetland area in the conterminous United States has been lost due to conversion and changes in climate and land use, with some estimates as high as 87% (Davidson, 2014). Wetlands are even threatened within protected areas like Grand Teton National Park (GTNP) and Yellowstone National Park (YNP), where lower precipitation and higher temperatures have been linked to wetland desiccation (Ray et al., 2019). Understanding the ecological consequences of wetland changes requires tools that can provide a large-scale, long-term, and comprehensive picture.

Indicator species often are used for biodiversity monitoring, given limited resources (reviewed in Caro, 2010), yet some indicators may not capture ecosystem complexity (Hilty and Merenlender, 2000). For example, amphibian richness has been used as a proxy for other taxa in montane wetlands (Sergio and Pedrini, 2007), but the importance of wetlands to other animals, such as terrestrial and volant mammals, often is less understood (Kingsford et al., 2016, Mas et al., 2021). Combining autonomous monitoring technologies with field-based surveys provides an opportunity to expand the indicators monitored, providing a more holistic assessment (Boullhesen et al., 2021, Pimm et al., 2015) of wetland biodiversity.

The Greater Yellowstone Inventory and Monitoring Network (GRYN) of the National Park Service (NPS) conducts long-term monitoring of wetlands and amphibians in YNP and GTNP. GRYN visits 31 catchments (Fig. 1A), sampling over 300 wetlands annually since 2006 (Gould et al., 2012). Other taxa disproportionately use wetlands for elements of their life cycle, but have not been studied systematically in these biodiverse areas. Our main aim was to explore what additional insights we could gain about wetland biodiversity by combining GRYN's amphibian surveys with data from autonomous monitoring technologies. We focused

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on wetlands in GTNP and used descriptive metrics to summarize our findings.

2. Materials and methods

2.1. Study area

GTNP is located in western Wyoming (Fig. 1B). Approximately 10% of the park is covered by surface water, with all waters draining into the Snake River. Terraces rising above the floodplain, primarily covered by sagebrush (*Artemisia* spp.) and grasses, are occasionally interrupted by glacial moraines and buttes. The forests consist of lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*) and aspen at lower elevations, with Engelmann spruce (*Picea engelmannii*), whitebark pine (*Pinus albicaulis*), and subalpine fir (*Abies lasiocarpa*) at higher elevations.

Wetlands across GTNP are the fullest from mid-June to early July and begin drying in late August (Ray et al. 2019). Average temperature is −3.6° C in January and 25.3° C in July, with most snowfall from November and April. GTNP is home to 4 native amphibians: boreal chorus frog (*Pseudacris maculata*), Columbia spotted frog (*Rana luteiventris*), western tiger salamander (*Ambystoma mavortium*), and western toad (*Anaxyrus boreas*), and 1 nonnative amphibian: American bullfrog (*Lithobates catesbeianus*); these species are the focus of GRYN's wetland monitoring. Surveys also document presence of reptiles (mainly terrestrial gartersnake, *Thamnophis elegans*).

2.2. General methods

We selected 1 permanent wetland in 4 of the 7 catchments in GTNP visited annually by GRYN (Fig. 1C); these 4 catchments represent a north–south gradient. Wetland permanence was classified based on the USFWS National Wetland Inventory and data collected by GRYN (see Brice et al., *this issue*). These 4 wetlands are characterized as lakes, ponds, or wet meadows with 50–75% cover of sedges, rushes, and grasses. GRYN completed visual encounter surveys for amphibians following Bennetts et al. (2013). We deployed wildlife cameras and acoustic recorders (1 of each per wetland) in early and late summer 2017 (details in Table 1) to document wetland use by other taxa. These exploratory efforts were part of a larger project, such that we were limited by available personnel and sets of identical sampling equipment. Although we sampled relatively few wetlands, our goal was to explore the utility of expanding to a larger sample in the future.

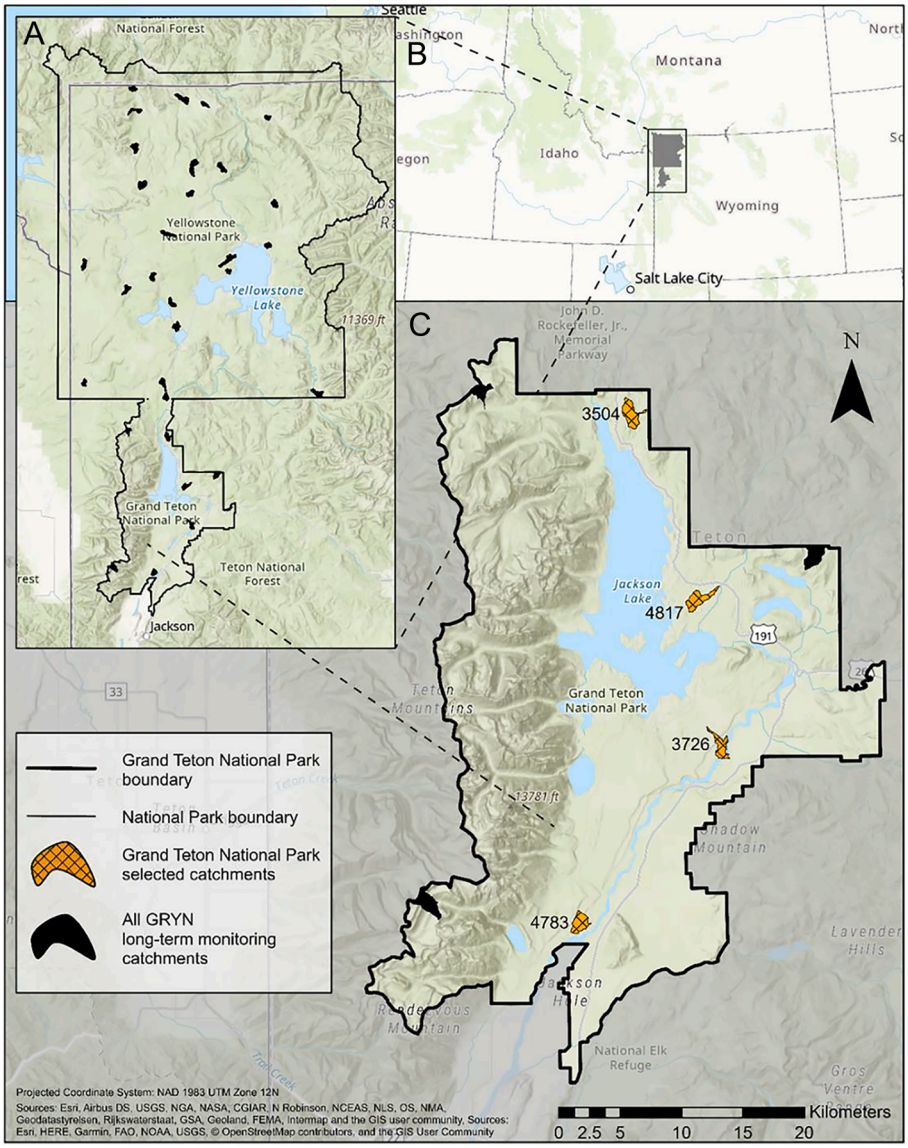

Fig. 1. A) Catchments (in black) sampled by the Greater Yellowstone Inventory and Monitoring Network (GRYN) in Yellowstone and Grand Teton national parks, which are B) located in Montana and Wyoming. Each catchment is comprised of multiple wetlands. C) We selected and sampled 1 permanent wetland in 4 of the 7 catchments in Grant Teton National Park, Wyoming (sampled catchments are numbered and in gold, others are in black), summer 2017 (Table 1). Map courtesy of Jana Cram, GRYN.

Table 1
Taxonomic richness at 4 permanent wetlands (identified by catchment and wetland number) sampled in summer 2017, Grand Teton National Park, Wyoming (Fig. 1C). The Greater Yellowstone Inventory and Monitoring Network completed visual encounter surveys for amphibians in late June and July. We deployed and co-located cameras and ultrasonic recorders in early and late summer; we also sampled audible acoustics (Fig. 2). Wetland 3504-1 was sampled July 2–8 (early)/Aug 20–25 (late), 3726-3 was sampled June 23–29/Aug 12–18, 4783-68 was sampled June 24–30/Aug 25-Sept 1, and 4817-12 was sampled July 1–7/Aug 25-Sept 3. Due to equipment anomalies, no ultrasonic data were collected at 2 wetlands during late summer. Area is based on GPS track data collected while walking the wetted perimeter of each site; we did not record an area for 4783-68 in early summer.

Wetland	Elevation (m)	Wetted Area (m^2)		Amphibian Richness	Camera Richness (mammals)		Camera Richness (birds)		Bat Richness	
		Early	Late		Early	Late	Early	Late	Early	Late
3504-1	2299	2271	980	2	0	1	0	0	8	8
3726-3	2034	891	412	2*	0	0	0	0	5	5
4783-68	1961	–	774	0	1	1	1	0	6	–
4817-12	2081	4998	4739	2	0	0	0	1	2	–

* Terrestrial gartersnake also was observed.

2.3. Wildlife cameras

We used infrared cameras (Stealth Cam PX18CMO, GSM Outdoors, Irving, TX), which were motion-triggered, but in operation 24 hours/day. Wildlife cameras were attached to aluminum conduit (~1.5 m high), pointed at the wetland and positioned to capture as much of the wetted area as possible, with the same orientation during both sampling periods. The visible proportion of the wetland varied; no wetlands were completely in view (wetted edge to wetted edge) in early summer and only 1 was in late summer. We applied a 30-second delay to the trigger to minimize incidental photos. All images were processed by the senior author, who had extensive experience sampling wildlife in this area. To account for equipment malfunctions and standardize effort, we tallied the number of species captured in images during the first 4 days of each sampling period.

2.4. Audible and ultrasonic acoustics

Audible acoustics were recorded with Song Meters (SM3BAT, firmware version 1.3.1) and acoustic microphones (SMM-A2, Wildlife Acoustics, Inc., Concord, MA) at a sampling rate of 44.1 kHz and gain of 0 dB. Each unit was attached to the same pole as the camera (~1.5 m high). We oriented microphones to minimize sound interference, with the same orientation during both sampling periods. Audible recordings were continuous, starting 30 min before sunrise and ending at sunset, saved as uncompressed .WAV files.

Processing acoustic recordings to identify individual species requires time-intensive effort from experts or algorithms trained for a particular region (e.g., Kahl et al., 2021). As an alternative, we used an index to summarize bioacoustic activity in the audible recordings within the frequency range of calls of most avian species. A variety of acoustic indices have been used to represent biodiversity (Buxton et al., 2018), and we specifically chose the acoustic complexity index (ACI, Pieretti et al., 2011) as it has been shown to describe avian diversity during the dawn chorus. Although other species, like the boreal chorus frog, produce audible signals in this area, our audible recordings and calculation of ACI were only during day time hours, when frogs are typically less vocal. We used custom scripts built in Program R (R Core Team, 2021) to first convert files to calibrated 1-second, 1/3 octave band sound pressure levels (dB $Leq_{,1s}$) between 12.5 and 8000 Hz (based on Merchant et al., 2015), then calculated ACI in 10-minute intervals (based on Buxton et al., 2018) within 1.6–8 kHz bands to capture the avian community. To standardize effort, we graphed the variation in ACI for each day a wetland was sampled.

We recorded ultrasonic sounds with the same Song Meters, attaching an ultrasonic microphone (SMM-U1, Wildlife Acoustics, Inc.) to the top of the conduit (~2.3 m high), pointed towards the wetland. Ultrasonic recordings were collected from sunset until 30 min before sunrise, using defined trigger settings (TRGWIN 3.0 s, TRGMAX 5.0 s, TRGLVL 12 dB, call duration: 1.5–300 ms). Frequencies were set to capture bats in GTNP (8–192 kHz). We processed ultrasonic sounds with Sonobat 4.2.1 (Arcata, CA), eliminating non-bat and poor-quality recordings with Sonobat Batch Scrubber 5.7, identified species with Western Wyoming classifiers in SonoBatch, and summarized output with SonoVet. Due to equipment anomalies, no data were collected at 2 wetlands in late summer; we sampled other wetlands for 3–7 nights. To standardize effort, we tallied the number of species and total number of calls identified (by species) during the first 3 nights of each sampling period.

3. Results

During visual surveys of these wetlands, GRYN documented 3 of the 4 native amphibians: boreal chorus frog, Columbia spotted frog, and western tiger salamander, along with terrestrial gartersnake (Table 1); they did not detect American bullfrogs. Using cameras and expert review, we increased the biological community sampled through the detection of 4 additional species: elk (*Cervus canadensis*), black bear (*Ursus americanus*), sandhill crane (*Grus canadensis*), and an unidentified bird, with images of animals captured in 3 of 4 wetlands (Table 1). Using ultrasonic recordings and bat identification software, we further increased the biological community sampled, identifying 8 bat species by their calls: big brown bat (*Eptesicus fuscus*), hoary bat (*Lasiurus cinereus*), silver-haired bat (*Lasionycteris noctivagans*), and 5 species of *Myotis*, with 2–8 species at each wetland (Tables 1 & 2). The number of identified bat calls varied among wetlands and between early and late summer; the majority of these calls were made by little brown myotis (*Myotis lucifugus*) (73%, Table 2). Using audible acoustic recordings processed with an index of avian diversity (ACI), we quantified variation within and among the wetlands and a decrease in bioacoustic activity in late summer (Fig. 2).

4. Discussion

Using several autonomous monitoring technologies improved our understanding of the ecological community in wetlands and could enhance GRYN's ongoing amphibian monitoring program. GRYN's visual encounter surveys provided a snapshot of wetland biodiversity, namely 3 of 4 amphibians (and 1 reptile). By investing some additional effort, we also documented avian species (via cameras, and a proxy for avian diversity using audible sound) and several mammalian taxa (via cameras, ultrasonic recordings) in the same wetlands. We detected 7 of 10 bat species documented by Keinath (2005) and also recorded California myotis, contributing to an important knowledge gap (Mas et al., 2021).

Autonomous monitoring technologies are non-invasive and can collect data over large temporal and spatial scales, potentially simultaneously (e.g., Blumstein et al., 2011). Deploying wildlife cameras and acoustic recorders required us to return to the sampled wetlands more often (4 times during the summer) than would occur following GRYN's monitoring protocol (1 visit), but we collected data at these sites for a

Table 2
Total number of calls identified for each bat species recorded at 4 permanent wetlands (Fig. 1C) during the early and late summer 2017 (Table 1), Grand Teton National Park, Wyoming; number of calls can be used as a proxy for relative activity. To standardize effort, we summarized only the first 3 days of each sampling period. Due to equipment anomalies, we did not collect ultrasonic data at 2 sites during the late summer (4783-68, 4817-12). We recorded big brown bat (*Eptesicus fuscus,* EPFU), hoary bat (*Lasiurus cinereus,* LACI), silver-haired bat (*Lasionycteris noctivagans,* LANO), California myotis (*Myotis californicus*, MYCA), western small-footed myotis (*Myotis ciliolabrum*, MYCI), long-eared myotis (*Myotis evotis*, MYEV), little brown myotis (*Myotis lucifugus*, MYLU), and long-legged myotis (*Myotis volans*, MYVO). Sonobat classified only a few recorded calls to 2 species (pallid bat, *Antrozous pallidus*, Yuma myotis, *Myotis yumanensis*); we did not include these in the species tally, given the small number of calls and that these species are less likely to be present in GTNP.

Early summer								
Wetland	EPFU	LACI	LANO	MYCA	MYCI	MYEV	MYLU	MYVO
3504-1	1	4	1	1	2	43	644	11
3726-3	4	5	5			1	4	
4783-68	13	58	26			7	67	3
4817-12						1	6	
Late summer								
Wetland	EPFU	LACI	LANO	MYCA	MYCI	MYEV	MYLU	MYVO
3504-1	66	115	320	2	3	47	153	5
3726-3	2	5	32			4	22	

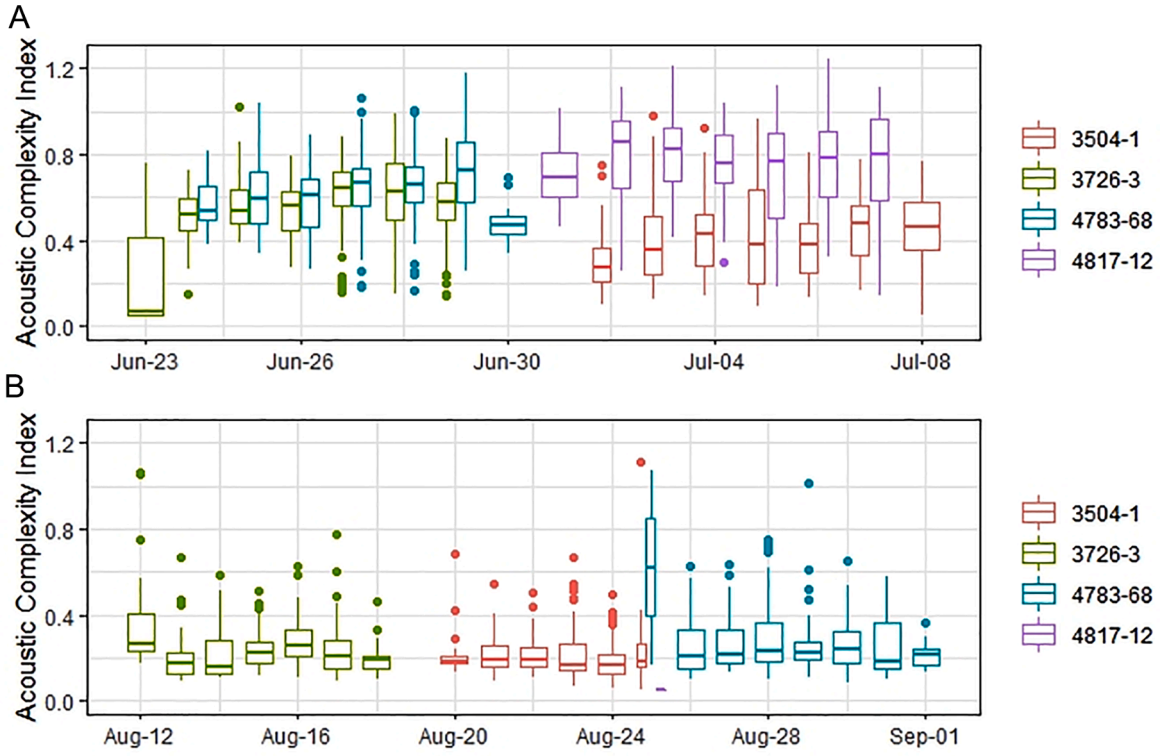

Fig. 2. Daily variation (median [line], first and third quartiles [boxes], 1.5 inter-quartile range [whiskers], and outliers [points]) in the acoustic complexity index (ACI) during **A)** early and **B)** late summer 2017 for 4 permanent wetlands, identified by catchment and wetland number, Grand Teton National Park, Wyoming (Table 1, Fig. 1C). We used ACI to summarize bioacoustic activity of the avian community. Acoustic equipment malfunctioned at wetland 4817-12 (purple) such that sampling occurred for only 1 day during the late summer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

longer time period, which could allow for additional insights. Despite relatively modest sampling effort, we documented changes over the summer in the species using these wetlands and the degree of activity (e.g., Table 2, Fig. 2). We also recorded seasonal changes in wetland size, water depth, and vegetation cover in camera images (Supplementary Information), with a finer temporal resolution than possible with annual site visits. Data from autonomous monitoring technologies also can be used to estimate occupancy or abundance, accounting for imperfect detection (MacKenzie et al., 2002, Marques et al., 2013), and insights can extend beyond the focal species (e.g., anthropogenic noise to study human activity patterns, Pimm et al., 2015). These tools can provide baseline information and be expanded over space and time to address questions related to climate change and other threats.

The ability to collect data without being on-site is an appealing quality of autonomous monitoring technologies, but substantial effort is still required. With current technology, monitored sites must be visited at least twice (once for equipment deployment and again to retrieve equipment) and potentially more often to maintain functionality. In addition, equipment can malfunction and result in data loss. The costs associated with equipment can be high, but more cost-effective models are increasingly available (e.g., Hill et al., 2018). The abundant data collected also require specialized software and extensive effort and expertise to process, store, and archive files. Increasingly, software packages include algorithms that automatically recognize potential

detections and identify species (e.g., Sonobat, Kahl et al., 2021). These algorithms help reduce processing time and effort, but are subject to errors and ambiguous results, often still requiring at least some manual verification or appropriate statistical modeling frameworks (e.g., Wright et al., 2020). Regardless of the approach, training is needed to ensure proper use of software and statistical analyses and a clear understanding of limitations.

5. Conclusion

Despite the importance of wetlands, there is a surprising lack of information on the diversity of species using these ecosystems. GRYN's monitoring program is filling that gap for amphibians, and our work demonstrates the utility of autonomous monitoring technologies to increase the breadth of the biological community sampled and document ecological patterns not possible with current survey efforts. No single survey method can detect all taxa or provide all of the insights gained by complementary tools. Decisions about which tools to employ given limited resources lead to inherent tradeoffs (e.g., number of tools versus sample size: breadth versus depth of insights) that must be informed by the specific monitoring objectives and priorities. Ultimately, integrating multiple, complementary methods will result in monitoring plans that are sustainable, in terms of cost and feasibility, and meaningful, in terms of ecological features that can be tracked as conditions change.

CRediT authorship contribution statement

Mary L. Levandowski: Conceptualization, Formal analysis, Investigation, Writing – review & editing, Funding acquisition, Project administration. **Andrea R. Litt:** Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Funding acquisition, Supervision. **Megan F. McKenna:** Formal analysis, Writing – review & editing, Visualization. **Shan Burson:** Formal analysis, Resources, Writing – review & editing. **Kristin L. Legg:** Conceptualization, Resources, Writing – review & editing, Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108205.

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