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# Predator telemetry informs temporal and spatial overlap with stocked salmonids in Lake Huron

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## Abstract

Double-Crested Cormorants (*Phalacrocorax auratus*), Walleyes (*Sander vitreus*), and Lake Trout (*Salvelinus namaycush*) are migratory predators that undergo extensive movements in Lake Huron. Stocking of juvenile salmonid fish (*Oncorhynchus* and *Salmo* sp.) is an important component of fishery management in Lake Huron and assessing the spatial and temporal extent of predator movements is a useful consideration for determining when and where to stock juvenile fish to reduce predation and maximize survival. Previous investigation indicated that some Walleyes migrate to the main basin of Lake Huron in spring from Saginaw Bay. Similarly, telemetry studies of Lake Trout movement in Lake Huron have indicated an onshore movement in the spring. We used detection histories of Walleyes implanted with acoustic transmitters tagged in Saginaw Bay and Lake Trout implanted in northern Lake Huron to estimate the arrival date of migrating adults at eight ports in Lake Huron, where hatchery reared juvenile salmonids are stocked. Satellite telemetry of Cormorants that return to nesting grounds in northern Lake Huron were used to estimate their arrival dates at the same Lake Huron ports. Arrival of Walleye at Lake Huron ports ranged from April 10th to May 7th. Cormorants arrived earlier than Walleye at most Lake Huron ports (April 11th–April 18th). Lake Trout were more variable with a range of onshore movement from March 28th to May 16th. Our results suggested stocking efforts at these ports should generally occur before April 14th to decrease predatory impact from Cormorants, Walleyes, and Lake Trout.

**Keywords** Telemetry, Predation, Stocking, Management

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## Background

Managing fisheries with stocking is a common practice across North America [61, 80]. Fish stocking is conducted to achieve a variety of management goals including establishment of new populations, population maintenance or put–grow–take fisheries, supplementation to reproducing populations, and for restoration objectives [63]. Fish stocking has often proceeded without clear definitions of success or a basis for evaluation [14]. Most measures of stocking success have been based on some sort of expected return to creel threshold [54, 29, 75], or as a relative proportion of the resulting year class [6, 27, 62], or both [53].

Survival of stocked fish is required if fish are to recruit, contribute to harvest, and thus is an important metric

Fielder *et al. Animal Biotelemetry* (2023) 11:25

Page 2 of 13

to fishery managers [8, 49]. Many variables can affect the survival of stocked fish and ultimately the efficacy of management and success of stocking. These variables include sufficient food resources in the receiving waters [64, 76], ability to transition to natural foods [25], adequate thermal conditions and flows [77], water levels [23], ability to compete with wild conspecifics [79], transportation and handling stress [36, 40], and suitable rearing practices in the hatchery [60]. Predation, however, is arguably one of the most influential variables affecting survival of stocked fish but can also be challenging to measure [11, 43, 45, 48, 51, 82].

Fish stocking often occurs when fish are at the juvenile stage [1] and may include release of newly hatched fry, age-0 fingerlings, or yearlings. Hatchery rearing and the practice of stocking can require releasing more fish than targeted to compensate for predation losses [14]. Subsequently, survival partly hinges on evading predators [59, 47, 71], often dependent on size of the stocked fish with larger fish generally having better survival rates [9, 13, 52, 73]. Although survival of stocked fish may increase with fish size, the cost of rearing can increase dramatically and may become prohibitive. Rearing large fish for stocking may also increase the risk of disease in the hatchery, or for some species, exceed size at smoltification necessary for imprinting to the release site [30, 81]. While some advocate dispersing stocking spatially and temporally to minimize the attraction of predators [81], others believe overwhelming predators with a full release may promote escapement by planted fish [30, 35].

The Laurentian Great Lakes are notable for their use of cultured Pacific salmon and trout (*Oncorhynchus* and *Salmo* sp.) for supporting a recreational fishery [78, 81, 83]. Species stocked most commonly in Lake Huron have been Chinook Salmon (*O. tshawytscha*), Lake Trout (*Salvelinus namaycush*), Steelhead (*O. mykiss*), Atlantic Salmon (*S. salar*), Brown Trout (*S. trutta*) and Coho Salmon (*O. kisutch*). Lake Trout stocking, principally performed by the U.S. Fish and Wildlife Service, has been in pursuit of restoration as a native predator [18, 28, 33], with the other salmonid species stocked as a put–grow-and-take recreational fishery. Culture and stocking costs are substantial and agencies spend nearly $10 million U.S. per year (MDNR FY2021 expenditures, unpublished data) in Michigan on these efforts.

For many decades, beginning in the late 1960s, salmonid stocking for put–grow-and-take recreational fisheries in Michigan's water of the Great Lakes was a dependable formula with reliable sport fishery outcomes, in part because of abundant and stable prey fish reserves [83]. Salmonid stocking peaked in 1988 in Lake Huron at 7.9 million fish among all agencies and jurisdictions [38]. Returns to creel for Chinook Salmon ranged from 60 to 90 fish per

1,000 stocked between 1987 and 1992 [41]. Concerns over declining growth rates and predator/prey balance led to management agencies capping stocking at 1992 levels of four million salmonids. Chinook Salmon stocking was further cut 20% in 1992 and cut 20% more in 1999 [16].

Stocking cuts were largely motivated by the declining non-native Alewife (*Alosa pseudoharengus*) population in Lake Huron, which was the principal prey item for most predators, especially Chinook Salmon [71]. In 2003, forage fish surveys conducted by the U.S. Geological Survey's Great Lakes Science Center revealed an enormous year class of age-0 Alewives but almost no adults. By 2004, Alewives were virtually extirpated from the lake [69, 70]. The Alewife decline resulted from profound food web changes in Lake Huron [10]. By 2018, Chinook Salmon growth and condition stabilized adjusting to the new reduced pelagic food web in Lake Huron [5].

In the absence of abundant Alewives, stocking success plummeted. Despite restoring predator/prey balance in Lake Huron through stocking cuts, return to creel for stocked Chinook Salmon declined to just 0.7 fish per 1000 stocked. Similarly, Brown Trout recreational harvest declined 93% during the same time period [38]. Johnson and Rakoczy [39] investigated the causes for the Brown Trout decline and documented that Alewives had previously provided a predation buffer on newly stocked trout. In fact, managers had moved the annual Brown Trout release date from early May to mid-June in Lake Huron to time the stocking with the onshore migration of Alewives [41]. The absence of Alewives after 2003 effectively closed this stocking window. Similarly, Johnson et al. [37] examined variables affecting Chinook Salmon survival after stocking and concluded that they too lost a critical predation buffer when Alewives declined. Subsequent research identified that predation losses on newly stocked Great Lakes salmonids has been one of the primary reasons for the declines in survival [7, 45].

Stocked salmonids can succumb to predation by many species in the Great Lakes, but three predators in particular, have been implicated in having substantial effects on survival of hatchery-reared salmonids released in Lake Huron in the spring. The piscivorous Double-Crested Cormorant (*Phalacrocorax auratus*, hereafter referred to as "Cormorants") [19, 39, 72], Walleye (*Sander vitreus*) [37, 39, 47]), and Lake Trout [37]. Cormorants make a northward spring migration throughout the Mississippi Flyway to nesting rookeries in the northern United States and Canada, which includes Michigan's Lake Huron coastline (Fig. 1; [26]. Cormorants feed along their migratory route and their populations have grown exponentially since the 1990s [84], with the Lake Huron population estimated at 8252 breeding pairs (in 2005) in the US waters alone [67]. Some attempts to minimize

Fielder *et al. Animal Biotelemetry*     (2023) 11:25

Page 3 of 13

Cormorant predation at stocking sites have included harassment or 'hazing' of feeding.

Cormorants. Dorr et al. [17] has shown that hazing of feeding Cormorants has proven to deter up to 90% of foraging attempts if applied to fish stocking sites.

Walleyes occur throughout Lake Huron [22] but abundance in Michigan coastal waters is highly influenced by the Saginaw Bay stock [20, 31]. In a study of Walleye movement patterns using acoustic telemetry, Hayden et al. [31] documented that 37% of Walleye tagged in the Tittabawassee River (a spawning tributary to Saginaw Bay) make annual post-spawn migrations in the spring to the main basin of Lake Huron and travel north and south along the coastline (Fig. 1), while the remainder stay resident to the bay year-round. The Saginaw Bay stock of Walleyes reached recovery targets in 2009 and the population averaged more than 9 million age-2 and older fish in 2021 [58, 21]. This suggests that more than 3 million adult Walleyes are making the spring migration into Lake Huron from Saginaw Bay.
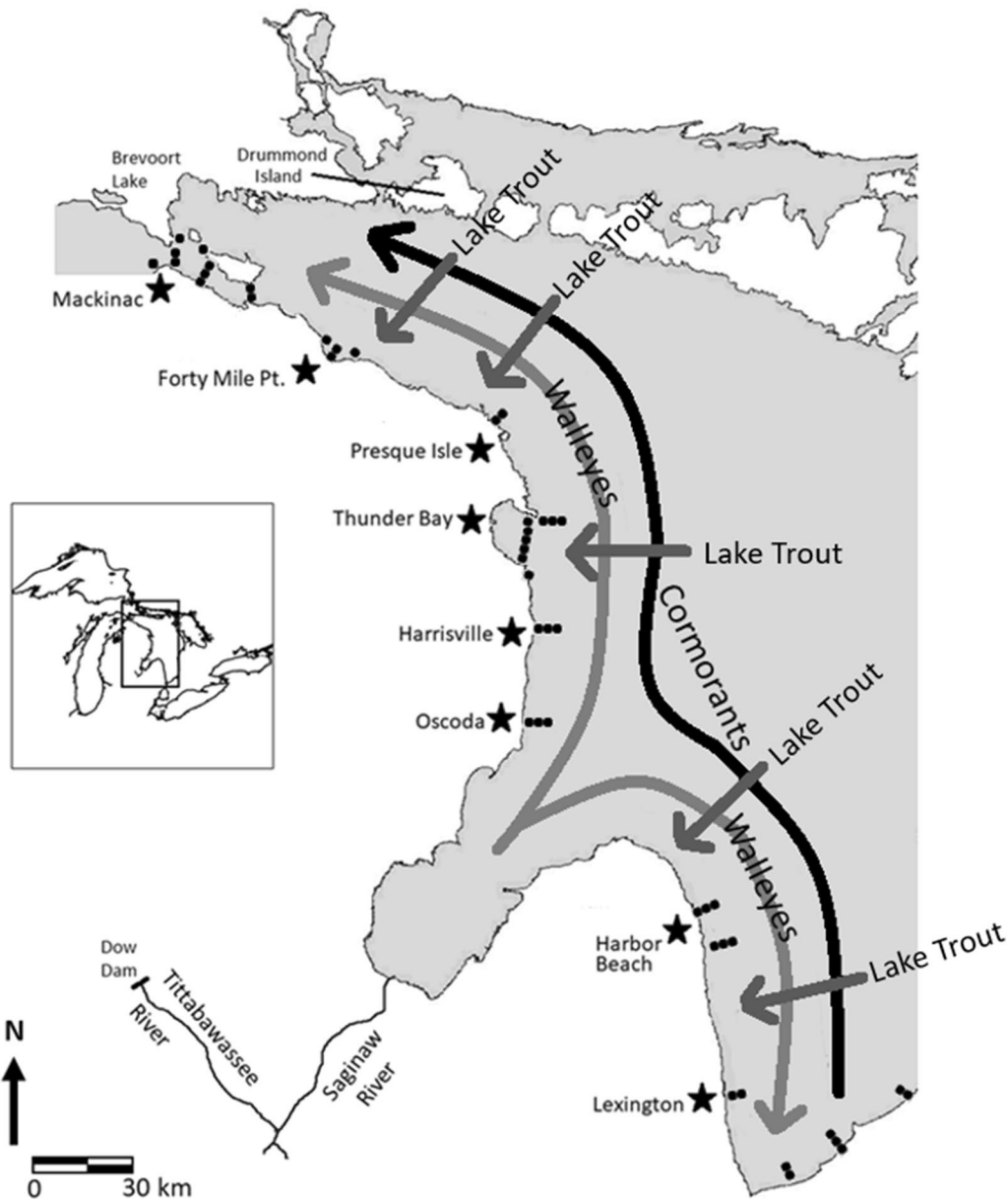


**Fig. 1** Spring migratory pathway directions of Cormorants, Walleyes, and Lake Trout in western Lake Huron. Stars indicate major salmonid stocking ports. Dots show locations of acoustic receiver arrays. Detailed descriptions of positions for acoustic receiver locations are available from Binder et al. [4] and Hayden et al. [31]

Lake Trout natural reproduction has increased greatly in Lake Huron in the absence of Alewives [24, 34, 50] and are approaching recovery targets in some regions of the lake. As of 2018, Lake Trout age 3+were estimated to number 1.25 million fish in the Michigan waters of Lake Huron alone [33]. Lake Trout typically overwinter in water around 40–50 m in Lake Huron and move to shallower water in the spring [3, 4]. The invasive Round Goby (*Neogobius melanostomus*) is an important prey item of Lake Trout and has replaced Alewives in their diets [71]. Onshore spring movement by Lake Trout may be more strongly motivated since 2004 by Round Goby movement from deeper winter habitat to shallower warmer waters [2].

Timing of salmonid stocking in the Michigan waters of Lake Huron has varied (Table 1). Most salmonids are stocked as yearlings except Chinook Salmon. Stockings have ranged from April 1 to June 15th. Brown Trout were stocked as spring yearlings until 2009 when they were switched to fall yearling releases (about mid to late October). Brown Trout stocking by the state was discontinued in 2012 because of poor survival, with only one permitted municipal stocking effort remaining. Lake Trout are stocked as spring yearlings and have averaged 150 mm in TL from 2011 to 2021 [57].

While stocking effectiveness has declined and natural reproduction of predators has increased in Lake Huron, fishery managers and stakeholders want to maintain a diverse recreational fishery for introduced salmonids consistent with the Fish Community Objectives for Lake Huron [15]. To compensate for declines in Chinook Salmon and Brown Trout, fishery managers have increased Atlantic Salmon stocking and renewed Coho Salmon stocking [55] in the belief that their feeding ecology may provide for better returns to creel. While the current level of understanding cannot fully determine, where predation ranks among all the forces affecting survival of hatchery reared salmonines in Lake Huron, predation remains as an important variable that influences stocking success. The Michigan Department of Natural

Resources (MDNR) has identified minimization of predation on newly stocked fish as a priority for salmonid management in Lake Huron [56].

We explored whether movements of predators and release locations of hatchery-reared salmonids overlap in time and space. Our analysis was motivated by the availability of three existing telemetry data sets that described the spring movements of Cormorants, Walleyes, and Lake Trout arrivals to ports in the Michigan waters of Lake Huron, where stocking of salmonids occurs each spring. The objective of this analysis was to determine the date that migratory Cormorants, Walleyes, and Lake trout first reach coastal stocking locations on Michigan's Lake Huron coast to help inform decisions on when to stock fish to minimize predation. If stocking efforts can be timed when migratory predators are not present or at minimal levels in Lake Huron, then survival of stocked salmonids might be higher than stocking after migratory predators arrive and become locally abundant.

## Methods

### Cormorant movement
Cormorant arrival dates at each stocking port were back-calculated from arrival date on breeding grounds in the north and applying a migratory rate from the literature. Cormorant arrival dates to the northern Lake Huron breeding grounds were determined using 2008 and 2009 data from satellite-telemetry tagged Cormorants from Scherr et al. [74]. The birds were previously tagged at breeding colonies in Georgian Bay, in Lake Huron, Ontario. Each Cormorant was outfitted with a Platform Terminal Transmitter (PTT) (Microwave Telemetry, Inc.). To overcome issues of loss of backpack PTTs, these PTTs were surgically implanted in the abdomens of each Cormorant. Battery life was 14 months which provided for tracking through the return of a second breeding season [74]. All data from the PTTs were received by Service Argos Inc. equipment situated on two National Oceanographic and Atmospheric Administration (NOAA) polar-orbiting satellites. Locations for these birds were determined every 3 days (equivalent to one upload cycle) during their spring northward migration to breeding grounds in the Great Lakes, after overwintering in southern states. In some cases, a location fix was not obtainable, or did not upload resulting in periods longer than 3 days between locations. In these cases, the midpoint (median) between the last date of northward migration and first date of detection on the breeding grounds was used to derive mean arrival dates for Cormorants. If an upload interval of more than five cycles (15 days) was missed between the last migration date and arrival date on the breeding grounds for an individual, then these data were excluded. Analysis was limited to tagged

**Table 1** Date ranges, age, and mean lengths at stocking of five commonly stocked salmonids in Lake Huron

| Species | Date range | Age | Mean length (mm) |
|---|---|---|---|
| Chinook Salmon | April 30–June 7 | 0 parr or smolts | 90 |
| Brown Trout | May 1–June 15 | Yearlings | 187 |
| Steelhead | April 8–April 30 | Yearlings | 196 |
| Atlantic Salmon | April 1–May 6 | Yearlings | 150 |
| Coho Salmon | April 14–May 15 | Yearlings | 139 |

birds that migrated up Michigan's Lake Huron coastline ($N = 14$).

Telemetry-based arrival date of Cormorants in nesting locations in northern most Lake Huron from the Scherr et al.'s [74] data was then used to back-calculate likely dates that migrating Cormorants first passed stocking ports (south of the breeding grounds) along the Michigan Lake Huron coastline. King et al. [42] reported that spring migrating Cormorants average 70.17 km per day. Applying this rate in Eq. (1), arrival dates of migrating Cormorants may be deduced at various stocking locations down Michigan's Lake Huron coastline:

$$D_{\mathrm{p}} = D_{\mathrm{a}} - (P/70.17), \tag{1}$$

where $D_{\mathrm{p}}$ is the day of year (DOY) of arrival at the stocking port in question and $D_{\mathrm{a}}$ is the DOY that Cormorants first arrived in northern Lake Huron, $P$ is the distance in km from the northern Lake Huron coastline (in Michigan's eastern Upper Peninsula) and 70.17 ($\pm 46$ as one SD) is the mean daily flight distance in km of migrating Cormorants. Analysis of optimal stocking dates, if and when Cormorants were the first predator arriving at stocking ports, included a secondary (later) date if Cormorant hazing might be applied as a practice to discourage feeding attempts at stocking sites.

**Walleye and Lake Trout movement**

Fish capture, tagging procedure, acoustic transmitter operating specifications, receiver deployment, and receiver operating schedule used to investigate Walleye leaving the Tittabawassee River spawning location (Saginaw Bay, Lake Huron; Fig. 1) was described by Hayden et al. [31]. Briefly, 260 Walleyes were collected and tagged with acoustic transmitters during spring (March–April) 2011 and 2012 with a few fish released in 2012 using recycled tags recovered from angler harvested tagged fish. Walleyes receiving transmitters averaged age 8 with a range of 2–18 years.

Binder et al. [4] similarly detailed methods used in an acoustic telemetry study of Lake Trout movement from two spawning localities, one in northern Lake Huron (Drummond Island refuge) and along the west coast of Lake Huron (Thunder Bay). A total of 430 Lake Trout were tagged between 2010 and 2011. Both telemetry studies (Walleye and Lake Trout) used the same transmitter type (Vemco inc. V16), which was surgically implanted. Transmitter battery life was about 5 years. In both studies the actual number at-large declined over time due to harvest or natural mortality or in some cases emigration from the study area.

Movements of tagged Walleye and Lake Trout were tracked on an array of 140 acoustic receivers located across the mouth of Saginaw Bay and in linear arrays throughout the littoral region of Lake Huron perpendicular to the Michigan coastline extending from the outlet of Lake Huron to the Straits of Mackinac (Fig. 1). To determine when Walleye or Lake Trout arrived at receivers in Lake Huron, we used detections only from eight receiver locations located in the main basin of Lake Huron and which approximately spanned important ports, where stocking occurs (Fig. 1).

Acoustic receivers were Vemco VR2W 69 kHz and receivers reached a depth of 40 m or less which ranged three to ten kilometers off-shore. Receivers had detection ranges up to several kilometers depending on local conditions [4, 31]. Receiver detection ability was determined from a 10 d static range test conducted in Lake Huron with test receivers placed 100 m apart in 5 to 11 m depth. Applying the transmission detection probability simulation methods of Pincock [65], tests indicated that a 1000 m spacing resulted in a 100% detection probability.

The coastal receivers used in our study's analysis located around the Straits of Mackinac were positioned closely together so they were collectively labeled "Mackinac" and treated as one site. Receivers were also positioned at Forty Mile Point, Presque Isle, Thunder Bay, Harrisville, Oscoda, Harbor Beach. Finally, a collection of southern Lake Huron arrays spanning from Lexington to Sarnia, ON in southern Lake Huron were included and were collectively labeled "Lexington" for the purposes of this study (Fig. 1). Hayden et al. [31] and Binder et al. [4] used different monikers for some of these locations and provided additional detail on the precise positioning of each receiver array. Acoustic receivers deployed for the study were recovered annually for data download and maintenance [4, 31] and were coordinated as part of the Great Lakes Acoustic Telemetry Observation System (GLATOS, [46]). Some of the shallowest receivers ($n \sim 1$–5) within each group were removed in the fall to prevent loss from winter ice scour and redeployed the following early spring. At least two receivers were deployed at all times during 2011 through 2014 in all groups except the Lexington location. Receivers in the Lexington location were not deployed until spring 2012 but were operated continuously through 2014. In general, all receivers were deployed ahead of anticipated predator movements. Battery life of implanted tags allowed for tracking of individual Walleye and Lake Trout movements from 2011 through 2014. Prior to analysis of migration timing of Walleye and Lake Trout, all fish detections were screened for false detections caused by environmental noise and signal collisions using the short-interval criteria [66]. False detections were identified as those that did not have at least one other detection on the same receiver within 1 h and were removed from the data set.

Analysis of Walleye and Lake Trout movement was based on number of individual fish detected at each receiver array and not total number of acoustic signals. If an individual fish's acoustic ID was logged at least twice (two true detections as defined by the false detection criteria) in a 24-h period at an array, that array was credited with the presence of that fish. Total number of fish detected each DOY (1–365) for each year (2011–2014) for Walleye and Lake Trout were calculated from detections for each receiver group in Lake Huron. Some level of tag detections for Walleye and Lake Trout were recorded year-round at most receiver groups; however, an increase in detections occurred each spring reflecting movement into the area by migrating fish. For analysis, all study years 2011–2014 were pooled and plotted as total detections of individuals (either Walleye or Lake Trout) by DOY. Interannual variability is accounted for in our analyses as the multiple years of detections were combined to assess arrival day of year. The first date of arrival by Walleye or Lake Trout at each receiver group was defined as the DOY, where the number of detections of individuals increased exponentially, as indicated by the first tripling of number of detected individuals that spring. If receivers at a location experienced few individual detections, such that no tripling occurred, then the first arrival date criterion was relaxed to the first doubling of the daily number of detected individuals.

## Comparison of predator arrival dates with stocking history

Optimal stocking dates for hatchery fish along Lake Huron's coastline were defined as any time before the first arrival of migrating Cormorants, Walleyes, or Lake Trout (i.e., potential predators). This date determination resulted in a threshold date of predator abundance that fishery managers might use to plan around for releases of hatchery fish. These dates were then compared to recent dates for salmonid stocking performed by the MDNR between 2011 and 2020 (Fig. 2; [57]). Median arrival date of the three study potential predators was also calculated as the midpoint of the range of DOY observed for arrival at ports in Lake Huron. All calculations of central tendency of dates were based on numeric values of DOY but reported as dates for convenience.

## Results

A total of 14 satellite telemetry-tagged Cormorants migrated from south to north along Michigan's Lake Huron coastline, a route that took only 6 days on average to complete based on daily movement rates. The mean arrival date on the breeding grounds for Cormorants with satellite telemetry tags was April 18th (Table 2). Applying the rate of travel of migrating Cormorants from Eq. (1), the back calculated arrival dates at Lake Huron ports were calculated. Median arrival date to Lake Huron ports was April 14th (Table 3).

Walleye out-migrating from Saginaw Bay ranged in their arrival date as indicated by first increases in
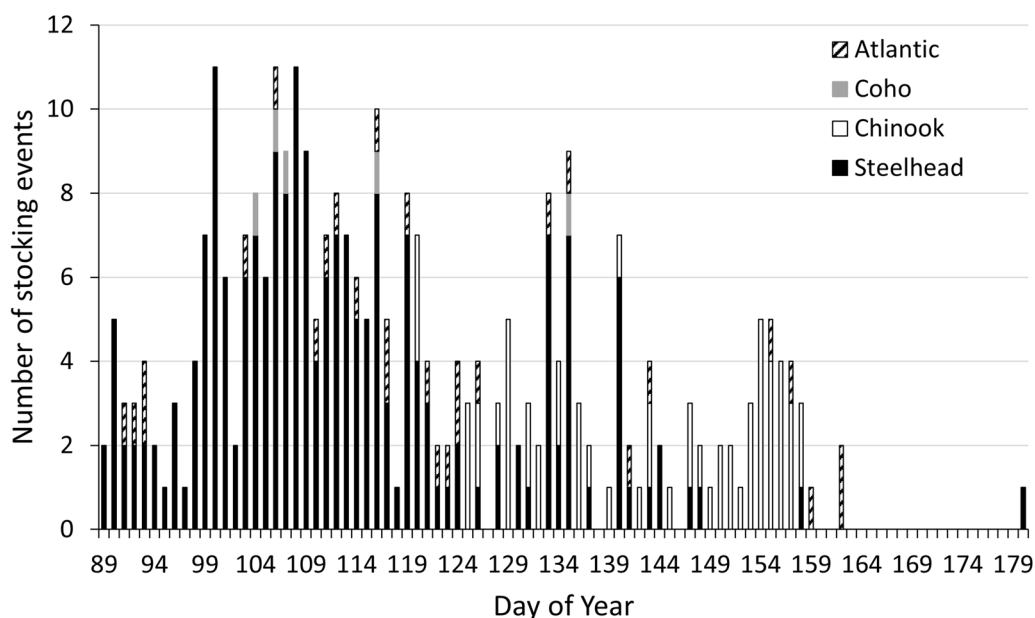


**Fig. 2** Number of stocking events by day of year for four salmonid species stocked in Lake Huron, 2011–2020 for Chinook Salmon, 2013–2018 for Steelhead, 2011–2020 for Coho Salmon, and 2011–2019 for Atlantic Salmon. Brown Trout stocking after 2011 (not shown in figure above) were conducted in the fall on or after day 283. In earlier years, they were typically released between days 135 and 166. Source is MDNR [57]

**Table 2** Arrival dates of satellite telemetry tagged Cormorants on breeding grounds as determined by the median between the last date detected in the northernly migration (before arriving on breeding grounds) and first date detected on breeding grounds. Data from Scherr et al. [74] of Cormorants migrating to breeding colonies in northern Lake Huron. Included is the overall mean arrival date for migrating Cormorants.

| Migratory dates used to determine arrival on breeding grounds | | | |
|---|---|---|---|
| Bird ID | Last date detected during northerly migration before arriving on breeding grounds | First date detected on breeding grounds | Median date indicating arrival |
| 74292 | 14-Apr | 21-Apr | 17-Apr |
| 74293 | 1-Apr | 16-Apr | 8-Apr |
| 74294 | 10-Apr | 17-Apr | 13-Apr |
| 74295 | 18-Apr | 25-Apr | 21-Apr |
| 74297 | 19-Apr | 26-Apr | 22-Apr |
| 74298 | 18-Apr | 3-May | 25-Apr |
| 74301 | 18-Apr | 25-Apr | 21-Apr |
| 74302 | 12-Apr | 19-Apr | 15-Apr |
| 81058 | 2-May | 9-May | 5-May |
| 81060 | 18-Apr | 30-Apr | 24-Apr |
| 81061 | 8-Apr | 24-Apr | 16-Apr |
| 81062 | 13-Apr | 23-Apr | 18-Apr |
| 81063 | 9-Apr | 16-Apr | 12-Apr |
| 81065 | 10-Apr | 13-Apr | 11-Apr |
| Mean | | | 18-Apr |

**Table 3** Arrival dates for Walleye, Lake Trout, and Cormorants at eight coastal sites in the Michigan waters of Lake Huron as determined by telemetry (2011–2014 for Walleye and Lake Trout and 2008–2009 for Cormorants). Cormorant arrival date is back calculated from mean arrival date on breeding grounds in northern Lake Huron by applying migration rates from King et al. [42]. The median dates are included within species.

| Port | Walleye | Lake Trout | Cormorant |
|---|---|---|---|
| Mackinac | May 7 | – | April 18 |
| Forty Mile Point | May 7 | April 19 | April 17 |
| Presque Isle | May 3 | May 16 | April 17 |
| Thunder Bay | April 10[a] | May 2 | April 16 |
| Harrisville | April 29 | March 28 | April 16 |
| Oscoda | April 20 | April 11 | April 15 |
| Harbor Beach | May 4 | – | April 13 |
| Lexington | May 7 | – | April 11 |
| Median | April 24 | April 14 | April 14 |

[a] May 1 may be used as the date Walleye increases were sustained

detections from April 10th to May 7th (Table 3; Fig. 3). The most distant migratory destinations for Walleyes were Mackinac to the north and Lexington to the south. These destinations both reflected arrival dates of May 7th. Thunder Bay was earliest at arrival destination on April 10th. Walleyes migrating from Saginaw Bay to Thunder Bay should have also been first detected at the coastal arrays of Oscoda and Harrisville (Fig. 1) but had later arrival dates than Thunder Bay to the north. Possibly, migrating Walleyes may have been farther offshore than the deepest or furthest receiver (~ 40 m) in the Oscoda and Harrisville receiver groups. Walleye arrival criteria was first met in Thunder Bay on April 10th but that increase was not sustained until May 1st. That date better fits the migratory pattern sequence and may more realistically serve as the date of sustained increases in spring Walleye abundance. The median arrival date for Walleye at Lake Huron ports was April 24th (Table 3).

Spring increases of Lake Trout were evident at five of the coastal arrays, while one location (Mackinac) showed higher abundance of individuals throughout the winter than elsewhere and no detectable increase during the spring (Fig. 4). This northern most location was in close proximity to the original tagging source population of the majority of Lake Trout study fish (Drummond Island). The two southern most receiver arrays (Harbor Beach and Lexington) detected too few individuals to assign an arrival date (Table 3; Fig. 4). The median arrival date for Lake Trout for Lake Huron ports that showed a spring increase in abundance was April 14th (Table 3).

In general, Cormorants were the first potential predator to arrive at most stocking sites on the Lake Huron coast line (Table 3). Walleyes were the first potential predator only in Thunder Bay but applying the second peak of
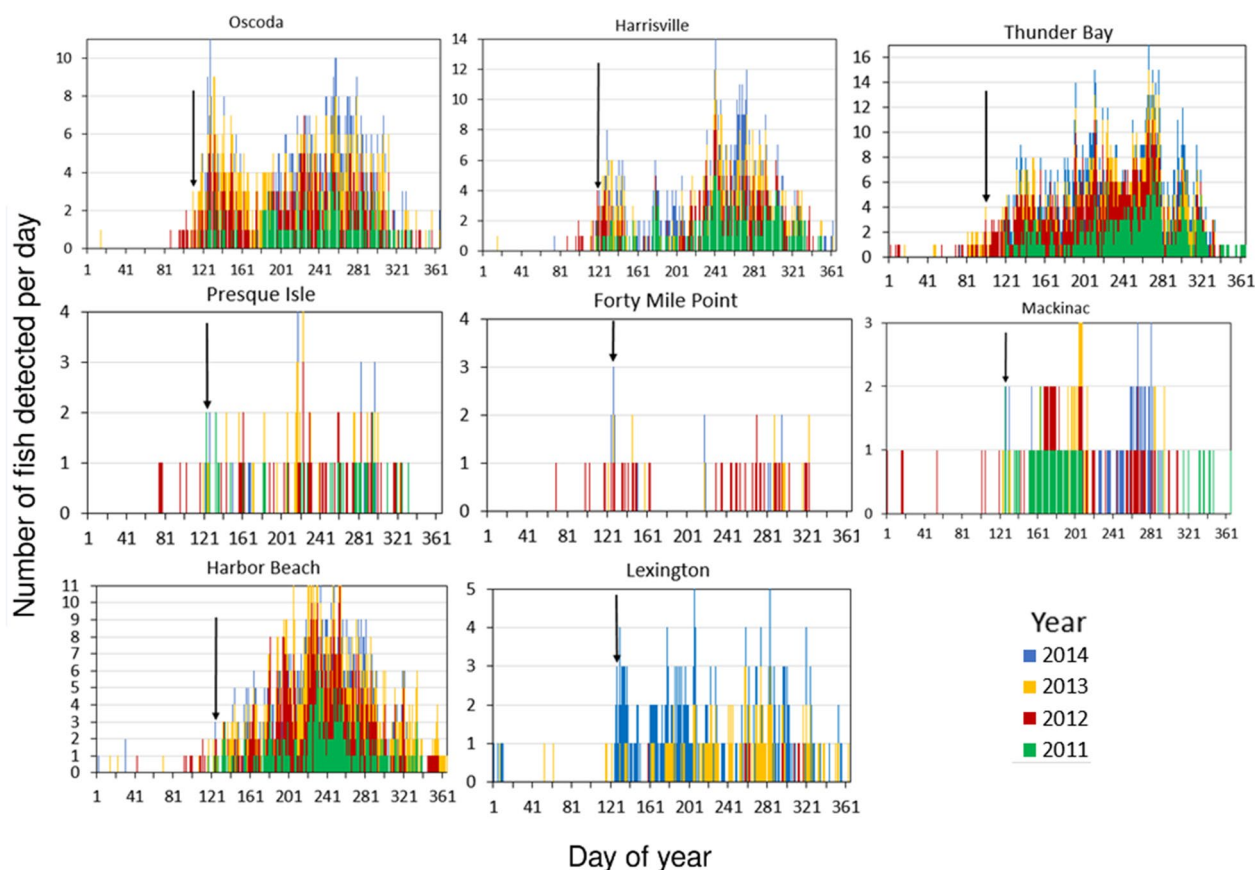
**Fig. 3** Number of Walleye acoustic detections (individuals) by day of year for cumulative years of 2011–2014 as detected by acoustic receivers in Lake Huron from Hayden et al. [31]. Vertical arrow denotes first arrival day of year in spring migration for that location

arrivals for that location, their arrival date of May 2nd was nearly the same as for Lake Trout in that location (May 2nd). Still, Cormorants would have superseded both fish predators at Thunder Bay with their arrival April 16th. Lake Trout was the first predator to arrive at Harrisville and Oscoda. Lake Trout were abundant the entire winter and spring in Mackinac with little or no variation in their abundance, thus Cormorants were the first migratory predator to arrive at that port to increase predation pressure. As such, the recommended fish stocking threshold for maximum predator avoidance reflects influences from all three predators (Table 4) but those thresholds based on Cormorant arrivals can be relaxed if Cormorant hazing is possible and can be sustained.

## Discussion
Optimal stocking dates for hatchery salmonids in Lake Huron to reduce predation losses typically would be before the arrival of Cormorants based on our analyses. Arrival times were variable among the predator species investigated, particularly for Walleye migrating southward from Saginaw Bay and Cormorants which uniformly

moved northward and, therefore, arriving much earlier at the southern stocking locations. Cormorants also migrated faster than Walleye resulting in a difference in arrival timing at northern locations. For example, Cormorants arrived at Oscoda only 5 days ahead of Walleye, but Cormorants arrived 18 days earlier at Mackinac, further north.

Avoidance of predation by timing of stocking is more complicated when considering Lake Trout onshore movements. Lake Trout did not show a clear pattern of arrival dates along the north–south coastline of Michigan, and at one location, never increased during the spring but remained abundant (Mackinac location; Fig. 4). In two locations (both central Lake Huron), Lake Trout were the first to arrive (ahead of Walleyes and Cormorants) and thus, become a consideration in choosing a timing for stocking fish. The lack of Lake Trout abundance in southern ports in the telemetry results likely reflected the use of northern segments of the population for the telemetry study and their fidelity to that part of the lake [68] as Lake Trout were abundant in southern Lake Huron [32]. Lake Trout onshore movements should
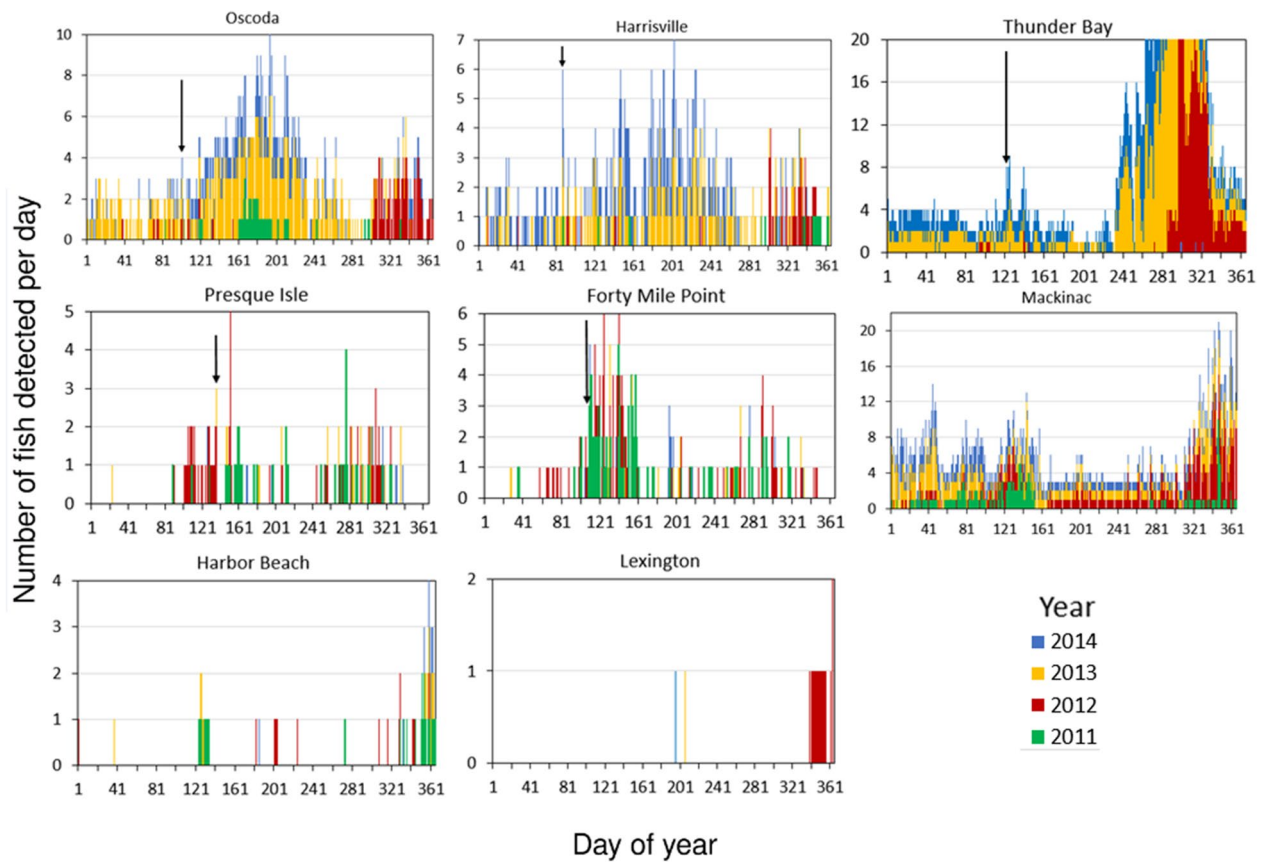
**Fig. 4** Number of Lake Trout acoustic detections (individuals) by day of year for cumulative years of 2011–2014 as detected by acoustic receivers in Lake Huron from Binder et al. [4]. Vertical arrow denotes first arrival day of year in spring migration for that location

**Table 4** Recommended dates for fish stocking to avoid onshore migrating predators (Cormorants, Walleye, and Lake Trout) in Michigan waters of Lake Huron and delayed stocking date when Cormorants are first predators if hazing can be implemented and sustained

| Port | For maximum predator avoidance | First predator | If sustained Cormorant hazing is available at release site |
|---|---|---|---|
| Mackinac | Before April 18 | Cormorants | Before May 7 |
| Forty Mile Point | Before April 17 | Cormorants | Before April 19 |
| Presque Isle | Before April 17 | Cormorants | Before May 3 |
| Thunder Bay | Before April 10[a] | Walleyes | Before May 1 |
| Harrisville | Before March 28 | Lake Trout | – |
| Oscoda | Before April 11 | Lake Trout | – |
| Harbor Beach | Before April 13 | Cormorants | Before May 4 |
| Lexington | Before April 11 | Cormorants | Before May 7 |

[a] May 1 may be used as the date that Walleye increases were sustained in which case Cormorants would be the first predator

be a consideration in stocking timing in southern Lake Huron but were not well-informed by this study.

Currently 77% of salmonid stocking effort in Lake Huron occurs after the median arrival (April 14th) for first predators in Lake Huron. One option to optimize avoidance of predators would be to reduce Cormorant predation pressure by implementing and sustaining hazing of Cormorants until after newly stocked fish

Fielder *et al. Animal Biotelemetry* (2023) 11:25

Page 10 of 13

dispersed. This strategy might provide fishery managers a later stocking date than if Cormorant arrival date is used. There may be additional advantages to early stocking dates for salmonids such as high river flows (to promote imprinting and out-migration of newly released fish) and cold water temperatures which may translate to lower energetic needs by predators and less feeding activity [13].

If sustained Cormorant hazing at stocking sites was not an option, then 77% of fish stocking effort would have to be adjusted earlier than in the past to reduce predation. Stocking strategies could take the form of timing releases before the arrival of Cormorants, Walleyes, and Lake Trout as suggested here or alternatively could delay into late spring or early summer after these predators have reached their destinations and Lake Trout have moved offshore. Our results suggest that a delayed timing could be about June 10th (Fig. 4). The latter strategy would have the added benefit of additional growth on stocked fish but may not be possible if releases are to be timed with smoltification. This strategy has been partly why so many of the recent salmonid releases have been delayed until late spring (Fig. 1), but based on that stocking history, a delay into June would likely be difficult or impossible to implement.

A fundamental aspect of telemetry studies is that tagged individuals adequately represent the movement and behaviors of the population from which they were sampled [44]. Although these telemetry data sets are not current, instead reflecting 2008–2009 for Cormorants and 2011–2014 for Walleye and Lake Trout, they are never-the-less assumed to be relevant, depicting animal behaviors which should be reasonably consistent. Actual interannual arrival times of Cormorants can vary by a week ([74]) or more suggesting on-the-ground conditions would need to be monitored to better refine stocking times. The median arrival date of Cormorants on breeding grounds in northern Lake Huron of April 18 from our analysis aligned closely with observations of arrival dates at two northern Lake Huron locations (Drummond Island and Brevoort Lake; April 17th) in 2004–2007 as reported by Dorr et al. [17]. The individual Walleyes making the migration from Saginaw Bay appear to be not only consistent among years in terms of their propensity to migrate, but to their specific destination as well [31]. This consistency means that the arrival dates by location revealed in our study should also prove consistent and dependable.

Unquestionably, there are additional Walleye reproductive sources within Saginaw Bay and in Lake Huron. The assumption of our analysis is that the overall timing of movement of fish tagged (primarily from the Tittabawassee River source) is reflective of all the migratory Walleyes from Saginaw Bay. Because there are some Walleyes that are resident to the littoral areas and rivers of the main basin of Lake Huron, there is likely some amount of Walleye present year-round in these stocking locations. Our analysis reflects increases in Walleye as migratory predators and not the complete absence of Walleyes outside of these migrations. Finally, while the majority of Cormorants nesting in the Michigan waters of Lake Huron are in the northern most reaches, there are breeding colonies in Thunder Bay and Saginaw Bay. As such, those migrating birds may have different timings than those represented in this study. For these reasons, our findings are a useful generalization of potential predator movements and spring timings but by no means reflect the only distribution of predators in the lake.

## Conclusion

Substantial adjustments in stocking timing would need to be made by agencies to implement a program to minimize predation potential by Cormorants, Walleyes, and Lake Trout. Weighing the costs and logistics of changing stocking programs would need to be evaluated with respect to increased survival of stocked fish due to reduced predation and increased recruitment to the fishery. Other techniques such as the use of pen-acclimation or other release methods may improve survival of stocked salmonids in Lake Huron [12, 37]. On-going climate change may also affect the timing of these migrations and suggested stocking thresholds. Ultimately, fishery managers will achieve the best outcomes by working with fish hatcheries to optimize reared fish size, condition, and timed for predator avoidance.

Next steps for informing salmonid stocking timing in Lake Huron would be to refine these predator movements in spatial scale and scope. Relating timing to environmental cues such as water temperature, river discharges, movements by prey species, and perhaps day length could lead to predictive models that might allow fishery managers to time stocking to the individual spring conditions each year. Additional telemetry work in Lake Huron from more sources of fish (e.g., Lake Trout from southern Lake Huron) combined with monitoring of environmental covariates will likely be required. Taken a step further, predation may be expressed as consumption demand by predators and related to rates of consumption on newly stocked fish to inform stocking numbers needed. Undoubtedly the dynamics between Lake Huron predators and salmonid juvenile prey is complex.

**Abbreviations**

| | |
|---|---|
| DOY | Day of year |
| MDNR | Michigan Department of Natural Resources |
| $D_p$ | DOY of Cormorant arrival at a stocking port |

$D_a$　　　　　　DOY that Cormorants first arrived in northern Lake Huron
$P$　　　　　　　The distance of stocking ports in km from the northern Lake Huron coastline

## Author contributions
DF performed Walleye field work, analyzed data, and initially drafted the manuscript. TH presided over the Walleye telemetry study, analyzed data and contributed to the writing of the manuscript. TB presided over the Lake Trout telemetry study, analyzed data and contributed to the writing of the manuscript. HC performed Cormorant telemetry field work, analyzed data and contributed to the writing of the manuscript. BD assisted with the analysis of Cormorant telemetry data and contributed to the writing of the manuscript.

## Availability of data and materials
Requests for the data sets analyzed for the study should be directed to the original telemetry article corresponding authors. Figure data from this study are available from the corresponding author on reasonable request.

# Declarations

## Ethics approval and consent to participate
Not applicable.

## Consent for publications
Not applicable.

## Competing interests
The authors declare that they have no competing interests. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The findings and conclusions in this publication are those of the authors and should not be construed to represent any official U.S.D.A. or U.S. Government determination or policy.

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Fielder *et al. Animal Biotelemetry*        (2023) 11:25

Page 12 of 13

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## Publisher's Note