Using bioenergetics and radar-derived bird abundance to assess the impact of a blackbird roost on seasonal sunflower damage

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Abstract: Methods aimed at reducing avian damage to agricultural crops are routinely implemented in situations where efficacy can be assessed by quantifying blackbird (Icteridae) abundance relative to environmental variables and extrapolating to ensuing crop damage. Concomitantly, Weather Surveillance Radar (WSR) data may have potential to enhance crop damage mitigation through improved monitoring of nuisance wildlife populations. We used WSR to derive daily abundance estimates of blackbirds at a fall roost in North Dakota, USA from 2012 to 2019. We integrated these estimates with previously developed bioenergetics-economic models to estimate local sunflower (*Helianthus annuus*) damage. The greatest losses usually occurred during a brief period in October, when peak blackbird abundance coincided with large percentages (>50%) of mature but unharvested sunflower fields. Most sunflower fields were harvested later than peak blackbird abundance (360,000–1,120,000 birds) and maximum daily damages ($900–$2,000 USD per day). This seasonal trend suggests advancing harvest time as a strategy to avoid the greatest losses in yield (up to $1,800 in savings at this 1 roost), which may be attainable by earlier planting of early-maturing crop varieties or crop desiccation.

Key words: aeroecology, autumn migration, blackbirds, crop damage, *Helianthus annuus*, human–wildlife conflict, Icteridae, North Dakota, radar monitoring, roost, sunflowers

Blackbirds (Icteridae) damage rice (*Oryza sativa*) in the southern United States, sunflowers (*Helianthus annuus*) in the Northern Great Plains, and field and sweet corn (*Zea mays*) across the continent (Linz et al. 2017). This damage results in national crop yield loss from blackbirds estimated at $100 million USD per year for corn and sunflowers (Linz and Hanzel 1997, Klosterman et al. 2013) and $13.4 million USD for rice (Cummings et al. 2005). National annual damages to corn were estimated to be $25 million USD in 1996 (Wywialowski 1996), while North Dakota, USA experiences a yearly average loss of $1.3 million USD (Klosterman et al. 2013).

Sunflower is a minor crop nationally. However, North Dakota is one of the leading states in the nation's sunflower production, with an estimated annual crop yield loss due to blackbirds to be $3.5 million USD per year (Klosterman et al. 2013), while total economic losses, including job loss, average $18.7 million USD per year (Ernst et al. 2019). Wildlife damage has deterred sunflower growers from planting in areas with abundant blackbird roosting habitat (i.e., cattail marshes [*Typha* spp.]; Kleingartner 2003). Although various factors influence whether producers will plant sunflowers, overall sunflower hectarage will likely trend downward without effective management strategies to reduce blackbird damage (National Sunflower Association 2010, Klosterman et al. 2013).

Currently, estimates of blackbird damage to sunflowers are not collected on an annual basis (Klosterman et al. 2013). Surveys of field damage at broad scales are both labor-intensive and

Figure 1. Blackbirds (Icteridae) flocking at a cattail (*Typha* spp.) marsh bordered by a sunflower (*Helianthus annuus*) field in North Dakota, USA (*photo courtesy of U.S. Department of Agriculture, A. Schumacher*).

difficult to achieve in a timely fashion because data must be collected in the short period between peak damage and harvest. Bird damage to sunflowers takes place over an approximate 8-week period from "seed-set" (i.e., anthesis), usually from mid-August to harvest in mid-October (Cummings et al. 1989). Crop damage is the greatest near roosts, where damage often exceeds 20% yield loss as opposed to ≤2% in fields further from roosts (Klosterman et al. 2013). Significant crop damage is usually found within 8–10 km of a wetland roost (Dolbeer 1990, Linz and Hanzel 1997), corresponding to the daily average foraging distances for pre-migratory blackbirds (Dolbeer 1990, Homan et al. 2005). Therefore, broad-scale damage surveys may not represent the severity of damage hotspots near roosts where economic impacts to producers are the most extreme.

An inexpensive and reliable method for estimating abundance and seasonal timing of blackbird aggregations would be useful for producers and managers interested in reducing blackbird depredation of agricultural crops (Figure 1). Peer et al. (2003) created a bioenergetics model to estimate regional-scale damages to sunflowers that was based on the North American Breeding Bird Survey June population estimates of blackbirds (Sauer et al. 2017). Although the method developed by Peer et al. (2003) is effective at estimating regional damage estimates, an understanding of the abundance and distribution of blackbirds over the damage period, as influenced by migration and flock aggregations, remains elusive. Currently,

the main method to count post-reproductive blackbirds in the fall is field surveys, which have logistical and labor constraints when scaled-up over space and time. In addition to these constraints, field observer roost counts typically lack validation (e.g., replicate independent counts), and ground observer data do not reflect true detectability when expansive roosts are spread across large cattail swaths (Arbib 1972).

The Next-Generation Weather Radar (NEXRAD) system is a potential alternative to field observer counts that could be used to remotely and retroactively estimate blackbird numbers. The NEXRAD is primarily used for forecasting and monitoring weather; however, it has been successfully used to estimate abundances of airborne species such as birds, bats, and insects. Recently developed methods in aeroecology have allowed for biological scatterings of radar to be translated into estimates of numbers of birds (or other airborne species) in an airspace (Gauthreaux et al. 2007, Chilson et al. 2012*a*, Kelly et al. 2012, Stepanian and Wainwright 2018, Bauer et al. 2019). The NEXRAD has been used to evaluate wildlife conflicts at wind turbine sites (Desholm et al. 2006) and airports (Phillips et al. 2018) but has yet to be used for evaluating bird damage to agriculture. Identifying roosts on radar could allow for estimates of local damages and discovery of trends in bird abundances that managers can use to optimize timing and deployment of management techniques.

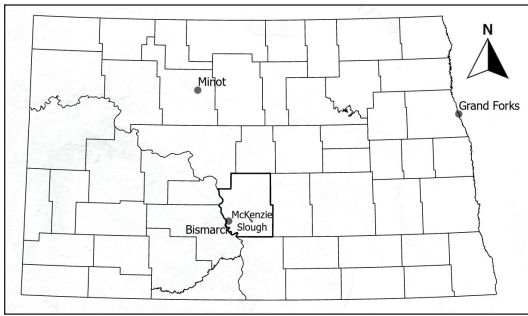Communal roosts can be comprised of a vari-

Figure 2. A map of North Dakota, USA with the location of the 3 NEXRAD sites (Bismarck, Minot, and Grand Forks), where we used Weather Surveillance Radar to derive daily abundance estimates of blackbirds (Icteridae) at a fall roost (McKenzie Slough).

ety of Icteridae species including red-winged blackbirds (*Agelaius phoeniceus*; RWBL), yellow-headed blackbirds (*Xanthocephalus xanthocephalus*; YHBL), common grackles (*Quiscalus quiscula*; COGR), brown-headed cowbirds (*Molothrus ater*; BHCO), Brewer's blackbirds (*Euphagus cyanocephalus*; BRBL), rusty blackbirds (*E. carolinus*; RUBL), and a species in Sturnidae, European starlings (*Sturnus vulgaris*; EUST). Although the numbers of many of these blackbird species are declining nationally, RWBL breeding populations are continuing to rise (>1.5% per year) in the Prairie Pothole Region (Sauer et al. 2017). The main species that feed on sunflowers in the Northern Great Plains are RWBL, YHBL, and COGR (Sedgwick et al. 1986, Cummings et al. 1989). These species also make up the majority of blackbird flocks roosting in cattails during the autumn in North Dakota (Homan et al. 2005). We examined whether one of these roosts could be monitored using a NEXRAD weather radar.

The NEXRAD data were publicly available with an ~25-year historical record (National Oceanic and Atmospheric Administration [NOAA] 2019) that can be examined to evaluate changes over time. It is the only survey method with an archive that can be used to evaluate historical blackbird populations, is available 24 hours per day, and allows estimation of bird abundance in the nonbreeding season. The network of NEXRAD is comprised of 148 radars across the United States (NOAA 2019). If roosts with known species compositions can be monitored with radar, bird numbers could be calculated and used to estimate the dynamics of blackbird roosts and the potential crop damages

in surrounding landscapes. Additionally, radar could be used to gather unbiased blackbird population estimates in multiple years before and after the implementation of management efforts, reducing the need for field observations, at a significant cost savings. Radar cannot detect species composition but can remotely gather unbiased estimates of abundances; thus, cross-referencing with online bird monitoring sites (eBird; Sullivan et al. 2009) or field observations are still needed for explicit species composition.

The main objective of this study was to present a method to estimate potential sunflower damage using radar-derived bird abundances for 1 roost and previously developed bioenergetics models. With sufficient radars distributed across the landscape, migration patterns and seasonal changes to the abundance and distribution of blackbirds could be monitored to inform both their conservation and effective management of human–wildlife conflict across the annual cycle. Our aim is to enable agriculturalists to assess and respond to damage at a landscape scale (i.e., coordinated early planting with neighbors and desiccation) and to improve the seasonal timing of tool deployment (i.e., hazing, evading strategies, habitat management, and chemical repellents) during the autumn damage season (Klug 2017).

Study area

A blackbird mega roost in the McKenzie Slough in North Dakota was routinely detected on the Bismarck radar (KBIS) from 2012 to 2019. The focal roost at the McKenzie Slough (UTM 388388.58 E, 5188115.17 N, Zone 14T) was approximately 12,000 ha, located ~20 km from Bismarck, North Dakota (Figure 2). This area within the Northern Glaciated Plains of the Prairie Pothole Region is a large complex of shallow wetlands with cattail sloughs and open water pocking the landscape (resembling potholes), grassland prairie, and surrounding agricultural crops, including small grains, sunflowers, corn, and soybeans (*Glycine max*; Johnson et al. 2005).

During the fall, sunflowers in the Prairie Pothole Region provide an ideal high caloric food source for pre-migratory blackbirds that need to store energy as fat (Linz 1982). In particular, sunflower seeds provide a key food

source for RWBL, YHBL, and COGR (Sedgwick et al. 1986, Cummings et al. 1989), which typically make up the majority of roosting blackbird flocks in cattails (Shaaf 2003, Homan et al. 2005). Other blackbird species found in fall roosts can include EUST, BHCO, BRBL, and RUBL. Although these species generally contribute low percentages to species compositions of roosts, they can still be found in sunflower fields usually taking seeds from the ground (Besser 1978). Thus, the presence of these other species may not greatly bias the damage estimates given that they are usually minor contributors to a roost's abundance. Field observations in 2019 indicated RWBL comprised the majority of the roost's blackbird species, though we acknowledge other species were likely to be found at this site from 2012 to 2019.

Methods
Field observations

Confirmation that biological scatter detected by WSR was blackbird (or other airborne species) required "ground-truthed" observations (Gauthreaux and Belser 1998). We observed blackbirds at the McKenzie Slough during fall 2019 from mid-September to late October. Using the methods described by Meanley (1965) and Arbib (1972), we estimated the number of birds per minute as they departed the roost in flight lines or flocks. Observers worked in pairs and observations began near sunrise when the first flock emerged. One individual focused on counting blackbirds while the other recorded data from the primary observer, taking general note of the dominant blackbird species. During the morning roost exodus, the primary observer counted birds per minute in each flight line in an area with a radius of ~300 m. We counted birds using 5-minute intervals assuming that the number of birds per minute passing a reference point changed throughout the departure period. Counts ended when blackbirds no longer emerged from the roost and lasted between 30 and 90 minutes per morning.

NEXRAD estimates of blackbird abundance

We collected estimates of blackbird abundance at the McKenzie Slough using data from the KBIS WSR, one of the radars comprising the NEXRAD network of 148 WSRs oper-

ated by the National Weather Service (NOAA 2019). Data from NEXRAD were publicly available with a historical record of ~25 years as of 2020 (NOAA 2019). The KBIS radar located in Bismarck, North Dakota was the closest radar (~20 km) to the roost (Figure 2). With each sweep of the radar, it sampled the airspace in 720 0.5° azimuths at set elevation angles. Data for each elevation angle and azimuth were collected every 10 minutes or less (NOAA 2019). Each sweep of the radar produced information on the amount of returned signal (radar reflectivity) at each range gate (250-m-distance bins) along each 0.5° azimuth. The returned signal indicated the presence of objects in the airspace, which could be precipitation, birds, insects, and bats (Chilson et al. 2012b). This measure of how much transmitted power is returned to the radar is known as radar reflectivity factor (Z), commonly expressed in log units (dBZ; NOAA 2019). For reference, birds in flight, usually migrating or departing from a roosting site, will be detected with reflectivity factor values of <35 dBZ (Gauthreaux and Belser 1998). Reflectivity >35 dBZ are likely meteorological phenomena. We accessed KBIS radar data from Amazon Web Services and opened it using the Py-ART package (Helmus and Collis 2016).

We downloaded reflectivity data for August 1 through November 30, 2012–2019. For each day, we processed data beginning 1 hour before sunrise and ending 2 hours after sunrise for the area immediately surrounding the roost (575-km^2 area from ~1200–1500 UTC) to encompass morning roost dispersal (Meanley 1962). Our analysis is limited to reflectivity data from the lowest sweep collected by the radar (0.5°). Manual screening of radar data using NOAA's Weather and Climate Toolkit indicated that blackbirds did not fly above the area sampled by the 0.5° elevation sweep (i.e., ~90–670 m above ground level). Flight altitude may be a limiting factor in using WSR to detect blackbirds, and distances between WSR and roosts are necessary to consider when monitoring and measuring magnitudes of reflectivity (Kelly et al. 2012). Other known blackbird roosts located farther from the radar (>20 km) were not detected by KBIS. Visual screening of the radar data also confirmed that the focal roost near Bismarck was routinely detected by KBIS from 2012 to 2019.

We censored reflectivity from hydrometeors to focus on values from animals flying in the airspace. We separated meteorological data and non-meteorological data (biological) using the depolarization ratio (DR) described by Kilambi et al. (2018). Prior to 2012, KBIS did not collect the dual-polarized data needed to calculate DR. Therefore, we could not confidently separate reflectivity data from blackbirds and hydro-meteors (henceforth, weather) before 2012. Following Kilambi et al. (2018), we censored samples with DR values less than or equal to -12.5 dB as weather and assumed values greater than this cutoff were biological. We are confi-dent reflectivities >35 dBZ were not blackbirds or other biological matter but rather meteoro-logical abnormalities or super-refraction of the radar beam. Occasionally, super-refraction of the radar beam occurs, which will cause a false reflectivity measure of true biological masses in the airspace (van den Broeke 2019). Based on this filtering, we identified 15 total days between 2012 and 2019 with high radar reflectivity val-ues (>35 dBZ) in August and early September that we are confident are not blackbirds. We removed data from these days from our calcula-tions. There were also 20 days between 2012 and 2019 when KBIS was not operating and there were no reflectivity data.

To estimate the abundance of blackbirds at the roost, we summed the total biological radar echoes within the domain surrounding the roost (575 km^2). Other animals flying in this area would also be detected by radar. Based on visual observations in 2019, we were confident that most biological scatters were RWBL or other similar-sized blackbirds in this location. Because patterns observed by radar were similar in all years, we assumed all years were primarily RWBLs as observed on the ground in 2019.

Using an equation from Horton et al. (2019), we estimated the radar cross section (RCS) of a RWBL (15.5 cm^2) from the average mass of North Dakota birds (60 g, assuming 50% males [73.7 g] and 50% females [46.5g]; Linz 1982). The range of values for the average mass of male and female blackbirds will influence the RCS value and ultimately the calculation of the number of detected blackbirds (i.e., larger RCS = fewer blackbirds). In a roost comprised of more males, the average body size of the roost will be larger, resulting in a larger RCS, where the opposite would be the case for a roost comprised of more females. Furthermore, an increase in the number of males increases the percentage of diet comprised of sunflowers and therefore damages while a female-biased sex ratio will result in less damage. In this study, we assumed a 50:50 ratio of males to females (Mayr 1939). We also calculated damages based on 40:60 and 60:40 sex ratios because most wild bird populations will have sex ratios within this range (Mayr 1939).

Determining the best RCS of any species is difficult due to the lack of empirical measure-ments, among-individual variation in size, and variation in the orientation of the animal rela-tive to the radar. Horton et al. (2019) found a positive relationship between body mass of bird species and measured RCS (cm^2) as described by the equation: [(log10 (cross-section) = 0.670 (log10 (body mass)]. Using this value, we esti-mated the number of blackbirds in a radar sam-ple by dividing summed reflectivity by the RCS of a single blackbird.

Economic damage estimates from bioenergetics models

Using bioenergetics calculations from Peer et al. (2003), we converted radar-based esti-mates of blackbird abundance to annual eco-nomic damage estimates for the area surround-ing the roost (Table 1). We estimated damage as the sum of field metabolic rate divided by metabolic energy content of sunflowers and then multiplied by diet, moisture, compensa-tion, hull price, and the number of blackbirds derived from radar estimates (Appendix A). Peer et al. (2003) used a categorical method to account for seasonal change in compensation and metabolic energy content of sunflowers with 2 periods: 14 days following anthesis and 28 days where the crops were at or near maturity (Sedgwick et al. 1986). Anthesis (R6) is defined as the completion of flowering when ray pet-als are beginning to dry and wilt (Schneiter and Miller 1981). Sunflowers reach maturity (R9) when the sunflower head bracts become yellow and brown (Schneiter and Miller 1981).

During anthesis, the metabolic energy con-tent (MBE) of sunflowers is 15.28 kJ/g (Connor and Hall 1997), which is half the energy con-tent of mature sunflower achenes at 30.56 kJ/g (Park et al. 1997). We have accounted for this

Table 1. Values derived from the equation: [(FMR/MBE) * diet * moisture * compensation * hull * price] developed by Peer et al. (2003). We have given a brief explanation of values, which are further detailed in the supplemental information (Appendix A).

Component		Value	Source
Metabolic energy content of achenes (MBE)		15.28 kJ/g (anthesis)	Connor and Hall 1997
		30.56 kJ/g (maturity)	Park et al. 1997
Compensation		0.85	Baltezore et al. 1994
Constants	Field metabolic rate (FMR)	168	Peer et al. 2003
	Diet	0.63	Linz et al. 1984
	Moisture	1.225	Peer et al. 2003
	Hull	1.25	Peer et al. 2003

difference by incorporating a gradual linear increase of MBE values (15.28–30.56 kJ/d) from the beginning of anthesis to maturity by using the equation [15.28 + (15.28 * % mature sunflower fields)] to reflect the increase in energy content of achenes as they mature. Instead of separating plant growth stages into 2 periods, we modeled a gradual linear change in compensation based on the percent of sunflower fields in their mature stages using the equation [0.85 + (0.15 * % of mature sunflower fields)] to represent decreases in compensation as more fields approach maturity.

Percent of sunflower fields in differing growth stages in North Dakota is reported on a weekly basis by the U.S. Department of Agriculture, National Agricultural Statistical Service (USDA-NASS). The USDA-NASS (2020) reports sunflower growth stage based on planting date and growing degree days at a statewide level. Regional, county, or local data surrounding the roost were not available. Therefore, our damage estimates assumed that the sunflower growth stages in the area surrounding the roost were typical of the state average. Recorded data on sunflower growth stage was not collected from September 29 to October 20, 2013 because of a U.S. Government shutdown. We accounted for this by calculating an estimated gradual linear change between these dates in percentages of mature sunflower fields.

Using our estimates of blackbird abundances, availability of mature sunflowers, and potential economic losses, we evaluated overlap in bird and crop phenology, compared damage severity at different time periods, and calculated potential cost-saving with alterations in the timing of method implementation.

We compared the dates when we detected the maximum number of blackbirds at the roost to dates of peak mature sunflower to determine potential causal relationships. We calculated an annual estimate of damage that could have been avoided if producers had harvested their sunflowers 2 weeks earlier (theoretically by crop desiccation or planting early maturing varieties earlier in the spring). To determine damage potentially avoided with advanced harvest, we shifted the growth stage to reach maturity 2 weeks earlier. Because Cummings et al. (1989) indicated damage is worse in the early stages (i.e., >75% of bird damage in 18 days following anthesis), we wanted to evaluate if early damage was significantly different than late damage. Thus, we compared the accumulated damage each year between the early damage (18 days following anthesis) and late damage (an 18-day period centered on the peak of sunflower maturity) periods. We then calculated the differences between these 2 periods. All damage estimates are reported in USDs.

Results

At the McKenzie Slough roost, blackbird numbers and damage estimates routinely peaked in mid-to-late October, coinciding with the peak of mature yet unharvested sunflowers in all years except 2012. The range of maximum blackbirds was 346,845–1,076,140 (mean = 612,156 ± 87,653 SE) in mid-to-late October or occasionally the first week of November. The year with the largest detected maximum daily abundance was 2016 at 1,076,140 blackbirds in late October. In 2013 and 2019, we found the lowest maximum daily number of detected blackbirds at 346,845 and 451,613 in early
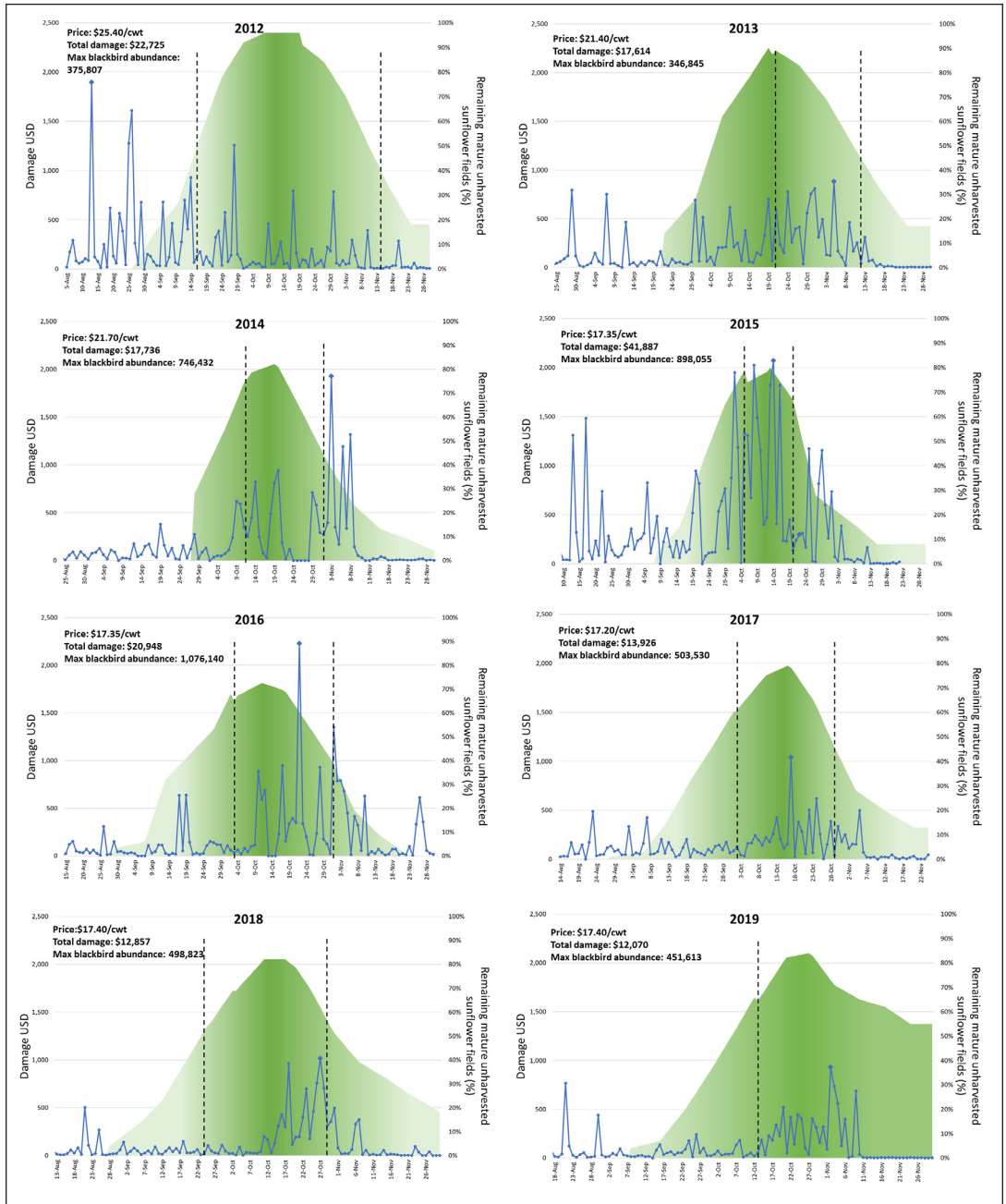
Figure 3. Annual timeseries of estimated daily damage to sunflower (*Helianthus annuus*) yields based on sunflower maturity, radar-derived blackbird (Icteridae) abundance, and bioenergetics calculations near the McKenzie Slough in North Dakota, USA (solid line) from 2012 to 2019. Each figure starts at the beginning of anthesis (R6), and the curve represents the percent of mature (R9) sunflower fields across the state. Mature sunflower fields decreased as fields were harvested, but we disregarded the number of harvested fields in our damage calculation. Dashed lines represent the beginning of sunflower harvest (left) and when 50% of the fields were harvested (right) statewide in North Dakota (except in 2019 when radar in-dicated migration prior to 50% harvest). The diamond on the solid line represents the maximum blackbird abundance at the focal roost (McKenzie Slough).

November, respectively. The radar counts had a positive correlation ($r = 0.7$) to our in-field estimates. We identified RWBL as the main species. Other species observed were COGR, YHBL, BRBL, and EUST. However, low-light conditions and estimated large number of blackbirds (>500,000) made quantifying species composition difficult, although we identified that RWBL were the dominant taxa. Daily observations in sunflower fields near the roost consisted largely of RWBL through late October.

We estimated that damage to sunflowers from blackbirds during 2012 to 2019 was greatest in 2015, when potential losses were $41,887 for sunflower fields near this 1 roost (Figure 3). All other years (excluding 2015) had a range of $12,070–$20,948 (mean = $16,839 ± 1,428 SE) for estimated damage. Damage estimates were highest in 2015 due to the large numbers of blackbirds detected early and persisting throughout the fall. We estimated blackbird numbers to be >300,000 birds in early August for both 2015 and 2012, which were on average 19 times higher than other years. Typically, blackbird numbers began to rise during the first week of October and reached maximum abundance by mid-to-late October when damages averaged $189/day (Figure 3). In 2015, the greatest daily average damage was $402/day while in 2018 and 2019 the lowest average daily damage was $116/day and $114/day, respectively.

If the sex ratio was 40:60, the average annual damage estimate (excluding 2015) was $16,007 (±1,358 SE), whereas if the sex ratio was 60:40 the damage was $17,691 (±1,501 SE). Compared to a 50:50 sex ratio, biased sex ratios changed the damage estimate by a about ±5% ($800).

On average, sunflower fields in North Dakota began anthesis (R6) on August 15 and started to become mature (R9) on September 7 from 2012 to 2019. On average, nearly all sunflower fields had reached maturity by October 19 in every year, with average harvest beginning on October 4. Mature fields that were yet to be harvested peaked on average on October 15. The maximum blackbird abundance detected at the McKenzie Slough roost averaged October 27 (disregarding 2012, an outlier, when maximum abundance was August 13). In 2012, sunflower fields exhibited earlier anthesis, maturity, and harvest, in addition to an earlier peak in blackbird abundance compared to other years. Timing of peak maximum blackbird abundance was moderately

well explained by timing of peak percent mature sunflower fields ($R^2 = 0.557$). The peak of sunflower maturity in North Dakota occurred in mid-October, coinciding with maximum blackbird abundance at the roost (Figure 3). Our estimated damages were on average 4 times higher during the 18-day period of peak maturity compared to the 18-day period following anthesis in every year except 2012. In 2012, blackbird numbers peaked during anthesis, where damages were 2 times higher than at maturity. Shifting sunflower growth stages to mature 2 weeks earlier would potentially reduce annual damage in surrounding fields of this single roost by $250–$1,800 (mean = $800 ± 160 SE).

Discussion

Integrating radar-derived blackbird abundance estimates with bioenergetics calculations developed by Peer et al. (2003) allowed us to estimate damages accumulated over the autumn season across multiple years. Our daily damage estimations are for an approximate 10 km radius area around the roost, which is the typical daily movement of blackbirds (Dolbeer et al. 1990, Linz and Hanzel 1997, Homan et al. 2005). We expected that daily economic damage estimated from bioenergetics models would be concentrated near the roost as suggested by Klosterman et al. (2013). Thus, these localized damage estimates may be more relevant to economic losses for producers with sunflower fields near large roosts but could be scaled up with the expansion of radar-based monitoring at broad scales. Although our study is at a single roost in North Dakota, an expanded radar network could be used to monitor bird populations known to damage other crops (e.g., corn and rice) across the continent.

Considering seasonal blackbird abundance and the energy content of sunflowers from anthesis to maturity, the potential economic damages surrounding our study roost were greatest after the peak percentage of sunflower fields reached maturity in North Dakota. The largest numbers of blackbirds (>100,000) overlapped the peaks in the percent of mature sunflower fields in North Dakota, suggesting birds may be aggregating to take advantage of this abundant food resource prior to migration departure. At the time of maximum blackbird abundance at the McKenzie Slough, most sun-

flower fields statewide remained unharvested; economic damage from blackbirds was likely severe at this time. One caveat of this interpretation is that data used for sunflower growth stages were based on the entire state, while this study focused on localized damage estimates near 1 roost (approximately <10 km). Specificity of damage estimates could be increased if local sunflower growth stage data become available.

Blackbird abundance and thus potential economic damages are severe in the mature stages just before harvest. Approximately $250–$1,800 (mean $800 ± 160 SE) of these damages could have been avoided if local growers harvested 2 weeks earlier and avoided the largest congregations of blackbirds. The strategy of evading damage by altering planting time to offset the synchronization of bird abundance and crop availability has been shown to be successful in reducing blackbird damage to sprouting rice during the spring migration (Wilson et al. 1989, Brugger et al. 1992). Our method of determining how much damage could be avoided if harvest were shifted earlier assumed that blackbirds would not alter their behavior in response to the timing of sunflower maturity. Although, in 2012, when both sunflower maturity and peak blackbirds were early, we saw the greatest savings with advancing sunflower maturity ($1,800).

Future analyses are needed to better understand factors driving changes in blackbird behavior and seasonal trends in abundance. With an expanded network, radar can be a method to understand continental-scale migration movements and aggregations of birds across the annual cycle (Chilson et al. 2012*b*), especially during spring and fall migrations when data are lacking (Marra et al. 2015). Specifically, how blackbirds respond to shifts in timing of crop growth, weather events, or climate change would be especially informative (Klug 2017). Future research evaluating blackbird behavior on spatially explicit landscapes would strengthen the understanding of how blackbirds disperse across the landscape and use crop fields relative to their roost locations across the damage season. Modelling this behavior could identify thresholds for percent of a landscape that needs to be synchronous in sunflower maturity to garner a benefit from advancing harvest without risking increased damage from attracting more blackbirds.

Our results are consistent with Cummings et al. (1989), who determined that sunflower damages were the most severe when blackbird numbers were the highest. However, the specific timing of this period differed between our study and Cummings et al. (1989). At the time of their study (1979–1982), the majority of bird damage was between August 15 and September 16, when sunflowers were in anthesis and when blackbird numbers were at their peak. We found that blackbird abundance at this roost peaked on average on October 27, coinciding with sunflower maturity in North Dakota and 70 days after the onset of anthesis, except for 2012 where blackbird abundance peaked 8 days after the onset of anthesis and early damage was 2 times late-season damage. The differences in chronology of blackbird abundances and crop damages compared to Cummings et al. (1989) may be accounted for by a combination of regional or landscape differences, improved crop hybrids, climate change impacting crop and bird phenology, and observation methods. These studies took place in different ecoregions with different landscapes (Lake Agassiz Plains vs. the Northern Glaciated Plains), and the composition of crops on the landscape and crop phenology are different today compared to 30 years ago (Johnston 2013, Klug 2017). Additionally, blackbird abundance and distribution may vary with blackbird migration phenology (Travers et al. 2015), which alters the timing of the breeding season, molt, and fall migration departure for each blackbird species.

The chronology of blackbird damages may have changed with changes in breeding and migration timing as a result of climate change. Temperatures in the Prairie Pothole Region have increased 3°C in the past 100 years (National Assessment Synthesis Team 2000), with significant increase in regional temperatures since the 1970s (Travers et al. 2015), while precipitation has decreased by 10% in some areas (National Assessment Synthesis Team 2000). Geographically isolated wetlands make up 88% of the wetlands in the Prairie Pothole Region and rely on precipitation, and the reduction of wetland areas may impact roost availability for blackbirds (Mitsch and Gosselink 2000, Dahl 2014). The change in climate conditions may consequently influence migration timing and the breeding season length (Van Buskirk et al.

2009). Van Buskirk et al. (2009) reported that RWBL in Pennsylvania, USA increased their intermigratory period (time from spring and fall migration) by >20 days from 1961 to 2006. In Fargo, North Dakota, Travers et al. (2015) found that RWBL (among other migratory birds) are arriving earlier in the spring compared to the 1970s. The shift of migratory timing and climate change in the last few decades suggest that the chronology of peak RWBL flocks could alter timing of blackbird damage locally.

Finally, our study differed from Cummings et al. (1989) in observation methods. During molt, blackbirds fly lower in August and early September (Linz et al. 2017). Thus, their lower flight height may result in reduced detections by radar and therefore radar abundance estimates could undercount numbers of birds near the roost. Populations later in the season (mid-to-late October) are in the hundreds of thousands, indicating that there are large aggregations of migratory and resident birds during this time (Bauer et al. 2019). Late-season aggregations may increase as more fields are harvested prior to migration. Blackbirds may leave smaller roosts and aggregate in a mega roost in the late fall before migrating in large numbers (Meanley 1971). Thus, birds may be more dispersed early in the season and not apparent on radar but still causing early damage. Further research is needed to compare methods and determine whether large numbers of blackbirds remain undetected by radar during molt. Our field observations of the roost in 2019 began in mid-September when the majority of blackbirds had completed molt (Linz et al. 1983, Twedt and Linz 2015, Klug et al. 2019).

Observations of blackbird abundance and flight height may give insight into the proportion of blackbirds detected on radar. This can strengthen our understanding of radar's utility to detect bird abundances for use in estimating economic damage estimates. The daily fluctuations in the blackbird numbers (based on radar sweeps) may indicate fluctuations in the blackbird population with waves of migration or may be an artifact of how radar samples the airspace and its ability to detect blackbird departure when behaviors such as timing, height, or size of groups vary. Thus, we emphasize the need for comprehensive studies that show the advantages and limitations of using radar to estimate flock abundances.

Radar can greatly reduce the need for in-field estimates of species abundance, yet a main caveat is that explicit species composition must be gathered from in-field observations or local knowledge. The YHBL migrates early in the fall season, often leaving the northern Great Plains in September, although they still contribute to crop damage before departing (Twedt and Linz 2015, Dolbeer and Linz 2016). In comparison, RWBL and COGR have later fall migrations (Linz et al. 1983; Klug et al. 2019). We suggest routine weekly observations at roosts of interest to strengthen the understanding of the composition of biological masses detected on radar. Damage estimates with varying blackbird species compositions can be calculated by simply modifying the RCS based on their body size and bioenergetics calculations. In our study, the McKenzie Slough roost had mostly RWBL, but knowing the species composition throughout the season could give more robust estimates of damages.

This study shows the potential future directions in using radar-derived counts of blackbirds to determine damage estimates surrounding roosts. More broadly, radar has the potential to be used for understanding populations of nuisance animals in human–wildlife conflicts. Monitoring wildlife with radar has been evaluated in wildlife collisions where identifying the presence of birds by radar can trigger shutting down wind turbines (Desholm et al. 2006) and diverting aircraft near airports (Phillips et al. 2018). As far as we know, our study is the first to evaluate uses of radar for monitoring agricultural damage from birds. Because radar provides consistent estimates and monitoring of biological masses in the airspace, it allows for more cost-effective assessments of the optimal seasonal timing of agricultural practices and deployment of wildlife damage management tools. With an expanded network of radars across North America, the future could see land managers accessing an application that predicts the real-time risk of bird damage based on the migration movements and aggregations of birds at broad continental scales.

Currently there are only 3 NEXRAD radars in North Dakota (Bismarck, Minot, Grand Forks). Other radars across the United States have the potential to monitor known blackbird roosts where the methods described in

this study could be applied to determine damages to sunflowers as well as corn and rice at stopover and overwintering sites. In addition to NEXRAD, mobile research radars provide possibilities for monitoring roosts that are not typically detected by KBIS. This system could allow for localized monitoring of blackbird roost numbers where the methods in this study could be used to gather daily estimates of blackbirds and crop damages. Another option would be to deploy mobile radars to strengthen the understanding of abundance trends of blackbirds at roosts where damage estimates could be useful for evaluating the efficacy of local management methods. On-demand systems could be developed to deploy autonomous tools (e.g., drones; Klug 2017) when radar identifies flocks entering protected areas (Ronconi and St. Clair 2006).

Management implications

Our analyses suggest that if sunflower producers within 10 km of this single roost had shifted harvest 2 weeks earlier, they may have saved up to $1,800 a year. We emphasize that a coordinated harvest with neighbors is important to avoid having isolated early-maturing or late unharvested fields that are likely to attract large numbers of birds. We found that potential damages are greatest when blackbirds reach their peak abundances, which for most years was during the mature stage of sunflowers. However, 1 year (2012) had more birds during anthesis, and thus potential damages were highest during this time. The variation in flock abundance and phenology at roosts identified on radar can aid managers and producers in testing management tools and methods by monitoring roosts before and after management implementation. Without a historical record of bird populations, it is difficult to ascertain if population responses are a result of management methods or natural variation in population abundance. Further examination of radar as a method for unbiased monitoring of blackbird abundance has the potential to enable more rigorous assessments of a variety of management tools (Linz et al. 2011).

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Appendix A.

Here we give a short explanation of the bioenergetics values, which we have derived directly from Peer et al. (2003), where their full determinations can be found. We took the average field metabolic rate (FMR) of red-winged blackbirds (*Agelaius phoeniceus*; RWBL), 168 kJ/d, derived from the Peer et al. (2003) determination that male and female red-winged blackbird FMR are 194 and 142 kJ/d, respectively. The metabolizable energy content (MBE) of sunflower achenes depends on their growth stage. From when petals are dry (anthesis), the MBE is 15.28 kJ/d (Connor and Hall 1997). However, as the sunflower approaches maturity, the energy content of sunflower achenes doubles to 30.56 kJ/d. Due to low energy content in the earlier growth stage following anthesis (petal drop), blackbirds would need to consume more to meet their metabolic requirements. In this growth stage, sunflowers can compensate more for losses and focus energy to achenes that are not damaged (Sedgwick et al. 1986, Peer et al. 2003). However, as these crops reach maturity, they are less able to compensate. Thus, Peer et al. (2003) separated the damage period into 2 periods: 14 days following anthesis and the subsequent 28 days where the crops were at or near maturity. Compensation during period 1 is 0.85 whereas in period 2 they removed compensation from the equation. Instead of separating plant growth stages into 2 periods, we have accounted for the change in compensation based on the percentage of sunflower fields in their mature stages using the equation [0.85 + (0.15 * % of mature sunflower fields)] to represent less compensation as more fields approached maturity and were unable to compensate for achene losses.

Constants derived from Peer et al. (2003) concerning the economic damage equation model included the proportion of sunflowers in diet, moisture of the wet mass of the sunflower achene, and the weight of the sunflower hull, which a producer is paid. For diet, we averaged the proportion of sunflowers for both sexes of RWBL diets to be 63%. Red-winged blackbird diets are comprised of 69% and 57% sunflowers for males and females (Linz et al. 1984). The moisture of the wet mass of the achene is 1.225 (Peer et al. 2003). The hull price that producers are paid is 1.25. Price of sunflowers varies annually by year, and the price received by farmers is reported by the USDA-NASS (2020). We gathered market prices from 2012 to 2019, corresponding with the years of collected radar data on bird abundances. The resulting economic loss calculation provides an estimate for damages from an individual bird. We used this estimation and multiplied it by the number of blackbirds derived from radar-based estimates.

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