Received: 27 June 2022 | Accepted: 5 December 2022
DOI: 10.1111/mms.12997

Marine Mammal Science

ARTICLE

Fly with care: belugas show evasive responses to low altitude drone flights

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Funding information
Donner Canadian Foundation; Earth Rangers; Fondation de la Faune du Québec; Kenneth M. Molson Foundation; Natural Sciences and Engineering Research Council of Canada

Abstract

Drones have become an important research tool for studies of cetaceans, providing valuable insights into their ecology and behavior. However, drones are also recognized as a potential source of disturbance to cetaceans, particularly when flown at low altitudes. In this study, we examined the impact of drones on endangered St. Lawrence belugas (*Delphinapterus leucas*), and reviewed drone studies of cetaceans to identify altitude thresholds linked to disturbance. We repurposed drone footage of free-living belugas taken at various altitudes, speeds, and angles-of-approach, and noted the animals' reactions. Evasive reactions to the drone occurred during 4.3% (22/511) of focal group follows. Belugas were more likely to display sudden dives during low-altitude flights, particularly flights below 23 m. Sudden dives were also more likely to occur in larger groups and were especially common when a drone first approached a group. We recommend that researchers maintain a lower altitude limit of 25 m in drone-assisted studies of belugas and approach larger groups with caution. This recommendation is in line with our literature review, which indicates that drone flights above 30 m are unlikely to provoke disturbance among cetaceans.

KEYWORDS
Delphinapterus leucas, dive, recommendation, remotely piloted aerial system, RPAS, UAV, unmanned aerial vehicle, unoccupied aerial vehicle, white whale

1 | INTRODUCTION

Unoccupied aerial vehicles,[1] also known as drones, offer researchers an unprecedented view of wild animals and the natural environment. Drone technology has been used for diverse biological applications, including landscape mapping, population monitoring, photo-identification, body condition assessment, and increasingly, behavioral studies of wildlife (Christiansen, Dujon, et al., 2016; Fearnbach et al., 2019; Goebel et al., 2015; Krause et al., 2017; Pomeroy et al., 2015; Torres et al., 2018; Watts et al., 2012). Modern multirotor drones are ideal for behavioral studies because they can be deployed in restrictive remote conditions, they can hover above animals, and they can collect high-definition images of study subjects (Watts et al., 2012). Drones are particularly valuable for behavioral studies of wild cetaceans because these animals are exceptionally difficult to observe in their natural habitat (Fiori et al., 2019). Despite these advantages, researchers must also consider whether drones have the potential to disturb the animals they are investigating.

Although initially touted as a noninvasive research tool, the potential for drones to disturb wildlife, including cetaceans, has received considerable attention in recent years (Arona et al., 2018; Bevan et al., 2018; Brisson-Curadeau et al., 2017; Mulero-Pázmány et al., 2017; Raoult et al., 2020; Rebolo-Ifrán et al., 2019; Vas et al., 2015). Indeed, it is now apparent that drones have the potential to disrupt the behavior of wild animals, and that certain precautions must be taken to avoid disturbing study subjects (Hodgson & Koh, 2016; Smith et al., 2016; Weston et al., 2020). In an early study of drone disturbance of wildlife, Vas et al. (2015) found that waterfowl respond negatively to vertically approaching drones, but do not respond to changes in drone speed or color. Subsequent studies have shown that responses to drones are highly species-specific; some species appear highly sensitive to drone disturbance, while others seem entirely unaffected (Bevan et al., 2018). It is likely that different features of the behavioral ecology of each species influence their species-specific reactions to drones. Given that drones may produce both a visual and an auditory disturbance, various species may respond differently to drone cues (Mulero-Pázmány et al., 2017). While some birds may confuse the appearance of the drone with an aerial predator (Mulero-Pázmány et al., 2017), elephants may confuse the whine of a drone for a swarm of bees (Bennitt et al., 2019).

Marine animals may be less likely to react to drones than terrestrial animals (Rebolo-Ifrán et al., 2019). Since the air-water interface attenuates drone sounds, marine animals are less likely to be disturbed by drones when underwater (Christiansen, Rojano-Doñate, et al., 2016; Erbe et al., 2017). However, marine animals may still be exposed to acoustic cues during surface behaviors. This is particularly salient for cetaceans, which spend much time at the surface for respiration, socializing, and other activities. In addition, marine animals may be sensitive to drone visual cues, whether they are at the surface or underwater (Fettermann et al., 2019).

Responses to drones are broadly categorized as "alert" and "evasive" reactions (Bennitt et al., 2019; Mulero-Pázmány et al., 2017). Alert reactions are noted when animals display vigilant behaviors directed towards the drone (Bennitt et al., 2019). During alert reactions, common bottlenose dolphins (*Tursiops truncatus*) perform spy-hops, side-floats, and side-rolls, or swim in tight circles, likely in an effort to visually inspect the drone (Ramos et al., 2018). Bottlenose dolphins also perform more tail-slaps in the presence of a drone, possibly indicating a stress response (Fettermann et al., 2019). While these responses may seem mild, they nonetheless indicate that animals' natural behaviors are disrupted by the presence of a drone. Evasive reactions are noted when animals actively attempt to evade drones (Mulero-Pázmány et al., 2017). Many birds take flight in response to drone disturbance (Weston et al., 2020), while marine mammals may dive or reorient themselves to swim away from a drone (Domínguez-Sánchez et al., 2018; Fettermann et al., 2019). In extreme cases, animals may desert an area entirely in response to drone disturbance, as noted in Antillean manatees (*Trichechus manatus manatus*; Ramos et al., 2018). Such responses are particularly concerning because they carry a considerable energetic cost and provide evidence that drones induce large disruptions to normal behavior that may result in fitness costs. For example, a study of captive Antillean manatees also showed persistent changes in respiration rate and activity budgets following drone flights, suggesting that evasive responses could be correlated with less conspicuous, but nonetheless deleterious responses (Landeo-Yauri et al., 2021).

Although the potential for drone disturbance has been assessed for many marine mammals (for a review see Smith et al., 2016), the impact of drones on the behavior of belugas (*Delphinapterus leucas*) has yet to be examined in detail. An early study found that belugas show no response to a radio-controlled model aircraft flown at 150–200 m above sea level (Sleno & Mansfield, 1978), but the stimulus of a model aircraft flown at high altitudes is not comparable to that of a modern multirotor drone. More recently, Palomino-González et al. (2021) noted that belugas approached by a drone hovering at altitudes of 15 m or less displayed avoidance behaviors, particularly when the drone hovered in front of the animals. However, these approaches were opportunistic and limited in number. As such, the response of belugas to drone disturbance has yet to be examined in depth, despite increasing interest in using drones to study wild belugas (Aubin et al., 2021; Boyd et al., 2019; Vergara et al., 2021).

The St. Lawrence beluga population is listed as endangered under Canada's Species at Risk Act and has shown little sign of population recovery despite decades of conservation efforts. While this population once numbered 10,000 whales, today fewer than 900 individuals remain (Mosnier et al., 2015). Threats to the population include anthropogenic noise and disturbance, chemical contaminants, and a shortage of prey (Lesage, 2021). Several initiatives have been proposed to reduce disturbance including "Windows on Belugas," an innovative project lead by non-profit and governmental partners promoting whale watching from terrestrial sites equipped with drones relaying live images to visitors. Drones are also used in ongoing morphometric studies attempting to link female body condition, calf production, and survival. To guide these efforts, we aimed to establish guidelines that would minimize the potential for drone disturbance of belugas and enhance our overall understanding of the effect of drones on cetaceans.

In this study, our goal was to quantify the responses of belugas to a drone under a range of conditions relating to the intensity of exposure to visual and acoustic cues, and the sensitivity of animals to disturbance. Exposure to drone acoustic and visual cues may intensify during low altitude flights (Fettermann et al., 2019; Rümmler et al., 2016), vertical descents (Vas et al., 2015), rapid flights (Erbe et al., 2017), when animals are approached head-on (Domínguez-Sánchez et al., 2018; McEvoy et al., 2016), on the first flight in a sequence of flights (Ramos et al., 2018), and in low wind conditions (Christiansen, Rojano-Doñate, et al., 2016). In addition, marine mammals may be more prone to disturbance when they are alone or in small groups (Ramos et al., 2018), when offspring are present (Pomeroy et al., 2015; Richardson & Würsig, 1997), or while resting (Filby et al., 2014; Payne et al., 1983; Richardson & Malme, 1993). In light of these previous findings from other animals, we hypothesized that belugas would respond to a research drone and predicted different responses to the drone depending on exposure to acoustic and visual cues, and the susceptibility of animals to disturbance (Table 1). With drones being of increasing value to understanding important aspects related to the conservation and management of at-risk beluga populations, this study informs guidelines to minimize drone impacts on this species.

TABLE 1 Predicted responses of beluga whales to multirotor drones, based on previous studies of marine organisms, in relation to different types of variables relating to exposure to drone cues and the susceptibility of groups to disturbance.

Type of variable	Variable	Predicted likelihood of response
Exposure to drone acoustic and visual cues	(1) Drone altitude	Increase at low altitude
	(2) Drone vertical speed	Increase with vertical speed
	(3) Drone horizontal speed	Increase with horizontal speed
	(4) Drone approach	Increase during head-on approaches
	(5) Flight number	Decrease with number of flights
	(6) Wind speed	Increase with decreasing wind speed
Susceptibility of group to disturbance	(7) Group size	Increase with decreasing group size
	(8) Group composition	Increase in groups with calves
	(9) Group behavior	Increase in resting groups

2 | METHODS

2.1 | Drone flights

We flew drones to observe St. Lawrence belugas from July 20, 2017, to August 12, 2017, and from July 8, 2018, to August 19, 2018. We used a Phantom 4 and a Phantom 4 Pro (DJI, Shenzen, China), both commercially available, vertical-take-off-and-landing drones that have been used extensively in drone wildlife studies (Bevan et al., 2018; Schofield et al., 2017; Torres et al., 2018). The drone was launched from a 6 m observation tower erected in Ste-Marguerite Bay, in the Saguenay Fjord in Quebec, Canada (Figure 1). For both sampling years, the tower was constructed and disassembled during neap tides when belugas were absent from the area. The location of the tower was originally chosen to accommodate two studies focused on mother-calf communication space (Vergara et al., 2021) and allocare (Aubin et al., 2021). We analyzed a total of 143 drone flights obtained over 27 sampling days, for 28 beluga herd encounters. Flights lasted on average 18.3 min and were recorded in their entirety in 4,096 × 2,160 pixels (4 K) resolution, at a frame rate of 29.97 frames per second. We considered that a herd included all animals visible within the study area, and occasionally recorded two herds on one day when a first herd left the bay, and later another herd arrived. The drone was piloted by three certified pilots (J.A.A., M.A.M., and V.V.), alternating based on availability. The drone footage was initially collected to study beluga ecology and conservation, rather than to assess the disturbance potential of drones. However, since our flights showed a range of piloting styles (approach, altitude, speed, etc.) and the groups of belugas varied widely in size, composition, and behavior, the collected data could be repurposed to examine contexts relating to drone disturbance.

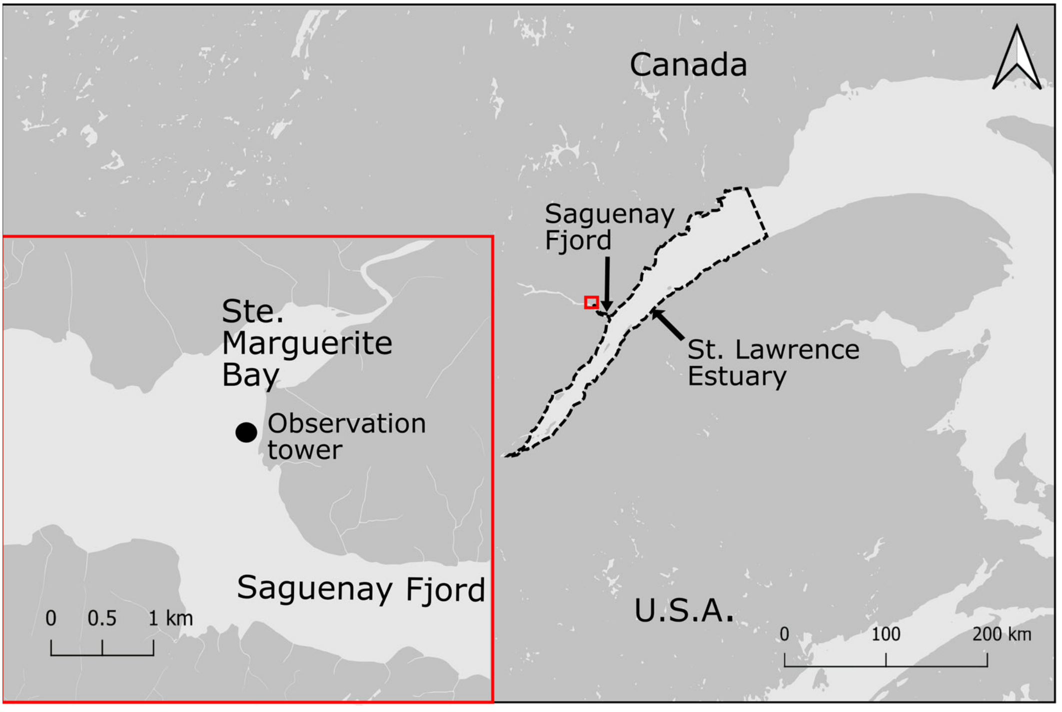

FIGURE 1 Map of Ste-Marguerite Bay, located in the Saguenay Fjord in Quebec, Canada, north of the St. Lawrence Estuary, including a detailed map of the study area (inset). The filled circle marks the approximate location of the observation tower from which the drone was launched.

2.2 | Group focal follows

We analyzed a total of 143 drone videos with a total duration of 43.6 hr. All videos were analyzed in the event logging software BORIS, version 7.9.19 (Friard & Gamba, 2016). J.A.A. and M.A.M. analyzed 86 and 26 videos, respectively, as sole observers. An additional 31 videos were analyzed by both observers to verify their interrater reliability; the two observers' agreement, calculated using Cohen's kappa, ranged from strong to almost perfect (Table 2; McHugh, 2012) and therefore we did not include observer in our analyses. Belugas display fission-fusion social dynamics (Alekseeva et al., 2013), and the observed groups were highly fluid, often changing size and composition from minute to minute. Therefore, rather than attempting to follow rapidly changing social groups, we instead defined a focal group as all belugas under the drone that were near enough to determine their age-class and behavior.

Each video was initially viewed using a survey-follow protocol (Mann, 1999), during which we defined the start and end of each focal group follow and the type of drone approach. We began each focal group follow when the behavior and composition of the focal group could be accurately determined. We assigned an arbitrary, unique identifier to each focal group. We defined the drone's approach as “head-on” or “from behind” if it clearly approached the majority of the focal group head-on, or from behind, respectively. We defined the drone's approach as “other” if it approached the majority of the group from the side or if the approach type was not obvious. We ended a focal group follow if any of the following conditions were met: (1) a new approach was initiated, clearly recentering on a new group while leaving the previous focal group behind, (2) the focal group dove or exited the frame for more than 20 s, or (3) the altitude of the drone or the angle of the gimbal increased such that the behavior and composition of the focal group could not be determined for more than 20 s.

2.3 | Defining disturbance behaviors

When evaluating each focal follow, we recorded all instances of beluga behaviors that could be indicative of disturbance. We defined a series of possible disturbance behaviors based on reports from previous drone and aircraft disturbance studies of cetaceans: (1) spy-hop, (2) belly-up, (3) tail slap, (4) chin slap, (5) circular swim, (6) sudden change in direction, and (7) sudden dive (Bevan et al., 2018; Fetterman et al., 2019; Fiori et al., 2020; Pirotta et al., 2017; Ramos et al., 2018; Richardson & Würsig, 1997; Table 3; Figure 2). We categorized the spy-hop, belly-up, tail slap, chin slap, and circular swim as alert reactions because the belugas showed an apparent interest in the drone. Some alert reactions, such as spy-hops and belly-ups, are also frequently observed in the absence of a drone or other obvious sources of disturbance and may also be related to social interactions (O'Corry-Crowe et al., 2009). Therefore, we only included spy-hops where the subject looked up toward the sky, rather than across the surface of the water, and we only included belly-ups that did not occur in interaction with another individual. We categorized sudden changes

TABLE 2 Interobserver analyses of videos scored by the two observers shows strong to almost-perfect levels of interobserver reliability. We performed the interobserver analysis on 31 out of 143 videos, representing 9.0 hr of a total 43.6 hr, or 20.6% of observation hours.

Variable compared	Cohen's kappa	Interpretation (McHugh, 2012)
Approach type	0.85	Strong
Timing of interval samplings	0.91	Almost perfect
Group size	0.90	Strong
Group composition	0.90	Strong
Group behavior	0.90	Strong

TABLE 3 Potential beluga disturbance behaviors in response to a drone, chosen and defined based on reports from previous drone and aircraft disturbance studies on marine mammals (Bevan et al., 2018; Fetterman et al., 2019; Fiori et al., 2020; Pirotta et al., 2017; Ramos et al., 2018; Richardson & Würsig, 1997).

Type of reaction	Disturbance behavior	Definition
Alert	(1) Spy-hop	Beluga orients body vertically such that both eyes are clear of the water, with rostrum oriented vertically. Equivalent to “rostrum-up” in Ramos et al. (2018).
	(2) Belly-up	Beluga turns its body at the surface with one eye clear of the water, with no social interaction Encompasses the side-roll, full-roll, and belly-up from Ramos et al. (2018).
	(3) Tail slap	Beluga strikes the surface of the water with its tail.
	(4) Chin slap	Beluga strikes the surface of the water with its chin.
	(5) Circular swim	Beluga swims in tight circles under the drone
Evasive	(6) Sudden change in direction	Majority of animals within one body length show a > 90° change in swimming direction, away from the drone, during travel.
	(7) Sudden dive	Majority of animals within one body length dive abruptly, with an increase in swimming speed.

in direction and sudden dives as evasive reactions because the belugas seemed to be escaping from the drone. Given that disturbance behaviors were often too subtle to classify reliably, each suspected instance of disturbance was jointly reviewed by J.A.A. and M.A.M. to reach a consensus.

2.4 | Interval sampling

Every 20 s during a focal group follow, we recorded the maximum number of belugas observed, whether calves were present (calves were recognized as dark brown or gray animals, less than half adult body length), and the behavior of the group. We defined group behavior as “milling/resting,” “socializing,” “traveling,” “feeding,” “underwater,” or “out-of-sight” (Table 4). Although socializing belugas often engage in surface behaviors (O'Corry-Crowe et al., 2009), we did not rely on surface behaviors that could be mistaken for alert reactions (Table 3) to determine social behavior. Focal group behavior was always defined based on the activity of a majority of the focal group. We later summarized the behaviors as “Milling/resting,” “Socializing,” and “Other,” to avoid overfitting our models.

2.5 | Analysis of focal group follows

Because most focal group follows lasted longer than 20 s, most focal groups were assessed across multiple sampling intervals. Therefore, we summarized our 20 s sampling intervals for each focal group follow in the following ways. If an alert or evasive reaction was observed in any of the 20 s sampling intervals during a focal group follow, we assigned a score of 1 for alert or evasive reactions to that focal group. If no reactions were observed, we assigned a score of 0 to that group for alert or evasive reactions. We calculated the average observed group size across each focal group and recorded whether calves were observed. If calves were observed during at least one sampling event, we considered that calves were present during that focal group follow. The predominant group behavior observed across all 20 s sampling intervals for a focal group was considered the group behavior for that focal group. For each focal group, we extracted data on the minimum altitude of the drone (measured from the water surface, taking into account tidal height), and the drone's maximum absolute vertical speed and horizontal speed from flight records.

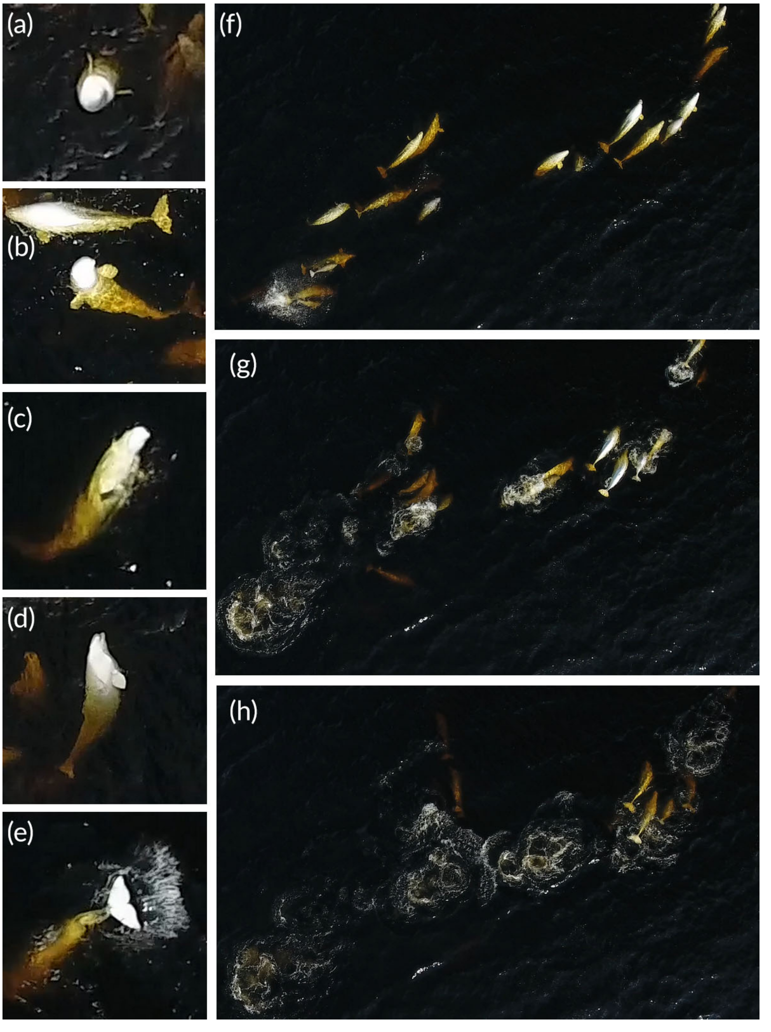

FIGURE 2 Potential drone disturbance behaviors observed in St. Lawrence belugas. a, b: spy-hop; c, d: belly-up; e: tail slap; f, g, h: time sequence of a sudden dive event lasting approximately 2 s.

Altitude data were collected by the drone's internal altimeter, which may vary by several meters in its accuracy. For each flight, we determined wind speed using archival meteorological data from the Pointe Claveau weather station. Because wind speed data were recorded hourly, all focal group follows within a flight were associated with the same windspeed value. For focal groups that displayed alert or evasive reactions, we ignored all data collected after the first reaction, because a disturbance that occurred after a reaction could not have caused it.

2.6 | Data analyses

We first visually inspected the data and used Pearson's correlations, Kruskal-Wallis tests, and chi-squared tests to check for correlations between variables. These tests revealed a correlation between calf presence and drone altitude: videos with calves tended to occur at lower altitudes. This may be because calves were less visible at higher altitudes. As such, it was apparent that we could not disentangle the effects of altitude and calf presence, and therefore we chose to exclude the group composition variable.

TABLE 4 Beluga focal group behaviors as observed from the drone, recorded at 20 s intervals, based on previous behavioral studies (Howe et al., 2015; Lemieux Lefebvre et al., 2018; O'Corry-Crowe et al. 2009; Panova et al., 2012; Sjare & Smith, 1986); a group was considered to be displaying a particular behavior if more than half of the animals showed the same behavior.

Behavior	Definition
Milling/resting	More than half of animals swimming slowly, in circles or half circles, drifting with the current or motionless at the surface.
Socializing	More than half of animals showing frequent interaction with other belugas: body contact, orienting towards other belugas, chasing, or sexual behavior.
Traveling	More than half of animals showing sustained unidirectional movement.
Feeding	More than half of animals showing focused diving in one particular location, with periodical fluking, referred to as “milling” in some studies.
Underwater	Belugas only visible as blurry shapes underwater.
Out-of-Sight	Belugas could not be observed. Angle of the camera changed, or the focal group was not visible for more than half of the sampling interval.

2.7 | Model construction

We constructed a series of generalized linear mixed-effect models (GLMMs) incorporating variables relating to exposure to the drone's acoustic and visual cues and the susceptibility of groups to disturbance, using the function *glmer* from the R package “lme4” (Bates et al., 2022). We chose to use mixed models, given that focal groups were sampled from a set of herds that frequented the study site, and consequently the data were not truly independent. We usually conducted multiple flights on the same day, targeting the same herd, and so we likely repeatedly targeted some individuals. We were able to partially account for this by including *herd identity* as a random effect. Both alert and evasive reactions were coded as binary variables, where the presence of any reactions during a group focal follow was coded as a 1, and an absence of a reaction coded as a 0. Given that our data were binomial, with a large number of zeros and few ones, we used binomial error structure with a cloglog link. We used the ‘DHARMa’ package (Hartig, 2022) to check for violations of model assumptions and found that all models were sound. We constructed one model set that included alert reactions as the response variables, and one model set that included evasive reactions as the response variables. For each model set, we used a null model that included only the random effect, *herd identity*, and a series of models including a single fixed effect (Table 1) in addition to the random effect.

2.8 | Model averaging

We then used Bayes' information criterion (BIC) model averaging to average each model set to a single model using the function *model.avg* from the R package “MuMIn” (Bartón, 2022). BIC model averaging first ranks models according to their explanatory power (BIC weight), then averages each model according to its BIC weight. This eliminates the need to use arbitrary cut-offs to define “top models.” We also repeated the model averaging using Akaike's information criterion (AIC). We used conditional model averaging as it is more sensitive to small effects. We then examined the outputs of the average models to determine which variables were strongly related to alert and evasive reactions. For variables that appeared to be strongly related to alert or evasive reactions in the average model, we investigated the R^2 values for their relevant models using the function *rsquared* from the package “piecewiseSEM” (Lefcheck, 2020). We also used the function and package “segmented” (Muggeo, 2022) to perform a breakpoint analysis for the *altitude* variable, to determine the altitudes at which reactions became more likely. All statistical analyses were carried out in R, version 4.0.3 (R Development Core Team, 2014).

2.9 | Systematic literature review to evaluate impacts of drone altitude

In addition to the a priori literature review that informed our hypotheses (Table 1), we performed a post hoc systematic literature review examining the impact of drone altitude on cetaceans. The goal of this review was to identify altitude thresholds at which cetaceans typically display disturbance behaviors. We paired specific search phrases relating to drones (drone, remotely piloted, UAV, unmanned aerial, unoccupied aerial) to search words relating to cetaceans (cetacean, dolphin, porpoise, whale) to search the Web of Science database. We obtained a total of 72 drone studies of cetaceans published from 1979 to 2022. Of these, 41 made no assessment of drone disturbance. We summarized the results of the remaining 31 studies that reported drone disturbance, focusing on altitude thresholds. We considered that the assessment of drone disturbance was "cursory" if little to no details were provided on how disturbance was defined and measured, or "detailed" if specific disturbance behaviors were defined and measured. We also considered the drone models used in the study and the minimum flight altitude reported. We performed a breakpoint analysis comparing the minimum reported drone altitude to whether or not drone disturbance was reported. The results of this current study were not included in the breakpoint analysis to allow for comparison between our results and the published literature.

3 | RESULTS

Of 511 focal group follows from the 28 herd encounters, we observed a total of 57 alert reactions: 53 spy-hops, 3 belly-ups, and 1 tail slap. No chin slaps or circular swims were noted. We observed a total of 22 evasive reactions, all of which were sudden dives. Examining the distribution of alert and evasive reactions across focal group follows, we found that alert reactions occurred during 30/511 (5.9%) of group follows, while evasive reactions occurred during 22/511 (4.3%) group follows.

We noted that many sudden dives occurred almost immediately after the drone approach. Indeed, 8/22 (36.3%) sudden dives occurred during the first 20 s of a focal group follow, compared to only 5/57 (8.8%) of alert reactions. Given that the average group follow lasted 493.1 s, the first 20 s represents only 4.1% of the average group follow. We conducted two Bonferroni-corrected post hoc chi-squared tests to compare the observed proportion of alert reactions and sudden dives in the first 20 s to their expected proportion in the first 20 s. We found that sudden dives were more likely to occur in the first 20 s than expected by chance ($\chi^2 = 59.0$, $p < .001$), but we did not find this to be the case with alert reactions ($\chi^2 = 3.3$, $p = .07$; Figure 3).

Our drone flights included a wide range of drone altitudes, from 16.9 m to 124.9 m. On average the drone was kept at a relatively high altitude: 48.5 ± 18.8 m (*SD*). Vertical and horizontal speeds ranged from 0 to 5.1 m/s and 0 to 13.6 m/s, respectively. We recorded 46 focal groups where the drone approached the group head-on, 71 where the drone approached the group from behind, and 394 where another approach style was used. We had a maximum of 11 flights per day, with an average of 3.9 ± 2.4 flights. Wind speed was highly variable, ranging from 1 to 37 kn, and averaging 16.8 ± 10.1 kn. On average, we recorded 6.7 ± 5.3 whales per focal group, and group size ranged from 1 to 39 whales. We recorded 318 focal groups that were predominantly milling or resting, 44 groups that were socializing, and 107 focal groups that were engaging in other activities or for whom group behavior could not be accurately assessed.

3.1 | Alert reactions

The results of the alert reactions model showed that alert reactions increased with beluga group size and when belugas were engaged in social behavior. The output of the averaged model featured only two noteworthy variables: group size ($p < .0001$) and social behavior ($p = .02$; Table 5). Both variables were associated with a positive beta

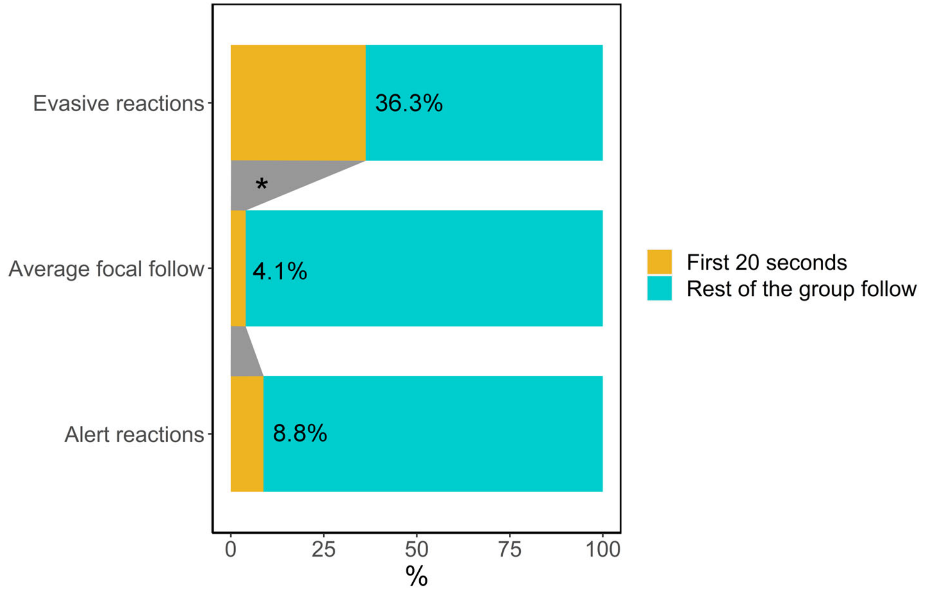

FIGURE 3 Evasive reactions were more likely to occur in the first 20 s than expected by chance ($p < .001$), but alert reactions were not ($p = .07$). We compared the percentage of evasive and alert reactions that occurred in the first 20 s to the percentage that the first 20 s represents for the average focal follow. The average focal follow lasts 493.1 s, such that the first 20 s represents 4.1% of the average focal.

TABLE 5 Output of averaged models for alert reactions and evasive reactions of belugas in response to drones; alert reactions appear to occur significantly more often in larger groups and in groups engaged in social behavior, while evasive reactions occur more frequently as altitude decreases and as group size increases. Variables associated with $p < .05$ are in bold.

Alert reactions average model			Evasive reactions average model		
Variable	β coefficient	*p*	Variable	β coefficient	*p*
Altitude	−0.01	.36	**Altitude**	**−0.04**	**.02**
Vertical speed	0.13	.34	Vertical speed	0.19	.12
Horizontal speed	0.08	.27	Horizontal speed	0.11	.14
Approach: Front	0.03	.97	Approach: Front	0.33	.75
Approach: Other	−0.14	.81	Approach: Other	0.41	.59
Flight number	0.09	.29	Flight number	−0.20	.10
Windspeed	0.03	.24	Windspeed	−0.01	.82
Group size	**0.11**	**.000007**	**Group size**	**0.08**	**.005**
Group behavior: Social	**1.07**	**.03**	Group behavior: Social	−0.83	.43
Group behavior: Other	−0.70	.22	Group behavior: Other	−0.28	.57

coefficient, revealing that the likelihood of alert reactions increased with group size and during social behavior. However, both the *group size* and the *group behavior* models had low explanatory power. The *group size* model had a marginal R^2 of 0.02 and a conditional R^2 of 0.07, and therefore only 2% of the variance in alert reactions was explained by group size. Likewise, the *group behavior* model had a marginal R^2 of 0.01 and a conditional R^2 of 0.10, and therefore only explained 1% of the variance in alert reactions.

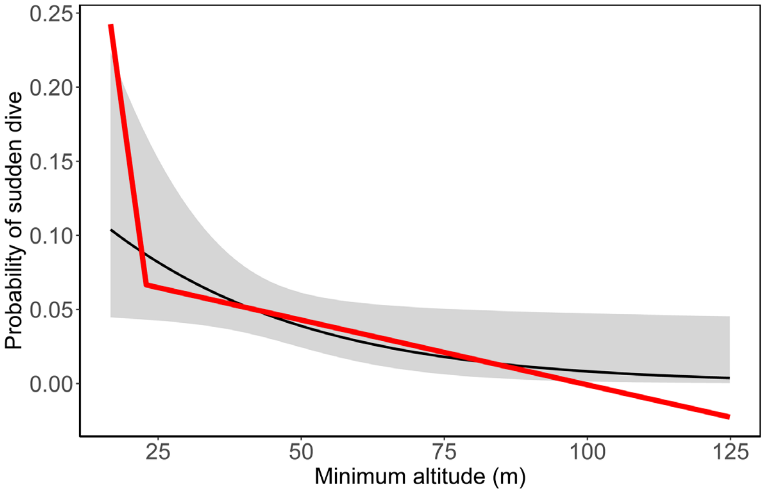

FIGURE 4 The breakpoint analysis of sudden dives versus minimum drone altitude shows that belugas are more likely to show evasive reactions to a drone as minimum drone altitude decreases, particularly at altitudes lower than 22.9 m. The black curve shows the modeled fit of the data, and the gray area shows the 95% confidence interval. The red lines represent the breakpoint regression model estimates. A breakpoint was identified at 22.9 m.

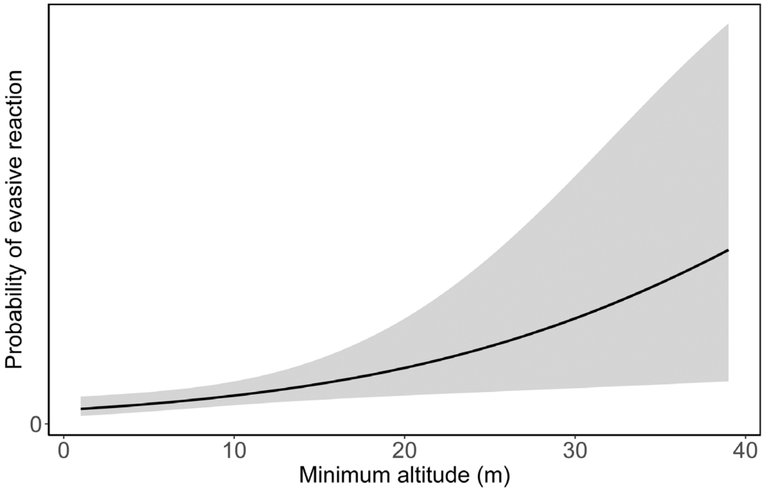

FIGURE 5 The modeled probability of sudden dives in relation to average group size shows that belugas are more likely to show evasive reactions to a drone as their average group size increases. The black curve shows the modeled fit of the data, and the gray area shows the 95% confidence interval.

3.2 | Evasive reactions

The results of the evasive reactions model showed that sudden dives increased with group size and with decreasing drone altitude. Both beluga group size and drone altitude were associated with small *p*-values (.005 and .03, respectively; Table 5). Altitude had a negative beta coefficient, suggesting that evasive reactions became more likely as drone altitude decreased (Figure 4a) while group size was associated with a positive beta

TABLE 6 Literature review of drone-assisted studies targeting cetaceans and reporting on drone disturbance, arranged in order of minimum drone altitude.

Order	Species	Drone model	Minimum altitude	Disturbance assessment	Disturbance observed	Reference
Mysticetes	Blue whale	DJI Phantom 2	5 m	detailed	yes	Domínguez-Sánchez et al., 2018
	Southern right whale	DJI Inspire 1 pro	5 m	detailed	no	Christiansen et al., 2020
	Humpback whale	Custom-built quadcopter	<10 m	cursory	yes	Pirotta et al., 2017
	Southern right whale	DJI Inspire 1 Pro; APH-22; Splashdrone	16 m	cursory	no	Dawson et al., 2017
	Humpback whale	DJI Matrice 200	20 m	cursory	no	Horton et al., 2019
	Gray whale	DJI Phantom 3 Pro; 4 Pro	25 m	detailed	no	Torres et al., 2018
	Humpback whale	HexH2O	30 m	detailed	no	Fiori et al., 2019
	Humpback whale	HexH2O	30 m	detailed	no	Fiori et al., 2020
	Humpback whale	Splashdrone	30 m	cursory	no	Christiansen, Dujon et al., 2016
	Blue whale	APH-22	50 m	cursory	no	Durban et al., 2016
	Bowhead whale	TD100E fixed-wing	120 m	cursory	no	Koski et al., 2015
Odontocetes	Beluga	DJI Phantom 4 Pro	1.5 m	cursory	yes	Palomino-González et al., 2021
	Bottlenose dolphin; sperm whale	Splashdrone	3 m	cursory	no	Centelleghe et al., 2020
	Bottlenose dolphin	DJI Phantom 2; 3 Pro; 4	5 m	detailed	yes	Ramos et al., 2018
	Bottlenose dolphin; common dolphin	DJI Phantom 2	5 m	detailed	yes	Castro et al., 2021
	Bottlenose dolphin	DJI Phantom 4	5 m	detailed	yes	Giles et al., 2021
	Risso's dolphin	DJI Phantom 4	7 m	cursory	no	Hartman et al., 2020
	Various river dolphins	DJI Phantom 3,4	10 m	detailed	no	Oliveira-da-Costa et al., 2020
	Bottlenose dolphin	Splashdrone	10 m	detailed	yes	Fettermann et al., 2019
	Dusky dolphin	DJI Phantom 4	10 m	cursory	no	Orbach et al., 2020

TABLE 6 (Continued)

Order	Species	Drone model	Minimum altitude	Disturbance assessment	Disturbance observed	Reference
	Australian snubfin dolphin, humpback dolphin	DJI Phantom 4 Pro	15 m	cursory	yes	Christie et al., 2021
	Beluga	DJI Phantom 4, 4 pro	16.9 m	detailed	yes	This study
	Dusky dolphin	DJI Phantom 4	20 m	cursory	no	Weir et al., 2018
	Beluga	DJI Phantom 4, 4 pro	20 m	cursory	yes	Aubin et al., 2021
	Sperm whale	DJI Inspire 1 Pro	25 m	cursory	no	Dickson et al., 2021
	Killer whale	APH-22	35 m	cursory	no	Durban et al., 2015
	Various dolphin species	DJI Mavic Pro 2	50 m	cursory	no	Barreto et al., 2021
	Beluga	Telemaster model fixed-wing	150 m	cursory	no	Sleno & Mansfield, 1978
Mysticetes and odontocetes	Blue whale; humpback whale; killer whale	DJI Inspire 2; Mavic Pro	3 m	detailed	yes	Atkinson et al., 2021
	Various mysticetes and odontocetes	Thunder Tiger model helicopter	13 m	cursory	yes	Acevedo-Whitehouse et al., 2010
	Humpback whale; killer whale; harbour porpoise	Cryowing Micro Scout	120 m	cursory	no	Aniceto et al., 2018

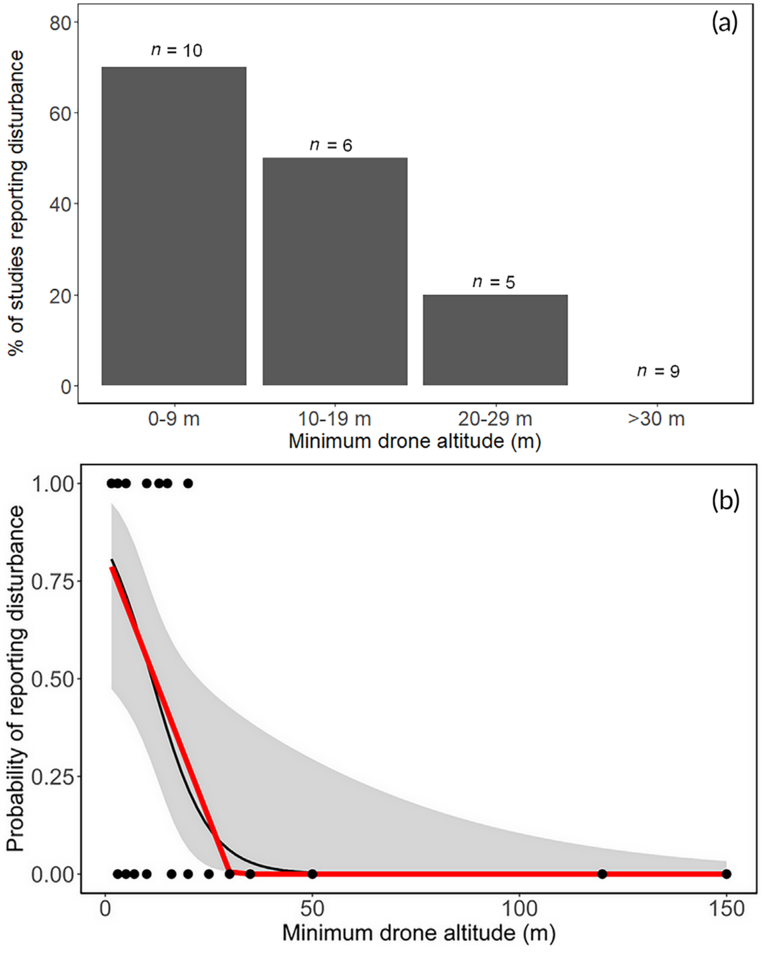

FIGURE 6 Low altitude drone flights provoke more disturbance reactions among cetaceans than higher altitude flights. (a) Percentage of drone-assisted studies targeting cetaceans that reported that drone disturbance occurred, by minimum drone altitude reported. (b) Drone studies where disturbance was (1) or was not (0) reported, by minimum drone altitude. Each data point represents a study in the literature review. The black curve shows the modeled fit of the data, and the gray area shows the 95% confidence interval. The red lines represent the breakpoint regression. A breakpoint was identified at 30.2 m.

coefficient, suggesting that the likelihood of alert reactions increased with group size (Figure 5). However, both models had low explanatory power. The *group size* model had a marginal R^2 of 0.01 and a conditional R^2 of 0.03, and therefore only 1% of the variance in alert reactions is explained by group size. Similarly, the *altitude* model had a marginal R^2 of 0.03 and a conditional R^2 of 0.06, and therefore only 3% of the variance in alert reactions is explained by altitude.

3.3 | Breakpoint analyses

The breakpoint regression model for altitude identified a breakpoint at 22.9 m. When the drone was lower than 22.9 m, the likelihood of provoking a sudden dive increased rapidly compared to flights where the drone was maintained at an altitude greater than 22.9 m (Figure 4b).

3.4 | Ideal drone altitudes for observing cetaceans

Our review of 31 drone-assisted studies of mysticetes and odontocetes showed that most (7/10) studies with flights lower than 10 m reported disturbance, compared to 3/6 studies with minimum altitudes of 10 to 19 m, and 1/5 for studies with flights from 20 to 29 m (Table 6). No studies with minimum altitudes of 30 m or more reported disturbance (Figure 4). Our breakpoint analysis of minimum drone altitude identified a breakpoint at 30.2 m, beyond which the probability of drone disturbance fell to zero (Figure 6).

We also found that studies with detailed disturbance assessment were more likely to report drone disturbance than studies with cursory disturbance assessment: 58.3% (7/12) of studies with detailed disturbance assessment reported drone disturbance, compared to only 20.0% (4/20) for studies with cursory disturbance assessment.

Finally, all studies examined used small drones (<5 kg), such as the DJI Phantom and Mavic series and the Swellpro Splashdrone. Some studies used larger drones such as the Freefly Alta 6 (13.6 kg) and the DJI M600 (10.0 kg), but these studies did not assess drone disturbance (Colefax et al., 2018; Gray et al., 2019).

4 | DISCUSSION

In a detailed analysis of the responses of endangered St. Lawrence belugas to drone flights, we identified relatively few alert and evasive reactions to the drone. We found that group size and social behavior had a weak effect on the occurrence of alert responses, while group size and drone altitude had a weak effect on the occurrence of evasive responses. Our prediction that disturbance would increase during low altitude flights was the only one that received support. All other predictions related to vertical and horizontal speeds, approach style, habituation, wind speed, group size, calf presence, and group behavior were not supported. Nonetheless, our analyses show that drones can disturb belugas and suggest that establishing flight altitude guidelines might help protect belugas from drone disturbance.

4.1 | Alert reactions

Although we found that alert reactions were most common while the whales were socializing in large groups, it is possible that the alert reactions observed did not, in fact, represent reactions to the drone. The vast majority of alert reactions were spy-hops, when a whale positioned itself vertically with its head outside of the water. We had predicted that reactions would increase when the whales were milling/resting because studies on the impacts of occupied aircraft suggest that belugas, right whales (*Eubalaena* spp.), and bowhead whales (*Balaena mysticetus*) are most responsive to aircraft while resting (Payne et al., 1983; Richardson & Malme, 1993). Instead, we found that alert reactions were more common during social behavior. It is possible that belugas are sensitive to disturbance while socializing, but this may not be the most plausible interpretation. As noted earlier, social behavior is often associated with surface behaviors, including spy-hops (O'Corry-Crowe et al., 2009). Although we did not rely on such surface behaviors to categorize group behavior, surface behaviors are still expected to be more common while belugas are socializing. We attempted to control for this by excluding belly-ups and spy-hops that were clearly oriented towards other individuals. However, it was difficult to distinguish between behaviors that were oriented toward other belugas and behaviors that were not. Giles et al. (2021) reported a similar finding in their study of drone disturbance of bottlenose dolphins: they found that behaviors such as belly-ups, head-ups, and tail slaps were most likely to occur in groups that were socializing. Like us, they concluded that these were likely normal social behaviors rather than alert reactions to a drone.

We also found that alerts reactions were more common in larger beluga groups, suggesting that we may have observed more alert reactions simply because we were observing more animals. We had predicted that smaller groups would be more sensitive to disturbance than larger group, given that bottlenose dolphins primarily responded to drones when alone or in small groups (Ramos et al., 2018), and Burrunan dolphins (*Tursiops aduncus australis*) respond more frequently to vessels when in small groups (Filby et al., 2014). It is possible that larger groups are more sensitive to disturbance due to an overall increase in vigilance by larger groups. A known advantage of social behavior is that large groups provide safety through collective vigilance (Pulliam, 1973). However, if the "alert reactions" observed were in fact normal beluga behaviors associated with surface social behaviors, it seems equally likely that more alert reactions were observed in larger groups simply because more animals were being observed performing normal surface social behaviors.

4.2 | Evasive reactions

All evasive reactions observed were sudden dives. We noted that sudden dives commonly occurred when the drone first approached the focal group, supporting the idea that sudden dives represent reactions to the drone. We found that evasive reactions were more common when the drone was flown at lower altitudes. This was expected, as our literature review of 31 drone-assisted studies of mysticetes and odontocetes clearly showed that drone altitude impacts the likelihood of drone disturbance on cetaceans. Disturbance was frequently reported in studies that conducted low altitude flights, but the probability of drone disturbance fell to zero when minimum reported drone altitude was greater than 30 m. A more in-depth look at some of the individual studies featured in the review reveals similar trends. For example, bottlenose dolphins produce more tail slaps and reorient more during 10 m versus 25 m flights (Fettermann et al., 2019), produce more alert responses during flights between 11 and 30 m altitudes (Ramos et al., 2018), and are more likely to show changes in behavior as drone altitude decreases (Giles et al., 2021). It seems likely that the sudden dives that we observed were a startle reaction by belugas in response to a low altitude drone. We may have also observed some startle responses that were unrelated to the drone, and instead were related to other disturbances such as vessels. This may be the case for sudden dives that occurred when the drone was at very high altitudes, when the drone was almost undetectable to us. We found that the likelihood of sudden dives increased rapidly for drone altitudes below 22.9 m. This finding aligns with the results of our literature review of mysticete and odontocete drone studies, that showed that drone disturbance was much more likely to occur at drone altitudes below 30 m.

We also found that sudden dives became more likely as beluga group size increased. Sudden dives were unrelated to individual behavior, as we considered that a sudden dive occurred if more than 50% of a group dove suddenly and simultaneously. Therefore, we did not observe more sudden dives in larger groups simply because more whales were observed. Instead, it seems likely that sudden dives increased in large groups because large groups are more vigilant to threats than small groups or lone individuals, as noted above (Pulliam, 1973). Bottlenose dolphins also show a similar response: as group size increases bottlenose dolphins are more likely to show a change in behavior in response to a drone, likely due to the "many eyes" effect (Giles et al., 2021).

Although we found that group size and altitude impacted the likelihood of sudden dives, these trends were relatively weak. Group size and drone altitude only explained a small portion of variance in sudden dives, and large groups and low altitude flights were not associated with disturbance as a rule. For example, the focal group with the lowest drone altitude did not dive suddenly, nor did the largest group observed.

4.3 | Other variables examined

Although we found no relationships between drone speed and beluga disturbance, nor flight number, approach, and windspeed, these variables should not be dismissed as variables of interest in understanding how belugas or other animals react to drones. The horizontal speed of the drone may still be an important factor, given that increases in drone speed increase rotor noise (Erbe et al., 2017), increasing the likelihood of the drone being detected. Differing angles of approach may also result in differing responses, given that vertical approaches appear to be more disruptive than horizontal approaches (McEvoy et al., 2016; Vas et al., 2015). In addition, the direction of approach relative to the study animals may be an important consideration. Blue whales (*Balaenoptera musculus*) only responded to a drone when approached head-first rather than tail-first, while belugas responded to a hovering drone that was in front of them, but not behind them (Domínguez-Sánchez et al., 2018; Palomino-González et al., 2021). Sequential flights might also impact responses, as bottlenose dolphins were less likely to show disturbance behaviors after repeated drone flights (Ramos et al., 2018). Although we did not find evidence of habituation in terms of decreased likelihood of response with number of flights, sudden dives were significantly more likely to occur when the drone first approached the whales. Finally, wind speeds may impact responses, as drone noise may be particularly noticeable during low wind conditions (Christiansen, Rojano-Doñate, et al., 2016).

4.4 | Limitations

The flights that we analyzed for this study were not originally intended for a drone disturbance study, and consequently we were somewhat constrained by our data. In particular, our study design was complicated by the correlation between calf presence and drone altitude, which compromised our ability to make inferences about drone altitude, disturbance, and the presence of calves. Future studies examining drone disturbance on cetaceans should examine the effects of calf presence on disturbance reactions. In addition, this study assessed disturbance from only two similar drone models (the DJI Phantom 4 and Phantom 4 Pro), which are both small drones (<5 kg). Similarly, all studies in the literature review that reported on disturbance used small drones. As such, any recommendations derived from our study and literature review may not be sufficiently stringent for studies using larger drones, which tend to be louder than small drones (Erbe et al., 2017).

4.5 | Recommendations and best practices

Based on our analyses of beluga responses to drones, and our review of the literature on cetacean drone disturbance, we present the following seven recommendations.

1. Drone-assisted studies of belugas that involve small drones in contexts similar to those reported here can likely be flown with minimal disturbance at altitudes >23 m. To be cautious, we recommend a limit of 25 m for such studies.
2. Researchers using drones to study cetacean species with no specific drone altitude recommendations should weigh the degree of disturbance caused by low altitude flights against the conservation benefit to the species.
3. Special caution should be used when flying drones over large groups, because larger groups increased the likelihood of reaction for both belugas and bottlenose dolphins, and this may also be the case for other species.
4. Drone pilots should employ caution when first approaching a group, given that animals may be more easily startled when first approached by a drone.
5. More data are needed to determine the impact of larger drones (>10 kg) on cetaceans. Given this lack of data, researchers using larger drones should be particularly vigilant to disturbance reactions and should report on the presence or absence of disturbance reactions in their published studies.
6. Our literature review showed that studies that made only cursory assessments of drone disturbance were less likely to report drone disturbance, suggesting that drone disturbance may be missed if specific disturbance behaviors and parameters are not defined and assessed. Future drone-assisted studies should take care to define potential disturbance behaviors and parameters *a priori* and report on any disturbances observed. Studies should also report the model and size of the drones used, and the altitude ranges at which they were flown.

7. Finally, although we found no effect of drone speed, approach style, or wind, previous studies have suggested that these variables may impact the likelihood of disturbance (Christiansen, Rojano-Doñate, et al., 2016; Domínguez-Sánchez et al., 2018; Erbe et al., 2017; Palomino-González et al., 2021). Adopting a precautionary principle, and given these previous findings, we recommend that drone pilots avoid sudden accelerations, avoid approaching whales head-on, and maintain caution during low wind conditions, when the noise of the drone is particularly apparent. These precautionary measures may reduce the likelihood of drone disturbance of cetaceans.

By employing the precautionary principle, researchers should minimize the potential for negative impacts of drone studies targeting belugas and other cetaceans.

ACKNOWLEDGMENTS

We wish to thank Michel Moisan, Timothée Perrero, and the Groupe de Recherche et d'Éducation sur les Mammifères Marins for in-kind support and assistance in the field. This research was supported by funding from the Natural Sciences and Engineering Council of Canada, the Société des Établissements de Plein Air du Québec, Parks Canada, Earth Rangers, The Fondation de la Faune du Québec, the Donner Canadian Foundation, and the Kenneth M. Molson Foundation. The authors have no conflicts of interest to declare.

AUTHOR CONTRIBUTIONS

Jaclyn A. Aubin: Conceptualization; data curation; formal analysis; investigation; methodology; writing – original draft; writing – review & editing. **Marie-Ana Mikus:** Conceptualization; data curation; formal analysis; investigation; methodology. **Robert Michaud:** Funding acquisition; project administration; resources; writing – review and editing. **Daniel J. Mennill:** Project administration; resources; supervision; writing – review and editing. **Valeria Vergara:** Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; writing – review and editing.

ETHICAL NOTE

Our fieldwork methods were reviewed and approved by the Memorial University Animal Care Committee (Animal Use Protocol: 20190640). Our research, and specifically, the use of research drones in the Saguenay St. Lawrence Marine Park was covered by research permit SAGMP-2018-28703 issued by Parks Canada and QUE-LEP-001-2018 issued by Fisheries and Oceans Canada.

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ENDNOTE

[1] Here, we use the term "unoccupied" to eliminate the gender bias inherent to the more widespread term "unmanned" (Smith, 2004).

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How to cite this article: Aubin, J. A., Mikus, M.-A., Michaud, R., Mennill, D., & Vergara, V. (2023). Fly with care: belugas show evasive responses to low altitude drone flights. *Marine Mammal Science*, 1–22. https://doi.org/10.1111/mms.12997