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Using long-term citizen science data to understand distribution and habitat use of an irruptive species

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ABSTRACT

Unpredictable movement patterns of irruptive migrants make them difficult to study through structured survey methods. We used citizen science data to assess the distribution and habitat usage of an irruptive migrant outside its core area of occurrence. We curated 50 years of citizen science data on Red crossbills (*Loxia curvirostra*) in Arkansas and field observations to 1) assess their distribution and habitat use outside their core area of occurrence, 2) determine if Red crossbills breed in Arkansas, 3) characterize the occurrence and abundance of Red crossbills in Arkansas, and 4) identify "call types" or ecotypes of Red crossbills present in Arkansas during 2017–18 irruption. We constructed a sample bias-corrected species distribution model using elevation, land cover type, and monthly temperature and precipitation as predictors for MaxEnt algorithm. The most significant predictors of Red crossbill distribution were land cover type, elevation, and precipitation of October. The probability of Red Crossbill occurrence was high in developed areas, areas with large water bodies, open areas, and evergreen forests. Red crossbills were found to breed in Arkansas based on field observations and historical records. The time-series captures the major irruption years within last 50 years in Arkansas. It also depicts months when the probability of finding Crossbills in Arkansas is highest. In addition, we documented four "call types" or ecotypes of Red crossbills in Arkansas, including type 1 and 4 that were previously unreported. Our study illustrates utility of citizen science observations for understanding the occurrence, distribution, and habitat use of difficult to study nomadic species.

1. Introduction

Nomadic and irruptive species are especially difficult to study (Runge et al., 2015; Woinarski et al., 1992). They exploit resources that vary greatly in abundance and distribution from year to year (Koenig and Knops, 2001), and they seldom stay in the same area long enough for detailed study. Moreover, irruptive species are hard to follow because band recoveries for these species are few, most species are too small for currently available satellite trackers, and radio tracking is logistically difficult at high latitudes (Newton, 2006). There are survey programs designed to collect count-based data across large geographic areas (e.g. North American Breeding Bird Survey [BBS]; (Sauer and Link, 2011)), and work well for species that have predictable movements or are faithful to specific sites at regular times of the year. However, these programs are less useful for nomadic and irruptive species for which we have less knowledge (MacKenzie et al., 2004; Thompson, 2013). Consequently, other sources of information, including that scattered widely in the ornithological literature, have been used to characterize the movements and distributions of nomadic and irruptive species (Newton, 2006). Increasingly, citizen science data is used to supplement the existing ornithological literature to elucidate the distribution and habitat use of various species (Bradter et al., 2018; Robinson et al., 2018), and could prove useful for nomadic species especially in regions outside their core area of occurrence.

Repositories of observations made by citizen scientists are increasing in size and scope. eBird, 2020 (https://ebird.org) is currently the largest citizen science repository, with over one billion observations and growing. These big datasets can be further combined with information in state-level bird records and structured surveys such as BBS (Sauer and Link, 2011) and Christmas Bird Count [CBC] (Link and Sauer, 1999) for better insight. Although data from eBird and other data bases are not without limitations (Geldmann et al., 2016), they can be deployed in

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presence-only species distribution models (SDMs; Elith et al., 2006, Phillips et al., 2006, Elith and Leathwick, 2009). SDMs relate environmental variables to species occurrence records to help predict habitat suitability across large scales (Elith and Leathwick, 2009).

Here we used three sources of citizen science data (eBird, CBC, and Arkansas bird records database) to further our understanding of Red crossbills (*Loxia curvirostra*) distribution and habitat use in Arkansas, which is outside their core zone of occurrence and where our knowledge of this species is limited. Red crossbill is an irruptive migrant that feeds year-round almost entirely on seeds that they extract from conifer cones (Benkman and Young, 2020; Newton, 2006). The North American Red crossbill complex is comprised of 10 "call types" or ecotypes (Types 1–8, 10, 11) that differ in vocalizations and morphology including bill size (Benkman, 1999; Groth, 1993; Young, 2011) and palate structure (Benkman, 1993, 2003; Benkman and Young, 2020; Irwin, 2010) with most of the call types specialized on a single conifer (Benkman and Young, 2020). Call type 9 was recently given species status, now Cassia Crossbill (*Loxia sinesciuris*), because of its genetic distinctiveness (Parchman et al., 2016) and strong and constant reproductive isolation (Benkman et al., 2009; Smith and Benkman, 2007). During the Red crossbill irruption in Arkansas in 2012–13, Type 2 (Ponderosa Pine crossbill), Type 3 (Western Hemlock crossbill), and Type 5 (Lodgepole Pine crossbill) were reported (Smith et al., 2015). Red crossbills have also been reported in Arkansas during other irruption years, as well as between the major irruption years (James and Neal, 1986; Smith et al., 2015). Our objectives were to: 1) create a SDM based on climatic, topographic, and vegetation variables to characterize their distribution and habitat use in Arkansas, 2) evaluate their breeding status in Arkansas, 3) characterize the occurrence and abundance of Red crossbill in Arkansas using 50-years of citizen science data, and 4) use sound recordings to identify call types of Red crossbills present in Arkansas during the 2017–18 irruption.

2. Methods and material

2.1. Species distribution modelling

We created a SDM for Red crossbills in Arkansas using MaxEnt. MaxEnt is a popular machine-learning algorithm for modelling species distributions because it is both easy to use and considered to produce robust results with sparse, irregularly sampled data, and minor location errors (Elith et al., 2006; Phillips et al., 2006). MaxEnt uses the principle of maximum entropy to relate presence-only data to environmental variables to estimate a species' niche and potential geographical distribution (Phillips et al., 2006; Phillips and Dudík, 2008).

We downloaded all georeferenced and verified observations of Red crossbill in Arkansas from eBird reported between 1970 and 2019 (number of observations [n] = 371) including observations submitted as complete checklists as well as incidental and historical records. To ensure that each survey occurred at a unique location, we filtered out multiple checklists from the same locations. We converted point observations into occupancy on a 1 km × 1 km grid using spThin (Aiello-Lammens et al., 2015) package in R (R Core Team, 2020) reducing the number of observations from 371 to 128 locations (Supplemental Fig. A.1). Most of the Red Crossbill observations on eBird were reported as incidental, hence, we used presence-only data to construct SDM.

We started with 22 raster layers (1 km^2 resolution) representing monthly minimum, maximum, and average temperature and monthly precipitation variables for the months of March, April, May, October and November (Fick and Hijmans, 2017), land cover types (NLCD 2016 Land Cover [CONUS] on https://www.mrlc.gov), and elevation (www.worldclim.com) to create a MaxEnt model (Table 1). We used the temperature and precipitation data for the months of March, April, May, October, and November only to examine if the observed crossbill distribution is related to climate variables that influence the seed production and seed fall in Shortleaf pine (*Pinus echinata*) and Loblolly pine (*Pinus taeda*) in Arkansas (Baker and Langdon, 1990; Cain and Shelton, 2000; Fowells, 1965; Yocom, 1971). Fall climate is more important for influencing the rate of seed release (Cain and Shelton, 2000). Using resampling, we changed the resolution of land cover data from 30 m to 1 km to match the resolution of other input layers. We used land cover data for 2016 for our model because less than 10% of presence locations showed change in land cover type from 1992 to 2016. We verified land cover change from 1992 to 2016 by extracting and comparing land cover type for all Red Crossbill presence locations (n = 128) for 1992 land cover data (https://gis.arkansas.gov) and 2016 land cover data (https://www.mrlc.gov). Most of the presence locations reported before 1992 lie either in national forest, state park, or cities which likely might not have undergone land cover change till 1992.

Table 1
Environmental predictor variables used to develop species distribution models for Red crossbill (*Loxia curvirostra*) in Arkansas using occurrence records derived from citizen science occurrence data.

Environment Predictor	Description
Land cover type	Data on land cover of Arkansas at a 30 m resolution with a 16-class legend based on a modified Anderson Level II classification system.
Elevation	Elevation in meters from sea level
Monthly minimum temperature	Monthly minimum temperature (°C) for March, April, May, October and November.
Monthly maximum temperature	Monthly maximum temperature (°C) for March, April, May, October and November.
Monthly average temperature	Monthly average temperature (°C) for March, April, May, October and November.
Monthly precipitation	Monthly precipitation (mm) for March, April, May, October and November.

Land cover data was downloaded from The Multi-Resolution Land Characteristics (MRLC) consortium (https://www.mrlc.gov) and all other environment predictor datasets from Worldclim (http://www.worldclim.org) defined for the years 1960–1990.

We accounted for sampling bias in eBird data by using targeted group sampling, a background point (or 'pseudo-absence') manipulation approach, which supplies designated background points selected from presence observations of related species collected using similar methods and with the same spatial bias as the focal species (Dudík et al., 2005; Phillips et al., 2009). That is, if background and presence points share the same sampling bias, then MaxEnt can identify ecological variables that differ between the two, rather than highlighting more heavily sampled regions (Phillips et al., 2009). To estimate sampling bias using target group species, we downloaded the coordinates of all verified complete checklists reported to eBird in Arkansas between 1970 and 2019. By using full checklists, we assume observed Red crossbills would have been reported as present. Even though the absence of an observation does not necessarily imply the absence of a bird, these checklists reasonably reflect sampling bias and can serve as appropriate background points. We used kernel density estimation to estimate sampling bias. We imported the resulting sampling bias raster into MaxEnt via the bias grid option. We used this bias grid with 10,125 points for background data.

We generated the SDM with the greatest predictive accuracy, measured as model performance using the area under the receiver operating characteristic curve (AUC-ROC curve) (Hanley and McNeil, 1982; Phillips et al., 2006). We also analyzed the jack knife plots, the variable importance, and variable response curves, and visual predictions generated by MaxEnt to ensure that our results were reasonable given the life history of Red crossbills. We prepared the occurrence data and bias file using R (R Core Team, 2020). We carried out modelling using the graphical interface of MaxEnt v 3.3.3 k (Phillips et al., 2006; Phillips and Dudík, 2008).

2.2. Field observations and historical data on breeding

During our field visits in 2017–2018, we also observed the behavior of the birds to look for any possible signs of breeding including evidence of nests or nest building, fledglings being fed, or adults accompanying dependent immatures. In addition, we collated information on breeding behavior reported on eBird or Arkansas bird records database (Arkansas Audubon Society, 2015; www.arbirds.org/aas_dbase.html) maintained by Arkansas Audubon Society by citizen scientists from 1970 to 2019.

2.3. Citizen science data to characterize occurrence and abundance in Arkansas

We compiled data on Red crossbills reports throughout Arkansas using volunteer-led structured surveys and opportunistic reports by citizen scientists from 1970 to 2019. The compiled data primarily came from three databases: Arkansas bird records database ($n = 210$), CBC ($n = 17$), and eBird ($n = 371$; the same eBird data downloaded for SDM; see section 2.1). To account for inaccuracies caused by incorrect identification, we limited eBird and Arkansas bird records database observations to those verified by regional reviewers. Using the three databases, we compiled raw abundance data for each month for the last 50 years to render a time-series of Red crossbill occurrence and abundance in Arkansas. To avoid overestimation of raw counts, we only selected one record from a unique location for each month, and we selected the record with the maximum number of individuals reported because our goal was to represent abundance of Red crossbill instead of only their presence or absence. We used CBC data for winters when Red crossbills were not reported on eBird or the Arkansas bird records database.

2.4. Sound recordings and field observation

From 2017 to 2018, we visited some locations of Red crossbills sightings from the 2012–13 irruption and Red crossbills sightings reported on ARBird listserv between 2017 and 18 to count the number of individuals and to record their vocalizations using Marantz PMD 661 digital recorder (Marantz, Japan), and Sennheiser MK66 or MK67 shotgun microphones with a Sennheiser K6 power module (Sennheiser Electronic, Germany). We made the recordings in stereo channel at 44.1 kHz sampling rate with an accuracy of 24-bit and saved them in lossless . wav format. We created spectrograms using Raven Pro 1.6.1 (Center for Conservation Bioacoustics, 2019) to visually identify call types.

3. Results

3.1. Red crossbill distribution model

Fig. 1a shows the probability of occurrence of Red crossbill for each 1 km × 1 km cell across Arkansas, after correcting for sampling bias. The most important environmental predictors were (in decreasing order) land cover type, elevation, and October precipitation (Table 2). The variable response curves (Supplementary Fig. B.1) indicated high occurrence of Red crossbill in habitats close to developed areas, open water, evergreen forest, and moderate to high elevation. The probability of their occurrence was higher in the areas where precipitation during the month of October was high (Supplemental Fig. B.1). Our MaxEnt model had a high AUC under ROC value (0.83).

3.2. Breeding status of red crossbill in Arkansas

Evidence of breeding was observed during field visits in 2016–2018. On 8 March 2016, a Type 2 female was observed feeding a fledgling (photograph available in Arkansas birds records) at Shores Lake, Ozark National Forest. On 7 Oct 2017, we recorded begging calls (chitoo call) of a fledgling Type 1 at Shores Lake, Ozark National Forest. On 10 Apr 2018, we observed a juvenile accompanied by an adult male and female

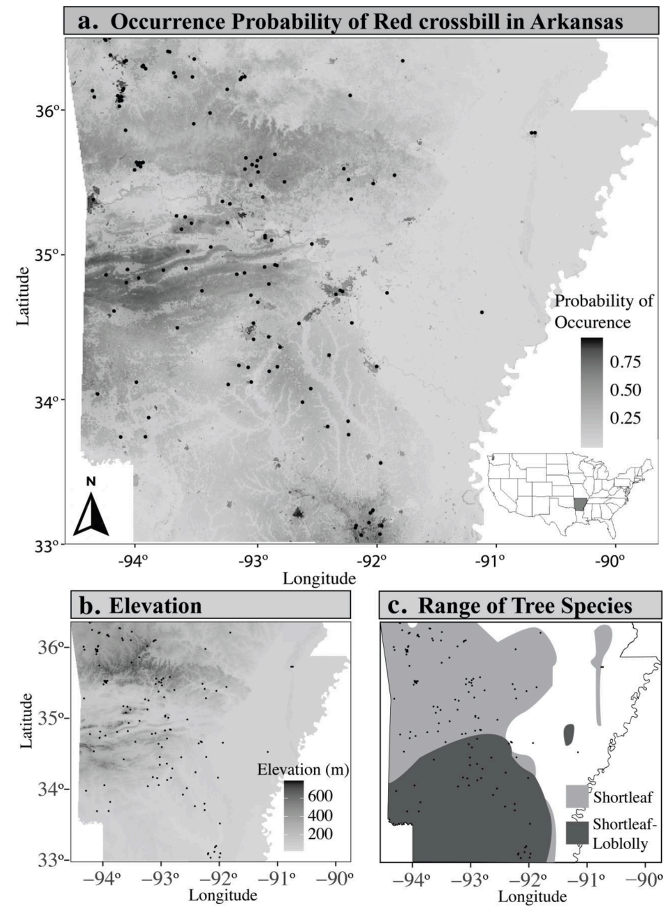

Fig. 1. (a) Bioclimatic species distribution map for Red crossbill (*Loxia curvirostra*) in Arkansas. Darker shades of grey represent higher probability of Red crossbill occurrence in any given 1 km × 1 km cell. Logistic outputs are shown in the above map. The black dots represent Red crossbill observations over last 50 years (1970–2019). (b) Depicts the elevation (m) for Arkansas and (c) represents the range of Shortleaf pine and Loblolly pine in Arkansas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Percent contributions for environmental predictors in species distribution model for Red crossbills (*Loxia curvirostra*) in Arkansas.

Environment Predictor	Percent contribution
Land cover type	62.3
Elevation	17.8
Precipitation in October	6.8

The variables with less than 4% contribution to the model were eliminated.

Type 2 at Fayetteville Country Club. The adults were relatively silent and motionless, as observed when parents accompany juveniles. Historical breeding observations reported juveniles being fed by adults, begging juveniles and juveniles accompanied by adults. These historical breeding records are from Ashley, Crawford, Dallas, Hot Springs, and Washington counties (Supplemental Table A.1.).

3.3. Red crossbill occurrence and abundance in Arkansas for last 50 years

Time-series of occurrence and raw abundance of Red crossbill in Arkansas for 50 years (1970–2019) is depicted in Fig. 2a. The probability of detecting Red crossbills was higher from November to May as

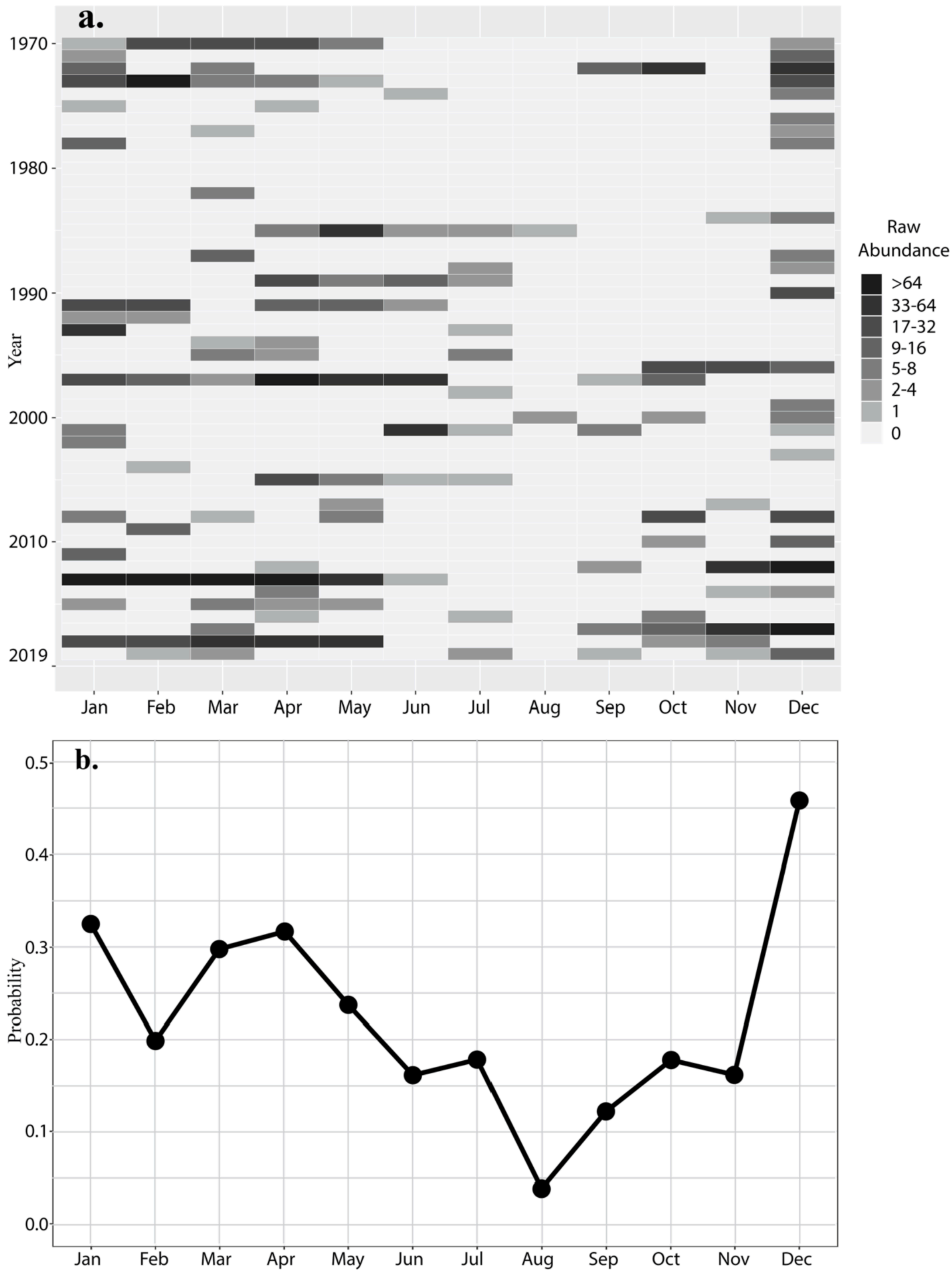

Fig. 2. (a) Raw counts of Red crossbills in Arkansas from 1970 to 2019 based on data from the Arkansas bird records database, eBird, and Christmas Bird Counts. The colour scale of raw counts is using logarithmic scale (logarithm to the base of 2). (b) Probability of detecting Red crossbills in Arkansas during any given month based on the 1970–2019 data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

compared to June through September (Fig. 2b). This time-series also captures the major irruptions of Red crossbill over the last 50 years: 1972–73, 1996–97, 2012–13 and 2017–18. Red crossbills were detected during at least one month in each of 44 of the 50 years.

3.4. *Red crossbill call types in Arkansas during 2017–18 irruption*

We recorded 4 call types of Red crossbill during the 2017–18 irruption: Type 1 (Appalachian crossbill; percentage of times when call type 1 was detected: 10%), Type 2 (Ponderosa pine crossbill; 80%), Type 4 (Douglas-fir crossbill; 25%), and Type 5 (Lodgepole pine crossbill; 10%) (Fig. 3, Supplemental Table A.1.). These were the first reports of types 1 and 4 in Arkansas.

4. Discussion

The well-documented and growing acceptance of citizen science projects in delivering useful data for research is associated with

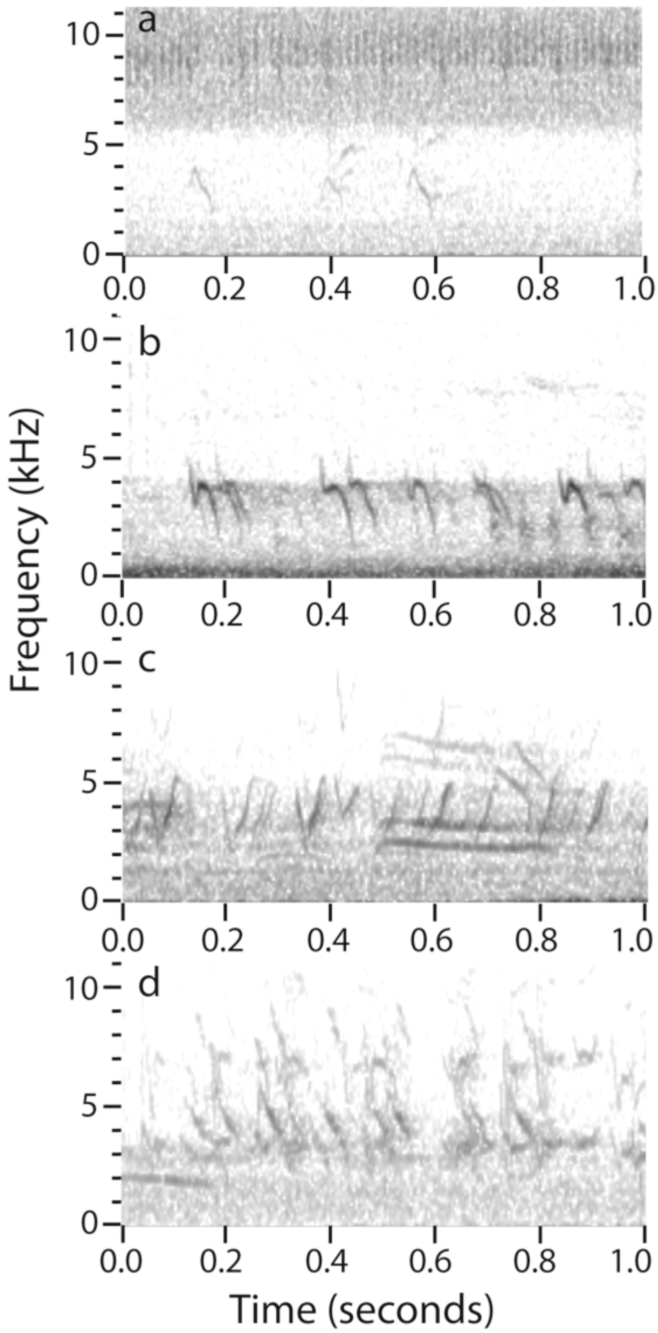

Fig. 3. Spectrograms of Red crossbill (a) Type 1 flight calls recorded on 07 Oct 2017 at Ozark National Forest Shores Lake Area, (b) Type 2 flight calls recorded on 29 Nov 2017 at Madison county Wildlife Management Area, (c) Type 4 flight calls recorded on 18 Dec 2017 at Hobbs State Park Visitor Center, and (d) Type 5 flight calls recorded on 17 Mar 2018 at Ozark National Forest Shores Lake Area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

incorporating more rigorous sampling techniques into unstructured data collection processes (Sullivan et al. 2014). In this study, we demonstrate the complex interplay between factors such as Land Use and Land Cover (LULC), elevation, and climatic variables associated with Red crossbill occurrence in Arkansas. Through this analysis, we established the distribution and habitat use by Red Crossbills outside their core area of occurrence, occurrence and abundance in past 50 years, breeding records, and call type diversity in Arkansas.

4.1. Red crossbill distribution model

Our model strongly suggests the importance of land cover, elevation, and October precipitation for predicting Red Crossbill occurrence. The probability of Red Crossbill presence was highest in developed areas, followed by areas with large water bodies, open areas, and evergreen forests. Given that most crossbills move into Arkansas presumably because of cone failures elsewhere rather than large cone crops in Arkansas, the importance of developed areas might reflect Red crossbills feeding opportunistically from the bird feeders (Benkman, 2016) and ornamental conifers. Many ornamental conifers are present as small woodlots or tree lines in relatively open areas such as golf courses or city parks. These ornamental conifers or native conifers stands in relatively open areas such as grasslands or pastures might explain the sightings of Red crossbill in grassland or open land cover type. Red crossbills require access to open water daily (Benkman and Young, 2020), thus, explaining their association with waterbodies. The association to evergreen forest cover reflects their reliance on seeds in the cones of Shortleaf pine (*Pinus echinata*) and Loblolly pine (*Pinus taeda*) (Fig. 1c). Shortleaf pine has shorter cone scales making it easier for smaller Red crossbills types to access seeds at their base. In addition, Shortleaf pine often holds seeds through winter and into spring (Fowells, 1965; Yocom, 1971), whereas Loblolly pine sheds most of its seeds by December (Baker and Langdon, 1990). Thus, Shortleaf pine is more likely to support crossbills in winter and spring than would Loblolly pine (see Benkman, 1993; Mezquida et al., 2018). The positive association with October precipitation in the model is consistent with moist conditions during and after cone opening (Cain and Shelton, 2000) delaying seed shedding and providing seeds over a longer time period for crossbills (see Mezquida et al., 2018). This reflects a greater likelihood of seeds being held in the cones through winter as October is often the period of greatest release of seeds from a cone (Cain and Shelton, 2000) quite similar to spring temperature and moisture for Scots pine (Wright et al., 2020). The model also suggests a higher probability of finding Red crossbills at high elevations (Fig. 1b), which is where Shortleaf pine is most common (e.g., high elevation ridgetops of the Ozarks and Ouachita mountains).

4.2. Abundance and breeding in Arkansas

Our observations support breeding in Arkansas during irruption years. Crossbills are known for their opportunistic breeding behavior (Benkman, 1990; Hahn, 1998), and they are known to breed outside their core area of occurrence during irruption years (Newton 1972). Although, no Red crossbill nest has been observed in Arkansas, the Arkansas bird records database contains several historical records suggestive of breeding (Supplementary Table A.2). Our breeding observations in 2017–18 irruption year and historical records, some even from years with no major crossbill irruption, indicate Red crossbills have bred in Arkansas during both irruption and non-irruption years.

The temporal pattern of citizen science observations and breeding records of Red crossbills suggest that Red crossbills are more common during the months of December and January in Arkansas (Fig. 2b). After December the number of seeds present in pine trees decline rapidly with almost all of the seed fall occurring by April (Lawson and Kitchens, 1983). The decline in seeds in the cones reduces food resources available to crossbills (Benkman, 1987; Mezquida et al., 2018; Summers et al., 2010), which presumably causes many of the crossbills to move out of Arkansas. However, multiple breeding observations throughout the year, some during non-irruptive years, along with crossbills being detected in 44 out of 50 years (Fig. 2a) suggests that some individuals might remain in Arkansas for more than a year (Supplemental Table A.2.).

4.3. Call types in Arkansas

Type 2 was the most common and widespread call type during the

2017–18 irruption. The pervasiveness of individuals of Type 2 may be due to their capability to efficiently extract seeds from a greater range of cone sizes and hardness (Benkman, 1993; Groth, 1993). This period also followed a large-scale cone failure of ponderosa pine (*P. ponderosa*) after several years of large cone crops and extensive breeding in the southern Rocky Mountains (C. Benkman, pers. comm.). We observed several flocks of Type 2 foraging in Shortleaf pines in Arkansas. The next most common call types were types 4 and 5 followed by Type 1. Type 1 is most regular in the Appalachians (Young et al., 2011) ~1300 km to the east of Arkansas. Type 2 and 5 were present during both 2012–13 (Smith et al., 2015) and 2017–18 irruption, whereas Type 3 was present only during 2012–13 irruption. Type 1 and 4 were reported for the first time in Arkansas in 2017–18 irruption. This difference between two consecutive irruption years may indicate that different call types rely upon different conifers whose cone crops are not synchronous.

5. Conclusion

For irruptive species such as Red crossbills, collection of data on their distribution and habitat use outside their core area of occurrence has often been considered a challenge. In this study, we were able to generate a SDM using 50 years of citizen science data to infer Red crossbill distribution and habitat use in Arkansas. The SDM highlights the importance of developed areas and presumably their associated bird feeders and ornamental conifers, access to open water, and native pine forests, as occurs in the Ozarks and Ouachita mountain ranges, for providing resources for Red crossbills during periods of food scarcity in their core area of occurrence.

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.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2021.101377.

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