An unseen synchrony or recurrent resource pulse opportunity? linking fisheries with aeroecology

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Hansen, Henry H.; Pegg, Mark; Van Den Broeke, Matthew; Watkinson, Doug; and Enders, Eva C., "An unseen synchrony or recurrent resource pulse opportunity? linking fisheries with aeroecology" (2020). *Papers in Natural Resources*. 1111.

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An unseen synchrony or recurrent resource pulse opportunity? linking fisheries with aeroecology

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Abstract
Understanding insect and fish interactions from a spatial and temporal perspective can have implications on large-scale phenology in freshwater systems, yet current information is limited. We employed a novel approach of combining information from acoustic telemetry for six freshwater fish species and weather radar to assess the phenology of mayfly emergence and foraging patterns of freshwater fish. We hypothesized that freshwater fish conduct synchronous movements with annual mayfly hatches as a pulse resource opportunity. Generalized additive models were developed to assess movement distance as a function of species and time; before, during, and after annual mayfly hatch events. A cross-section abundance index was also employed to quantify dynamics of aerial mayflies. Hatch dynamics revealed nocturnal emergence behaviour with annual variations in intensity, spatial extent, and origin. We found that the hatch was likely a pulse resource feeding opportunity for channel catfish, common carp, freshwater drum, and walleye instead of a synchronized feeding event. Bigmouth buffalo and lake sturgeon utilized riverine habitat away from the hatch and did not likely forage on the emerging mayflies. Remote sensing of fishes and emergent insects using our approach is the first attempt at bridging the capabilities of fisheries ecology and aeroecology to advance movement ecology.

Introduction
The arrival of spring initiates an annual sequence of multi-trophic level interactions in temperate-terrestrial ecosystems (Reinecke and Krapu 1986; Yarnell et al. 2010), but few studies have documented such interactions between emerging aquatic insects and fish in freshwater ecosystems (Thackeray et al. 2010; Brodersen et al. 2011). In terrestrial systems, the sequence starts with the germination of plants and emergence of insects, which are then followed by complex consumer and predator interactions at higher trophic levels. The phenology, or coupling of consistent timing and intensity of interactions, provides the blueprint necessary to fulfill life history demands of higher trophic level organisms (Visser et al. 2010). Phenological studies in terrestrial systems demonstrate that multiple taxa exhibit cyclical activities at spatial and temporal scales to access time-dependent resources (Thackeray et al. 2010). Migratory birds are the most widely recognized example of phenology where dependency on emergence of insects to complete life history demands is spatially and temporally specific (Richardson 1978, 1990).

Temperate freshwater systems also exhibit similar phenomena, but the knowledge gap regarding freshwater ecosystems and the phenology of higher trophic organisms persists due to the difficulty of quantifying fish and insect interactions from a spatial and temporal perspective. One of the challenges in investigating the potential linkage has been gaining a full understanding of both fish and insect behaviors. However, acoustic telemetry techniques have allowed fine-scale understanding of fish movement and ecology (Cooke 2008; Cooke et al. 2013;
Brownscombe et al. 2019). The wealth of telemetry data available has initiated a wave of applied and fundamental research produced under an interdisciplinary umbrella (Donaldson et al. 2014; Abecasis et al. 2018). Coupling fish behavior with timing of insect emergence is one such possibility. Remote sensing of insects via radar is a cutting edge technology that has provided valuable insight on timing and location of large hatches, but it has not been applied in conjunction with fish telemetry data to explore the linkage between aquatic and aerial ecosystems (Mueller and Larkin 1985; Chapman et al. 2010; Hu et al. 2016). Here, we consider combining these methods, telemetry and radar data, to infer the phenological relationships of fish movement and annually emergent insects in a large freshwater lake and its major tributaries.

Aquatic insects that undergo a mass synchronized emergence can be characterized as a resource pulse that reflects low frequency (e.g., annual), large magnitude (e.g., millions of individuals), and short duration (e.g., days) characteristics (Yang et al. 2008). The resource pulse opportunity provided by emerging aquatic insects is unique because the resource affords itself to consumers in aquatic, aerial, and terrestrial communities (Yang et al. 2010). Aquatic insects provide a broad range of ecosystem services; one of the more recognized benefits for humans includes food for consumers like fish (Suter and Cormier 2010). Aquatic insects are a chaotic event, such as olfactory and sound are likely the most effective means of navigating long distances. Fish can discriminate differing sounds and their locations but the extent of these abilities are largely unknown (Hawkins et al. 2015). Olfactory cues can inform directed movements but typically require abiotic factors to help transport scent and odors (Finelli et al. 1999; Johnson and Li 2010).

The mass emergence of burrowing mayflies such as Hexagenia limbata is an annual occurrence with peak intensity over a relatively short time window (i.e., 2-3 days). The magnitude of these events is often large enough to be observed via weather radar systems, with the highest density repeated hatches taking place in the Great Lakes region and the Mississippi River (Fremling 1964; Masteller and Obert 2000). Lake Winnipeg also has intense annual mayfly hatches where anecdotal reports have described recreational angling success to decrease intense annual mayfly hatches where anecdotal reports have described recreational angling success to decrease while sightings of surface feeding of mayflies by fishes becomes more common. Stomach contents of walleye Sander vitreus reveal extensive feeding on mayfly nymphs can occur (Fig. 1). Understanding how the phenology of insects supports life history demands of freshwater fishes is not only important from an ecosystem function perspective but is also critical for fisheries management and fish conservation (Olden et al. 2010; Brodersen et al. 2011). The timing of emerging insects in temperate regions generally occurs during a critical time for fishes to support somatic or reproductive investment. Depending on the species, most predatory fish reach sizes large enough to forage on insects within the first year of hatching. Furthermore, freshwater systems have been drastically altered since the industrial revolution with degradation of water quality, manipulation of environmental flows, reduction in floodplain inundation, and many other
anthropogenic mechanisms often resulting in changes in aquatic insect composition and thus food web dynamics (Carlson 1970; Robinson et al. 1992; Bunn and Arthington 2002; Grill et al. 2019). Given the importance of aquatic insects as a food source in freshwater ecosystems, investigating the behaviors of emerging mayflies establishes a new perspective on how aquatic, terrestrial, and aerial biomes are linked ecologically (Chapman et al. 2010; Bauer et al. 2017, 2018).

The aim of our study was to quantify the phenology or spatial dynamics of large-scale mayfly hatches as they relate to fish movement and foraging. Our goal was to relate patterns of fish movement before, during, and after to the spatial dynamics of the burrowing mayfly emergence. Our specific objectives were to: 1) assess the hatch dynamics and timing of emerging mayflies in Lake Winnipeg using weather radar, 2) evaluate the movement dynamics of tagged fish via acoustic telemetry, and 3) assess the phenology and synchrony of mayfly hatches and fish movement. The last objective specifically investigated the following hypotheses 1) all fish move in a directed manner toward the hatch, 2) fish that are already present when the emergence occurs stay in the hatch area until the emergence finishes, and 3) the same fish encounter the emergence every year.

Material and Methods

Study site and species
The study site includes the south basin of Lake Winnipeg, Manitoba, Canada and its major tributaries, the Red River of the North, and the Winnipeg River (Fig. 2). The lake is eutrophic and typically remains isothermal due to its shallow depth (mean depth of 12 m) and frequent wind-driven mixing. Bottom substrate of this basin comprises primarily of silt–clay mixtures and is homogenous in distribution. Current theory on the burrowing mayflies suggests that they can be present in most of the benthic habitat in Lake Winnipeg and exhibit annual hatches around mid-summer but many factors can influence the hatch intensity and timing of the burrowing mayfly (e.g., water temperature, life history strategies, growth rates) (Heise et al. 1988; Robinson et al. 1992; Corkum et al. 2006). Emergence and adult life stage of burrowing mayflies last up to 8 days (Carey 2002).

All of the targeted fish species for telemetry efforts are important species for fisheries management and conservation efforts. The lake and its tributaries also support commercial and recreational fisheries where walleye are targeted by both fisheries, whereas channel catfish *Ictalurus punctatus* is predominantly targeted by recreational anglers (Lake Winnipeg Quota Review Task Force 2011). Additionally, two fish species of biological interest are present in the system, freshwater drum *Aplodinotus grunniens* and bigmouth buffalo *Ictiobus cyprinellus*, both of which exhibit exceptional longevity for teleost fishes (Davis-Foust 2012; Lackmann et al. 2019). Common carp *Cyprinus carpio* is the predominant non-native fish species in Lake Winnipeg in terms of biomass and has been documented to damage peripheral wetlands (Badiou and Goldsborough 2010). Lake sturgeon *Acipenser fulvescens* are of high cultural importance to Canada’s indigenous population.

Radar data
Radar data from the Woodlands, Manitoba radar station (XWL; 50.153°N, 97.780°W) were downloaded from June 1 to August 31 for the years 2016–2018; an example is given in Figure 3. This C-band (5-cm wavelength) radar is located approximately 81 km southwest of the center of Lake Winnipeg’s south lobe, where mayflies were generally observed in the radar data (Fig. 2). At this range, centerline of the base-scan beam (0.48°) is approximately 1.1 km above radar level (ARL). Since mayflies emerge from the water and were rarely observed with substantial density above the base-scan level, only base-scan data instead of multi-level volumetric scans were used to estimate total mayfly radar cross-section. Mayflies were identified as areas of enhanced reflectivity factor (Z_{HH}) clearly collocated with all or a portion of the south lobe of Lake Winnipeg, with near-zero radial velocity and with uniform texture to distinguish echoes from precipitation and birds.

Acoustic telemetry data
Six species of fish were tagged with acoustic telemetry transmitters (VEMCO, V16-4H) between 2016 and 2018.
in the Lake Winnipeg basin including several tributaries (e.g., Red River of the North, Winnipeg River, Dauphin River; Fig. 2). Bigmouth buffalo ($n = 80$), channel catfish ($n = 161$), common carp ($n = 40$), freshwater drum ($n = 81$), lake sturgeon ($n = 44$), and walleye ($n = 357$) were tagged. Surgical procedures followed those described by Enders et al. (2019) and approved animal care and use protocols of Fisheries and Oceans Canada (FWI-ACC-2016-018, FWI-ACC-2017-001, FWI-ACC-2018-001) and the University of Nebraska-Lincoln (Project ID: 1208). Acoustic receivers ($n = 116$, VEMCO, VR2W and VR2Tx) were placed in the Lake Winnipeg basin (Fig. 2). Spacing...
between receivers varied, where lake receivers were spaced from 5, 7, or 14 km apart, and river receivers were spaced from 5, 10, and 30 river km apart. All receivers were downloaded and redeployed annually in the same locations.

**Analysis**

We viewed raw radar data using NOAA’s Weather and Climate toolkit (Ansari et al. 2010) to identify possible mayfly hatches, which were then validated by comparing hatch time to social media and local news reports (Fig. 4). Scans encompassing the mayfly hatch were exported to ASCII format so scans could be imported into Esri ArcMap 10.6 and visualized in vector format to allow for geometric calculations of hatch centers. We also converted raw radar data from the proprietary IRIS format to a netCDF format using Python 2.7 (Python Core Team 2015) and the Py-ART package (Helmus and Collis 2016). For each radar scan time with mayflies observed in the radar data and without precipitation contamination, the area with mayflies was manually selected. We assumed all echo (pixels where Z_{HH} was measured) within the subset region were due to mayflies, which could lead to a mayfly cross-section overestimate if a large number of other insects or birds was present. Within this subset area, the method used to calculate total scatterer cross-section (cm² km⁻³) followed previous work (Dokter et al. 2011;
Chilson et al. 2012; Van Den Broeke 2018). First, a linear value of Z_{HH} converted to dB (Chilson et al. 2012; Van Den Broeke 2018) was calculated for each pixel. As in prior work, biological scatterers are assumed to be mostly liquid water, so the complex dielectric constant was set to 0.93. Multiplying the value of linear reflectivity by volume of the radar sample volume represented by each pixel (Van Den Broeke 2018) yields a scatter cross-section value (cm²) for that pixel. Cross-section values are then summed across all pixels in the subset area to yield a total radar cross-section. Note that in prior work (e.g., (Diehl et al. 2003; Dokter et al. 2011; Stepanian and Wainwright 2018; Van Den Broeke 2018), this radar cross-section is divided by the backscatter cross-section (σ_b) of an individual scatterer to obtain a radar-derived population estimate. This was not done here since a representative value of σ_b is not available for a mayfly. Here the assumption was made that each mayfly is approximately the same size and shape, in which case the total radar cross-section scales linearly to the total number of mayflies present and a precise σ_b value is unnecessary.

We used R 3.5.2 (R Core Team 2018) and the following packages to assist in data preparation and analysis of fish movement: geosphere (Hijmans 2017), tidyverse

Figure 4. Examples of mayfly hatch reports in and around Gimli, Manitoba, Canada from both social media and local news coverage.
(Wickham 2017), lubridate (Grolemund and Wickham 2011), magritter (Bache and Wickham 2014), purr (Henry and Wickham 2019), and mgcv (Wood 2011). The visualization of unique detections in relation to ecosystem was based on receiver location. We characterized receivers located in rivers as riverine and receivers located in Lake Winnipeg as lacustrine. Only lacustrine detected individuals that had detections before and after each hatch event were included in the modeling process. Specifically, individuals from 2016 were not included in analysis as receiver installations were occurring before, during, and after the hatch. The median distance from each detection to the geometric center of the hatch was measured daily for each individual fish. The distance metric was then applied to a generalized additive model using a gamma distribution via a log link function as a function of ordinal day number (dnum; 1–365).

The methods for evaluating the second and third hypotheses involved two parts, (1) identifying individuals present in the hatch area during each hatch and (2) visualizing fish presence in the hatch area immediately preceding the hatch. We first converted the radar reflectivity rasters of each hatch to a vector data format, merged each hatch scan in ArcMap, and then queried the individual tagged fish within the hatch area when the hatch occurred. These individuals were then used to characterize all detections during the hatch to the end of the same month as either being within the hatch or outside of the hatch. The in/out hatch time series were then visualized as a logistic regression for each individual where only converged models were kept. Our approach was to only visualize and compare possible relationships of individuals to the hatch area and should not be considered a statistical analysis.

Results

Mayfly hatch

We identified a single mass mayfly hatch event via radar for each year (July 11, 2016; July 9, 2017; July 8, 2018). Hatches varied in intensity and location over time (Fig. 5). All hatches occupied the lower south-western portion of the south basin of Lake Winnipeg with the final hours of the hatches culminating near the western border of the lake. We did not explore whether directional movements were a directed movement from mayflies or was a product of wind conditions. Peak hatch intensity occurred between 10 PM and midnight (local time) for all hatches. The annual median cross-section index value was the highest in 2018 although it occurred in the shortest window of time (2016 = 128,719 cm², 2017 = 252,452 cm², 2018 = 562,743 cm²; Fig. 5). Mean hatch area and standard error for each year were as follows: 490.90 km² ± 52.73 km², 590.12 km² ± 48.62 km², 647.86 km² ± 91.07 km². Slight variation in the radar cross-section and hatch area between years may be caused by differing atmospheric conditions, which could cause the radar beam altitude to vary.

Fish movement

All tagged species except bigmouth buffalo regularly utilized the lacustrine habitat of Lake Winnipeg (Fig. 6). Bigmouth buffalo detections (99%) were overwhelmingly in a riverine environment and were not considered under the phenology analyses coupling fish and mayflies. Channel catfish were more riverine specific but still utilized the lake throughout the year (75% riverine, 25% lacustrine). Common carp detections were typically split between riverine and lacustrine environments evenly throughout the year (51% riverine, 49% lacustrine). Freshwater drum had higher detections in the riverine environments for the first ~40 day after tagging before they shifted overwhelmingly to the lacustrine environment but across the year the total number of detections were comparable (44% riverine, 56% lacustrine). Lake sturgeon utilized a riverine environment the majority of the year but showed higher lacustrine activity during times near the hatch events (96% riverine, 4% lacustrine). Walleye had extensive lacustrine utilization throughout the year with peaks of riverine activity occurring at about 100 day, likely for spawning (6% riverine, 94% lacustrine).

If one assumes hatch area reflects benthic distribution of mayflies, all lacustrine species except freshwater drum moved over distances that would allow the possible interception of mayflies (median distance moved per species: channel catfish = 28.4 km, common carp = 28.4 km, freshwater drum = 106 km, lake sturgeon = 29.8 km, walleye = 30.1 km). When analyzing the movements that occurred during the mayfly hatch window per year (Ordinal day 189–193), the majority of individuals of the lacustrine species had the opportunity to utilize hatch events (median distance moved between day 189 and 193: channel catfish = 28.4 km, common carp = 26.5 km, freshwater drum = 84.3 km, lake sturgeon = 30.5 km, walleye = 36.8 km). All five generalized additive models were significant but explained little variation in movement behavior (Table 1). Visual inspection of each model showed a decrease in distance to the hatch center prior to the hatch event and an increase in distance after the hatch event (Fig. 7). However, the minimum distances shown by models were not synchronized with the hatch events for any year with a range of day numbers from 1 to 273 (January 1 – September 30) associated with minimum distance. All fish species had a maximum distance occur
after the hatch with a day number ranging from 217 to 304 (August 5 – October 31).

Four species were detected within the hatch area during the study: channel catfish, common carp, walleye, and freshwater drum (Table 2). All species that had multiple years of detection data also had recurring individuals during hatch events. There seems to be no apparent relationship between yearly cross-section abundance and the number of individuals detected in the hatch area. Visualization of fish presence in the hatch area showed a wide range of departure and arrival to the hatch area for the hatch month (Fig. 8). Among all species that were detected in the area during hatch, evidence for three strategies was indicated, (1) leaving the area after the hatch, (2) arriving late to the area after the hatch, and (3) entering and leaving the area consistently across the month.

### Discussion

Our study is an initial examination of the potential ecological linkages between aerial and aquatic habitats that encompass the spatial and temporal complexities of insect phenology and fish movement using two typically separate methodologies. A phenological-driven movement of fish to capitalize on emerging mayflies is not apparent, but it is plausible to consider the hatch as a resource pulse feeding opportunity for channel catfish, common carp, freshwater drum, and walleye when they are in the lacustrine environment. Theory describes a resource pulse phenomenon as large fluctuations in resources with the potential of affecting adjacent community structure and coexistence mechanisms (Holt 2008). Resource pulse dynamics have been documented in other fish populations but are usually associated with lotic systems (Moore...
and Schindler 2010; Uno and Power 2015). A synchronized event where fish move in a directed fashion to the hatch would suggest that foraging fish are capable of learning and remembering the hatch, which we find unlikely given the variability of hatch location and intensity, as well as the unsynchronized arrival and departure of fish in relation to the hatch area. Learning and memory are critical factors for optimal foraging performance in fish but developing an improved fitness requires consistent attention and holistic awareness of opportunities (Warburton 2003). The turbidity of Lake Winnipeg would make such factors difficult to occur on an annual basis and would likely hinder predator efficiency when multiple predators are present in the same area (VanLandeghem et al. 2011). Recognizing that foraging patterns of freshwater fish can be linked to circadian rhythms and thus vary as a function of light may also hinder learning opportunities for non-nocturnal fishes (e.g., diurnal, crepuscular and nocturnal time periods; Emery 1973). All species in our study that could capitalize on the emergence have foraging patterns across all three light levels (Noeske and Spieler 1984; Noeske-Hallin et al. 1985; Boujard and Leatherland 1992; Hung et al. 2002; Harder et al. 2012). We explored the feeding opportunity from a 2-D perspective only, when in fact directed movements of fish on emergent mayflies may be better studied from a 3-D perspective.
perspective to see if depth usage reflects underwater emergence behavior (Furey et al. 2018).

Twining et al. (2019) showed that emergent aquatic insects are a more reliable source of omega-3 fatty acids than terrestrial insects, potentially increasing growth rates. For example, *Ephemerella maculate*, a migratory mayfly, is a primary food source for salmonids allowing for enhanced growth rates (Uno and Power 2015). Omnivorous consumers that target aquatic insects have an incentive to optimize foraging for aquatic insects that satisfy nutritional demands and improve fitness. Individuals of all lacustrine species that reside in the hatch area could benefit in terms of growth and survival by consuming burrowing mayfly larvae. Growth of both small and large walleye increases with benthic invertebrate density (Hoxmeier et al. 2006) and invertebrates may be an important diet item throughout all life history stages (Paradis et al. 2006). Similar findings have been reported for channel catfish in riverine and lacustrine environments (Hill et al. 1995; Dettmers et al. 2001; Michaletz 2006). Common carp have an omnivorous diet (García-Berthou 2007) and have been documented to aggregate at mayfly emergence locations for foraging (Lubinski et al. 1986). Lake sturgeon has a generalist feeding preference on benthic invertebrates (Jackson et al. 2002; Holtgren and Auer 2004). We hypothesized that the dietary preferences of each of these fish species in conjunction with the mass hatch event would be a fitness-driven mechanism to support annual synchronous movements. To the contrary, a generalist feeding preference may negate the possibility of synchronous movements when alternative prey items are readily available. The short temporal span of the hatch may be a limiting factor for large directed movements as a foraging fish may obtain a full stomach in a relatively short amount of time on the periphery of the hatch. Furthermore, the hatch occurred over large areas of Lake Winnipeg. Thus, given that the mayfly larvae likely occupy the majority of the lake, albeit at different densities, feeding opportunities on mayfly larvae likely exist throughout the system. Therefore, if the larva life stage is the target of predation then a directed migration should not be expected. The adult life stage is likely poorer food quality as they become available again to be consumed by fish as they have already released their gametes.

We did not explore the environmental covariates that may influence hatch dynamics but repeated and predictable resource pulses can allow for synchronized life history among other coexistence mechanisms (Holt 2008). Wind speed and optimal water temperatures (>20°C) seem to drive the variations in timing of burrowing mayfly in Lake Erie, which is a comparable ecosystem to Lake Winnipeg. We did not explore the environmental covariates that may influence hatch dynamics but repeated and predictable resource pulses can allow for synchronized life history among other coexistence mechanisms (Holt 2008). Wind speed and optimal water temperatures (>20°C) seem to drive the variations in timing of burrowing mayfly in Lake Erie, which is a comparable ecosystem to Lake Winnipeg.

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**Figure 7.** Scatterplots and associated generalized additive models for the five fish species detected in the lacustrine environment. X- The blue line is the generalized additive model trendline with a 95% confidence interval ribbon. The red dashed line indicates the relative hatch time for each year. All fish species had data from 2017 to 2018, except *Aplodinotus grunniens*, which had data for only part of 2018.

**Table 2.** Summary results of fish detected in the hatch area by year and species

| Fish Species          | 2016* | 2017 | 2018 | Same* |
|-----------------------|-------|------|------|-------|
| *Ictalurus punctatus* | 16    | 3    | 3    | 4     |
| *Cyprinus carpio*     | 11    | 1    | 9    | 5     |
| *Aplodinotus grunniens* | NA   | NA   | 4    | NA    |
| *Sander vitreus*      | NA    | 14   | 28   | 7     |
| **Total**             | 27    | 18   | 44   | 16    |

*The Same Column indicates the number of individuals that were present during at least two hatches from 2016 to 2018.

*During the 2016 hatch, receivers had not been completely installed in Lake Winnipeg. Walleye *Sander vitreus* was not tagged before 2017 and Freshwater drum *Aplodinotus grunniens* was only tagged in 2018.
Winnipeg (Corkum et al. 2006). During juvenile growth periods, nymph density can be vulnerable to water quality fluctuations (e.g., hypolimnion oxygen concentration and temperature), which would likely correspond to changes in hatch intensity and biomass available for fish forage (Giberson and Rosenberg 1992; Krieger et al. 2007). A longer evaluation of hatch dynamics in relation to both aquatic and aerial environmental covariates may provide better context as to what environmental conditions are optimum for Lake Winnipeg hatches but may also serve as potential cues for synchrony of other species (e.g., birds, bats). Variations in area and intensity can also be confounded by multiple factors beyond environment. A previous study reported burrowing mayfly populations in Manitoba may contain multiple life history strategies where juvenile growth time varied from 14 to 24 months before emergence, which in turn may lead to sporadic hatches as opposed to single mass hatch events (Heise et al. 1987). The boom and bust population cycles of the mayfly may be a function of life history timing more so than environmental conditions and predators.

Verification and validation of remotely collected data are prone to error. Our assumption was that a mayfly hatch detected by radar could serve as a proxy for emergence location from the water given that the mayfly is a poor flier (Corkum 1987). Another assumption was that the radar-detected hatch was comprised entirely of mayflies. Although the hatch occurred at night when foraging from birds should be minimal, predation from bats is probable, especially over terrestrial areas. Additionally, the alternative life history strategies of the burrowing mayfly suggest that multiple smaller intensity hatches may occur in the lake but would not be detectable on radar or confirmed via social media. Emergence traps are a possible means to quantify emerging insects for both aquatic and terrestrial environments (Davies 1984). A comparison of reported hatch timing between social media and floating emergence traps would help validate public reports and also identify other events that were not reported. We also assumed the phenology of the burrowing mayfly has been consistent over time so that a synchronous behavior would be possible. This assumption may be invalid if the phenology of the burrowing mayfly has already deviated from long-term norms if effects from ecosystem-wide disturbances such as global warming or eutrophication have taken place (Cotton 2003; Visser and Both 2005).

Radar tools have been in use for more than half a century, and as early as 1966, aerial insects have been detected and quantified via radar in the United States of America (USA) (Glover et al. 1966) and for birds, detection via radar occurred as early as 1941 (Bonham and Blake 1956). Only relatively recently has the technology become an accepted remote sensing tool for studying ecology of the airspace (Diehl et al. 2017). Our study demonstrates the possibility of using adult mayfly swarms measured via radar as a means to quantify aerial invertebrate abundance with high temporal resolution (e.g., 4–10 min scan intervals) and spatial resolution (e.g., 0.25–1 km) over an expansive area. What makes the radar approach particularly attractive is the longevity of the radar record and the spatial coverage of radar data throughout North America, which corresponds closely to the distribution of the burrowing mayfly. There is growing momentum to apply radar data to answer ecological questions (e.g., foraging, migration) (Chilson et al. 2011, 2012). Archived radar data are available in either open access or fee-based formats for many countries. For example, USA’s Next Generation Weather Radar (NEXRAD) system provides digital radar data from 1995 to present in an open-access format at no cost. Canada still
uses a proprietary data format and does not make radar data freely available (Hill and Baron 2015). The possibility of extending radar applications to other disciplines like fisheries depends on the quality of confirmation or validation information that can be used to verify radar signals. Our approach of scanning social media websites not only helped us identify hatch events but demonstrated that citizen engagement opportunities may be more important in the future of radar-based remote sensing studies (Shipley et al. 2018).

Combining acoustic telemetry and radar approaches provided a unique opportunity to explore movement ecology relationships between fish and mayflies. Our initial investigation showed five of the six fish species we studied using the lacustrine habitat of Lake Winnipeg regularly. However, we did not detect a synchronous movement event between fish and emerging mayflies. We posit the idea that generalist species may not have the bioenergetic incentive to undertake a directed movement when alternative sources of energy are readily available. Aquatic systems with limited food availability for fish may be influenced more by hatch events and is an open question of research. The application of radar for ecological questions concerning emergent insects is an untapped resource that could inform a range of topics (e.g., biomonitoring, fisheries) for North America’s freshwater systems.

Acknowledgments

The authors thank Fisheries and Oceans Canada personnel for leading the deployment and retrieval of receivers in Manitoba and University of Nebraska-Lincoln (UNL) personnel in the USA. Thank you also to UNL personnel for performing surgery and assisting with mark-recapture efforts. Thanks also goes out to the Minnesota Department of Natural Resources, North Dakota Game and Fish, Fisheries and Oceans Canada, and Brad Duric for assisting the surgery team and collecting individuals for surgery. Our special thanks goes to Jennifer Clausen for developing and providing scientific illustrations for the project. Funding was provided through NSF grant #1545261, Fish Futures, and the Manitoba Fish and Wildlife Enhancement, and the International Joint Commission. This project is also based on research that was partially supported by the Nebraska Agricultural Experiment Station with funding from the Hatch Act (Project NC 1189) through the USDA National Institute of Food and Agriculture. References to any commercial products do not imply endorsement by any of the authors or their employers.

Data Accessibility

Contact the authors for data access.

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