Measuring the effect of unmanned aerial vehicles (UAVs) on seabirds from onboard and ground-based video at Raine Island, Great Barrier Reef, Australia.

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ATTESTATION OF AUTHORSHIP

"I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning."

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ABSTRACT

Conservation science requires innovative approaches to study wildlife without disturbing the species it seeks to preserve. Video and photogrammetry from unmanned aerial vehicles (UAVs or drones) can efficiently survey animals, vegetation and topography over large, difficult to access and sensitive environments. This information can be analysed in geographic information systems (GIS) to estimate changes in population size, density, distribution, diversity and behavior. Observing organisms and habitats from above can avoid the potential effects of trampling and a human presence in ground-based surveys and provide data from an alternate perspective. However, the drones themselves can have impacts, particularly for easily disturbed species like nesting and roosting seabirds. This study assesses the ability of drone based aerial video and still images to monitor seabird disturbance during surveys flown at 8 heights between 20 and 120m. The results are compared to estimates made from a ground-based video camera and to counts of birds leaving the ground made by three ground-based human observers. Still images sampled from the drone videos were orthorectified in ArcPro GIS and subsampled to count flying birds over the same areas of ground viewed from different heights. Three second videos preceding each still image assisted in distinguishing flying birds in each image from bird shadows and other artefacts. The counts of flying birds made from the drone videos and images were comparable to counts made by ground observers but recorded smaller numbers of flying birds, particularly at lower altitudes. The counts of flying birds made from the ground-based video camera provided a good overall view of flying birds, but estimates were confounded by resampling the same birds when the drone's course directly approached the camera. The three survey methods each had advantages and biases and I make recommendations for conducting future research. For the ground-based observer and drone video methods, there was a general decrease in counts of flying birds when the drone was flown at greater heights. In these trials, only roosting birds took flight and most birds returned to the ground within a few minutes. The results suggest that, when necessary, flying a drone at least 60m above seabird colonies causes less disturbance. However, seabird responses to the drone varied greatly and there are other factors that require further investigation including the effects of type of drone and how it is flown, different seasons, population densities and species and the impact of less obvious physiological, feeding and reproductive effects on seabirds.

1 Introduction

There is clear and widespread evidence that Earth's ecosystems are changing rapidly and that human influences such as habitat destruction, over-harvesting, invasive species, pollution and climate change are responsible (Deem, Karesh & Weisman, 2008, Knutti, 2008). There is an increasing need for conservation science to guide and implement urgent management. Understanding the natural history and ecology of species and their environments is an essential building block for successful management (Bury, 2006). The increasing role of conservation biology in ecosystem preservation and restoration was described by Soulé (1985) as "…a new stage in the application of science to conservation problems, addressing the biology of species, communities and ecosystems that are perturbed, either directly or indirectly, by human activities or other agents. Its goal is to provide principles and tools for preserving biological diversity."

This study contributes to a multidisciplinary research programme supporting the Raine Island Recovery Plan (Dunstan et al., 2020). Islands have a unique role in conservation for their high level of endemism and as refuges for previously widespread populations and habitats (Towns 2023). Raine Island is located on the outer edge of the northern Great Barrier Reef (Figure 2). Despite being only a kilometre long and a few metres above sea level, it is the largest green turtle (*Chelonia mydas*) nesting area in the world and the most important seabird island on the Great Barrier Reef (Department of Environment and Science, 2022).

Turtles and seabirds are prone to overharvesting, fisheries bycatch, predation by invasive species, plastic and other pollution. The low-lying islands they nest on, the surrounding reef and the oceanic food webs they rely on, are also at risk from increasing high tides, temperatures, cyclones, coral bleaching and ocean acidification (Dawson et al., 2014).

The Raine Island Recovery Plan aims to address range of environmental, historic and cultural objectives including: assessing and improving the resilience of the island's wildlife; monitoring changes in turtle and seabird populations; undertaking management interventions such as artificially re-profiling and extending nesting beaches to raise turtle nesting sites above levels of tidal inundation; and fencing cliffs to reduce the number of turtles dying of exposure after falling or becoming trapped (Department of Environment and Science, 2022).

These activities also have the potential to affect other aspects of the island's ecology such as intruding on seabird nesting and roosting habitats and disturbance to nesting and

roosting seabirds from unmanned aerial vehicles (UAV's or drones). These are being used to count nesting turtles at night (with infra-red cameras) and make mark-recapture estimates of the large numbers of turtles swimming around the island by day. They are also being used in mapping island morphology, vegetation, reef biota, turtles and seabirds and in producing educational wildlife documentaries.

Seabirds share a suite of distinctive attributes: low reproductive rates, delayed onset of reproduction, protracted development, widespread distribution and long lifespans (Ricklefs, 1990). As sentinel species, seabirds have been instrumental in understanding the effects of fishing, habitat loss on island and mainland areas, introduced pests, pollution and climate change (Knudsen et al, 2011, Borowicz et al, 2018). However, monitoring seabirds travelling over large areas of ocean and nesting in often remote, inaccessible or sensitive environments can be costly, labor-intensive and the length of time available for surveys may be limited. This can lead to data being inconsistent, collected infrequently, subject to observer error (Dickinson, Freeman, Patrick & Lawson, 2018) and intrinsically variable due to natural variation in the distribution and behaviour of aggregating species.

The use of drones in remote sensing has become an increasingly important tool for surveying and monitoring wildlife (Rush et al., 2018, Chabot and Bird, 2015). When compared to photography from manned aircraft, satellite imagery or ground-based surveys, drone imagery can provide relatively cost-effective, timely, high-resolution data from a range of sensors (Hodgson et al., 2018). This technology becomes particularly useful in dangerous, difficult to access or sensitive areas, with potentially minimal impacts on wildlife (Dunstan et al., 2020).

Raine Island is managed by the Queensland Department of Environment and Science as a National Park (Scientific) and the surrounding waters are a Marine National Park Zone managed by the Great Barrier Reef Marine Park Authority (Figure 3, Table 1). Human access to these areas is highly restricted. One condition for the research permit and ethics approval to fly a drone in this area was to monitor the effect of research drones on the Island's nesting and roosting seabirds. This study contributes to a broader investigation on the effect of drones on the Island's seabirds but focusses specifically on developing and testing the use of onboard video imagery and ground-based video to assess levels of seabird disturbance during drone flights. If effective, this would allow for in-flight, 'self-monitoring' for obvious signs of seabird disturbance for varying drone types, environmental conditions, species, population densities and seasons.

The research goal of this thesis is to determine whether video from a drone flying at heights between 20 and 120m or video from a stationary ground-based camera can be used to monitor disturbances to seabirds at Raine Island. In this case, disturbance from the drone itself.

1.1 Research questions

In this study, I aim to address the following questions:

1. Can still images from videos acquired by drones be used to count the number of seabirds flying below as an approximate measure of the disturbance the drone causes?
2. How can counts of birds from drone videos flown at different heights be compared when the cameras field of view and sample unit area increase with altitude?
3. How do these estimates compare with counts of birds leaving the ground made by ground observers at three vantage points?
4. How do counts of flying birds estimated from a ground-based video camera compare with those from the above methods?
5. Is there a relationship between seabird disturbance and the height of the drone?
6. What recommendations for drone use can be made to limit seabird disturbance and monitor its impact?

This following section reviews the history, geomorphology, vegetation, and wildlife of Raine Island and the benefits and disadvantages of using drones to survey vulnerable species such as seabirds.

1.2 Raine Island

Raine Island (11°35′28″S 144°02′17″E) is located off the far northern, outer edge of the Great Barrier Reef (Dawson & Smithers 2010; Figure 2). Raine Island Reef is a planar, coral reef and lies: 100 km north-east of Cape Grenville, the nearest point on the Queensland mainland (Stoddart, Gibbs and Hopley, 1981); 192 km from Cape York (the northern-most point of Australia); and 620 km north of the City of Cairns. The Island is 27 ha in area and lies at the leeward, north-west end of the larger, oval shaped Raine Island Reef (Figure 6).

The Wuthathi People and Kemerkemer Meriam Nation (Ugar, Mer, Erub) People are the Traditional Owners and Native Title holders for this country and are integral partners of the area's management (Dunstan, Robertson, Fitzpatrick, Pickford & Meager, 2020). Raine Island is a significant cultural place for the Wuthahi Aboriginal people who are recognized as traditional owners and holders of the land and manage the native title rights and

interests in the region. Torres Strait Islanders from Erubam Le, Meriam Le, and Ugarem Le Islands to the north also hold indigenous rights and interests in the area (Queensland Government, 2006 – 2016, Hopley, 2008, Queensland Government, 2020). These rights include that Indigenous cultural resources, values, and practices will be recognized, respected, protected, and will be meaningfully involved in the planning for, and management of, these resources. This includes in particular, Aboriginal and Torres Strait Islanders asserting native title on Raine Island National Park (Scientific) and the adjoining marine park areas (Hopley, 2008). Raine Island was declared a 'Reserve for Departmental and Official Purposes 'in 1978 by the Queensland Government under the guidelines of the former Department of Aboriginal and Islander Affairs.

A 14 m high, unlit navigation tower built in 1844 (figure 1) from guano-based phosphate rock stands at the southeastern end of the Island marking the entrance to a major passage through the northern Great Barrier Reef (Figure 5). The beacon is listed on the State Heritage Register and the Register of the National Estate (Queensland Government, 2020) and includes 900 inscriptions including Erubam Le, Meriam Le, and Ugarem Le Torres Strait Islander names.

Figure 1. Navigation beacon built in 1844 from guano-based phosphate rock.

Figure 2. Location of Raine Island (red) at the northern end of the Great Barrier Reef, Queensland, Australia (Google Earth).

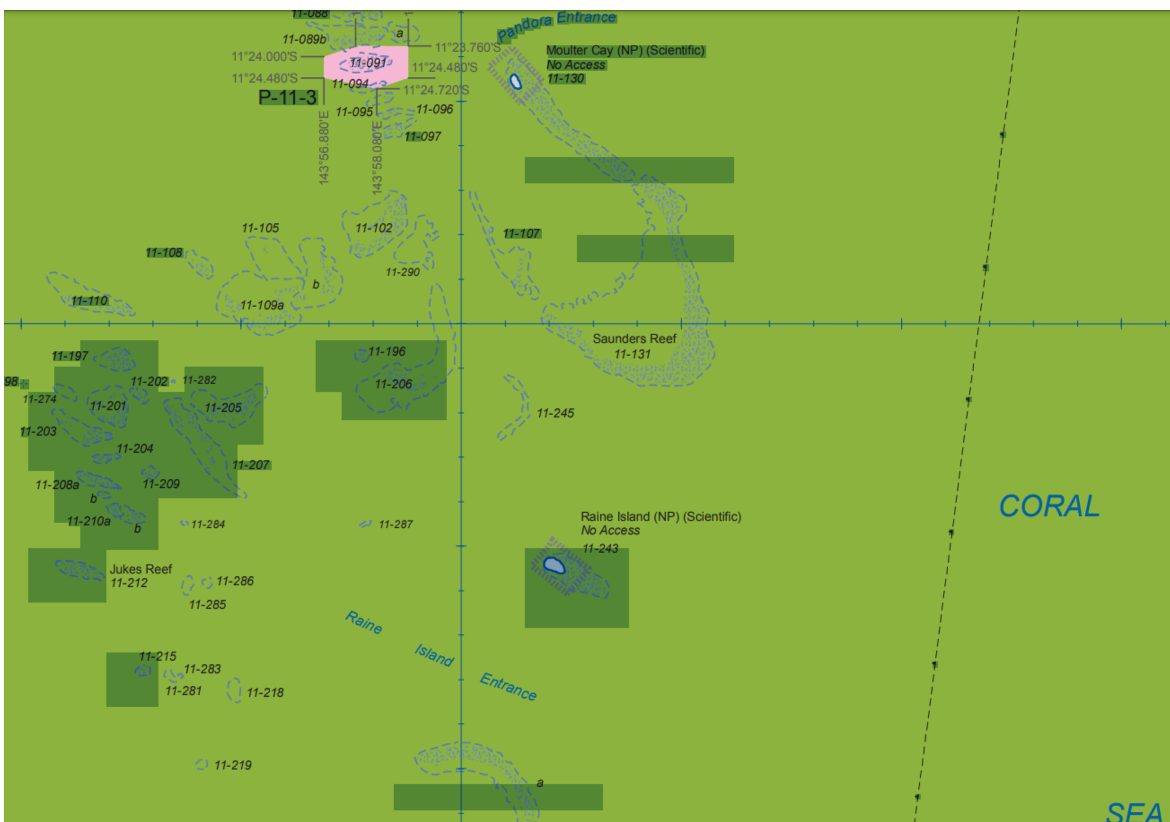

Figure 3. Great Barrier Reef Marine Park Authority multiple use zoning regulations around Raine Island (No public access (pink) and no-take Marine National Park (dark green) and nearby reefs in Buffer Zones (light green, where only surface trolling and traditional use are permitted).

Table 1. Human activities restricted or permitted in multiple use marine park zones (Great Barrier Reef Marine Park Authority).

ACTIVITIES GUIDE
(see relevant *Zoning Plans* and *Regulations* for details)

Activity	General Use Zone	Habitat Protection Zone	Conservation Park Zone	Buffer Zone	Scientific Research Zone [3]	Marine National Park Zone	Preservation Zone	State Zoning Only: Estuarine Conservation Zone
Aquaculture	Permit	Permit	Permit [1]	✗	✗	✗	✗	Permit
Bait netting	✓	✓	✓ [2]	✗	✗	✗	✗	✓
Boating, diving, photography	✓	✓	✓	✓	✓ [3]	✓	✗	✓
Crabbing (trapping)	✓	✓	✓ [4]	✗	✗	✗	✗	✓
Harvest fishing for aquarium fish, coral and beachworm	Permit	Permit	Permit [1]	✗	✗	✗	✗	✗
Harvest fishing for sea cucumber, trochus, tropical rock lobster	Permit	Permit	✗	✗	✗	✗	✗	✗
Limited collecting	✓ [5]	✓ [5]	✓ [5]	✗	✗	✗	✗	✓
Limited spearfishing (snorkel only)	✓	✓	✓ [1]	✗	✗	✗	✗	✓
Line fishing	✓ [6]	✓ [6]	✓ [7]	✗	✗	✗	✗	✓
Netting (other than bait netting)	✓	✓	✗	✗	✗	✗	✗	✓
Research (other than limited impact research)	Permit	Permit	Permit	Permit	Permit	Permit	Permit	Permit
Shipping (other than in a designated shipping area)	✓	Permit	Permit	Permit	Permit	Permit	✗	Permit
Tourism programme	Permit	Permit	Permit	Permit	Permit	Permit	✗	Permit
Traditional use of marine resources	✓ [8]	✓ [8]	✓ [8]	✓ [8]	✓ [8]	✓ [8]	✗	✓ [8]
Trawling	✓	✗	✗	✗	✗	✗	✗	✗
Trolling	✓ [6]	✓ [6]	✓ [6]	✓ [6,9]	✗	✗	✗	✓

1.3 Geomorphology of Raine Island

Raine Island Reef lies offshore from a major pass in the Great Barrier Reef and depths rapidly fall to more than 180 m beyond the reef edge. Raine Island Reef is thought be built on bioherms by calcareous green algae from the genus *Halimeda* during the Pleistocene age (Dawson, Smithers & Hua, 2014). The green leaves of *Halimeda* conceal a disc-shaped limestone skeleton and these algal reefs, many metres high and wide, exist today in narrow passes between outer reefs and include biodiversity unique to this biogenic habitat. *Halimeda* species also provide much of the sand for many coral cays on the Great Barrier Reef including Raine Island.

The Island is the largest oceanic cay on the outer fringe of the Far Northern Great Barrier Reef. Gibbs and Hopley (1981) described the island as 1000 yards (915 m) long, 500 ft (150 m) wide, and up to 20 ft (6 m) high above high water level. The topography of the island includes a 4 ha central depression of guano rock surrounded by sand dunes, a low escarpment and a beach (D. R. Stoddart, 1981). The central depression is a mostly flat, unvegetated hard surface formed from bird excreta deposited over hundreds of years

(Batianoff, 2007, Hopley, 2008), turtle skeletons and isolated rock and earth mounds and depressions remaining from guano mining (Dyer, 2003). The dune ridges surrounding the central depression cover an area of 9.6 ha in sand and low-lying grasses, succulents, creepers, and small shrubs (Stoddart, 1981, Hopley, 2008).

A 2 m high escarpment of weathered coral rock and shallow caves surrounds the vegetated dune ridge. This is a hazard for green turtles that manage to climb up the cliff but then fall and die on their backs in the sun as they are unable to turn themselves upright and return to the ocean. The caves, however, provide nest sites for red-tailed tropic birds regularly monitored at mapped locations around the perimeter of the cliff.

Below the cliff, low vegetated dunes, a shallow swale or depression, foredune and upper beach lead to a steep intertidal shore and coral reef. Around the mid-tide mark, low outcrops of limestone beach rock form from fragments of coral and other calcareous organisms cemented together through the chemical solution and deposition of calcium carbonate. The sometimes-recent origin of this “beach rock” is evident from the pieces of shell, coral, eggshells (Stoddart, Gibbs and Hopley, 1981) and at other locations, glass bottles embedded in it.

Coral sand cays are inherently unstable, and waves and currents are known to move and reshape shorelines through erosion and deposition, especially after cyclones and other storms (Batianoff, 2007, Dawson and Smithers, 2010). Calcifying reef organisms like corals, molluscs, echinoderms, calcareous algae and giant foraminifera contribute most of the sediment to the island. These may also be affected by ocean acidification, warming, sea level rise and an increasing number and intensity of cyclones (Hopley, 2008, Dawson and Smithers, 2010, 2014). The stability of the island’s geomorphology is therefore vulnerable under most climate change scenarios.

1.4 Vegetation

There are no trees on Raine Island and vegetation consists of 12-13 species of low shrubs, herbs, and grasses (Stoddart, Gibbs & Hopley, 1981, Hacker, 1990, Government of Queensland, 2021). The introduction of goats and later, phosphate mining in the 1890’s and planting of vegetables and non-endemic plants, would have affected plant species abundance and diversity (Government of Queensland, 2014, 2021). Observations in the 1840s indicate there were about 20 species of vascular plants on the island, but the number of species fell to 11 by 1874 and to 6-11 species by the 1950s and 1960s (Hopley, 2008).

Grasses and herbs on the upper part of the beach, foredune and swale vary in density and extent from year to year and during turtle nesting. During nesting, the beach can be completely dug over each night and may be devoid of vegetation (Limpus, Miller, Parmenter & Limpus, 2003). Two species of grass grow on the Island, *Eleusine indica*, an introduced species, and thin tail grass (*Lepturus repens,* Figure 4), a native plant common on the northern Great Barrier Reef islands (Stoddart et al., 1981). *L. repens* helps stabilize the island's soil (Hopley, 2008) and is abundant on islands and coasts in the warmer regions of the Pacific and Indian Oceans (de Lange, 2021). It is one of the dominant plant species on the island (David R Stoddart, 1991, Batianoff & Cornelius, 2005) and occurs seasonally above the beach and in the swale, and is often disturbed during the turtle nesting between November and February (Dawson & Smithers, 2010).

Plants on Raine Island arrive as seeds transported by currents, high winds, seabirds, and humans (Batianoff, 2007, Hopley, 2008, Hacker, 1990) and changes in ocean currents and human visitation may increase the arrival of seeds, including invasive plant species (Batianoff, 2007, Hopley, 2008). *L. repens* is dispersed around the island by birds and human disturbance (Hacker, 1990, Hopley, 2008) and this cover of grass may provide nesting habitat for several seabird species (Hacker, 1990, Batianoff and Cornelius, 2005). The island's vegetation is often affected by droughts and cyclones during the dry and wet seasons (Hopley, 2008). In the hot dry season, the ground may appear almost bereft of live vegetation but after heavy rains, the vegetation can become relatively dense with a continuous cover of 2-3 m high shrubs and tall grasses.

The area between the cliff and the beach is used for nesting by green sea turtles (*C. mydas*). However, the nests, especially in the swale, are being drowned by rising water levels, with a corresponding fall in hatch rate (Hopley, 2008). Beach re-profiling to raise the height of the beach and increase the area available for nesting is being used to enhance turtle hatch rates. However, this may also affect vegetation and those species of seabirds which use this beach and dune vegetation. Ongoing monitoring of vegetation has been recommended (Hopley, 2008) and drones have been used recently to map changes in the Island's vegetation, morphology and bird life (Chawhan 2021).

Figure 4. Thin tail grass (*Lepturus repens,* de Lange 2021)

1.5 Nesting green turtles

Nesting of green turtles at Raine Island was described by Jukes in 1847 and the island is one of the most studied turtle nesting sites in the world (Hopley, 2008). Each year, up to 130,000 female turtles travel from northern Australia and surrounding areas to Raine Island and nearby Moulter Cay, with up to 15,000 turtles coming ashore to lay in one night. (Dunstan et al., 2020). These turtles lay approximately 100 eggs each time but will come ashore up to six times to lay during the season between February and October (Mattocks, 2014b).

The eggs hatch in around 60 days but only 1 in 1,000 young survive until maturity (Dunstan et al., 2020). Survival and ongoing reproduction depends on weather patterns, ocean currents, El-Nino effects, nesting sites, food availability and predation by many species when young (Mattocks, 2014a, CJ, 2008), and by tiger sharks (*Galeocerdo cuvier*) when mature, although the sharks are mainly attracted to dead or sick turtles (Fitzpatrick et al., 2012).

Climate change affects green turtles through increases in temperature, sea level, rainfall and cyclones. Higher temperatures increase stress and mortality during nesting and alter sex ratios in hatchlings (Hamann, 2007). More female turtles are born in nests with higher temperatures (Laloë et al., 2014, Mattocks, 2014a, Jensen et al., 2018) and this ratio may increase with global warming (Mattocks, 2014a, Dunstan et al., 2020).

Sea surface temperatures on the Great Barrier Reef have increased by 0.4 degrees in the last 30 years. In 2016, the hottest temperatures in the history of the Great Barrier Reef were recorded (Heron et al., 2016) and a predicted rise in temperature of 2.6°C by 2100, could result in 99 % of turtle hatchlings being female (Blechschmidt et al., 2020) thereby

reducing the chances of fertilization dramatically. At nearby Moulter Cay, Fuentes et al (2009) predicts a female dominated sex ratio by 2070.

Hatch rates of turtles at Raine Island have also declined due to flooding of nests from a rising water table (Hopley, 2008, Veelenturf et al., 2020). Almost a third of green turtle nesting habitats on the Great Barrier Reef are predicted to be flooded due to climate change (Veelenturf et al., 2020).

Monitoring and management of changes in the island and its wildlife and cultural values is being carried out by the Queensland Department of Environment and Science, the Great Barrier Reef Marine Park Authority, the Great Barrier Reef Foundation, Biopixel Ltd, BHP-Biliton and the Traditional Aboriginal Owners, the Kemer Kemer Meriam Nation and universities including the Auckland University of Technology.

Over a kilometre of fencing along the cliff edge has prevented hundreds of adult turtle mortalities. The height of a trial section of beach has been raised and extended and has successfully increased the hatch rates of nestlings from this site. However, these areas are also used by seabirds, particularly in the upper beach and dune areas into which turtle nesting areas have been extended. The fence appears to have a positive effect for birds which perch on it, particularly red-footed boobies (*Sula sula*). This species prefers to roost and nest 'about a foot above the ground' (Dyer 2003) and the fence appears to provide additional habitat for, what are, along with birds on nearby Moulter Cay, the only red-footed booby colonies on the Great Barrier Reef.

1.6 Seabirds

Raine Island is the most important seabird island on the Great Barrier Reef. Fourteen of the 24 seabirds that breed on islands in Queensland breed on Raine Island (Batianoff & Cornelius, 2005). Species breeding here include black-naped tern, bridled tern, brown booby, common noddy, crested tern, greater frigate bird, herald petrel, lesser frigatebird, masked booby, red-footed booby, red-tailed tropic bird, silver gull, sooty tern and wedge-tailed shearwaters. Nankeen night heron seasonally occur on the island in large numbers to nest and prey on turtle hatchlings There are also banded rail, migratory shorebirds, and vagrants recorded (Stoddart, Gibbs, and Hopley, 1981).

Seabirds are a collection of species that spend most of their time in marine environments (Balance 2007) and include species such as albatrosses, petrels, gulls, terns, boobies, frigate and tropic birds, shags, gannets, and penguins (Whitehead & Dunphy, 2019).

Seabirds have high intrinsic, functional and scientific value and are sentinels of the condition other species and ecosystem processes. Marine environments present challenges for seabirds, and this has played an important role in shaping their life histories and physiology. Many have adaptations for swimming and diving such as webbed feet and dealing with salt water through salt glands, an extra-renal glands and relying on the water content of their food. Seabird bills are adapted for different prey and methods of feeding on active fish, squid and other prey that can be difficult to capture and handle. Frigate birds *(Fregata sp.*) catch flying fish using their hooked bills but are also kleptoparasites harassing other seabirds until they regurgitate or give up prey, and then stealing the food in mid-air as their feathers, unlike most seabirds, are not waterproof. Their wide, swept back wings and forked tail enable them to glide on thermals and fronts and maneuver quickly in pursuit of other seabirds and their stolen prey. The body shape of boobies is bullet shaped, an adaptation to deep dives from great heights to capture fish well below the surface (Schreiber & Burger, 2001, Farner & King, 2013).

"Seabirds are abundant, conspicuous, and wide-ranging marine predators that feed principally on planktonic crustaceans and small fish" (Piatt et. al. 2007). The use of seabirds as indicator species to monitor conditions of aquatic ecosystems has been well established (Mallory, Robinson, Hebert & Forbes, 2010). Seabirds respond to changes in their marine environment over a variety of temporal and spatial scales and make choices about where to feed and search for prey over large areas of ocean (Diamond & Devlin, 2003).

Species respond to environmental conditions according to their time and energy budgets, diet, reproduction, movements and other life history traits (Einoder, 2009). Indicator species are those that "are easily monitored and whose status reflects or predicts the conditions of the environment where they are found" (Quinn, Brandle, Johnson & Tyre, 2011, Siddig et al., 2016).

Seabirds have been identified by the Hauraki Gulf State of the Environment report as key ecosystem components (Gaskin and Rayner, 2013) and been used as mobile indicators of the state of oceanic ecosystems through shifts in size, behavior, and chemical signatures of individual tissues (Gaskin and Rayner, 2013).

Seabirds may spend most time at sea but nest on islands in colonies, often alongside groups of other seabird species. As seabirds are more easily observed on the ground, most knowledge of seabird biology has been obtained during that short part of their life history. But even here, seabirds are not easy to study, often nesting, feeding and migrating

in remote areas that are difficult to access, and it has been expensive to study seabirds (Ballance, 2007).

Monitoring of seabirds can be both labor-intensive and impractical due to seabirds often breeding in harsh, remote and sensitive environments and where time in the field may be limited. This can lead to surveys being inconsistent, infrequent with the potential for observer error (Dickinson et al., 2018). Ecologists increasingly rely on technology to help reduce some of these issues (Hodgson et al., 2018). For example, advances in tagging and tracking have greatly assisted the study of seabirds at sea (Piatt et al., 2007).

On land around colonies of nesting and roosting seabirds, population monitoring has often relied on observations from ground-based observers, sometimes with a limited view of all individuals and sampling only portions of the population. There is also the potential for observers to trample vegetation, nests, eggs and young and disturb adult birds causing them to leave nests with eggs or chicks exposed to predators and adverse weather and solar radiation.

Camera and video 'traps' triggered by motion or infrared detectors can be deployed to study wildlife by providing images of passing animals (Willi et al., 2019), although planting cameras in less accessible or sensitive habitats may also affect wildlife (Hodgson et al., 2018) or be dangerous for observers (Weinstein, 2017). The Raine Island Recovery Plan includes programmes with permanently mounted videos and acoustic listening posts located around the island. Data from these are transmitted by satellite to the mainland and analyzed for changes in seabird activity, abundance and species composition during the long periods of time that human observers are absent.

1.7 Remote sensing of wildlife using drones

Drones are an important tool in ecological research especially in inaccessible or sensitive areas (Damien, 2009). Drones were first used in World War I when the U.S. Navy asked Elmer Ambrose Sperry to build unmanned air torpedoes, launched by catapult and remotely guided to a target. In WWII, remote controlled unmanned aerial devices were used to target German bunkers (McDougal, 2013).

However, more recent developments in auto-stabilizing microcontrollers and battery technology have led to smaller, quieter, cheaper and more easily navigated and automated drones. Drones use Global Positioning Systems (GPS), differential GPS and Real Time Kinetic (RTK) systems to accurately fly and record either pre-determined coordinates and routes or free-fly using radio ground controls (Marcon et al., 2018).

Autopilot and flight-planning software can now be easily used by most operators (Wallace, Martin & White, 2018) with basic training. Most drones are equipped with motion sensors, object avoidance, return to home, follow and other navigation aids (Ivošević, Han, Cho & Kwon, 2015). They can carry a range of colour, multispectral, hyperspectral, LIDAR and thermal imaging sensors (Sandbrook, 2015).

One of the more positive uses of drones is in biodiversity conservation. They are used to map and identify habitats and species, monitor populations, understand behaviour and provide surveillance for protected areas. (Giacomo et., al, 2021). Drones have been used to map, monitor, track, and count many species of birds, mammals, reptiles and their habitats (Lahoz-Monfort & Magrath, 2021, Jiménez López & Mulero-Pázmány, 2019). Drones provide an alternative method of counting surface-nesting birds on islands (McClelland, Bond, Sardana, & Glass, 2016) that can potentially reduce disturbance, save time and provide a unique spatial perspective on species distributions and habitat use.

They reduce the need for observers to walk near or through breeding areas, potentially causing disturbance to nesting birds and trampling of vegetation, eggs, young and nests, including burrows (Valle & Scarton, 2019). A drone video or camera can provide spatial coordinates and high-resolution observations of animals, nests, vegetation, habitat, and behaviour. This reduces the effort required to relocate nests monitored through time and enables the analysis of spatial patterns in distribution, density and spacing. It also allows spatial and temporal relationships between vegetation, topography, other species and human activities to be mapped and analysed (Valle & Scarton, 2019).

1.8 Disturbance of wildlife by unmanned aerial vehicles.

While drones may reduce disturbance by reducing the presence of ground observers, drones can also have adverse effects. Drone surveys may reduce the time spent near nests during ground counts, but drone flights have caused panic among birds causing them to fly away from nesting areas (Valle & Scarton, 2019). As the use of drones in avian research is relatively recent, there have been few studies on their impact (Gallego & Sarasola, 2021). Weston et al. (2020) suggests “One prominent potential negative effect of drones interacting with birds is disturbance; the disruption of normal states caused by responses such as escape.”

In addition to obvious escape behaviors, drones may also affect other aspects of behavior, physiology, reproduction, predation and disease. (Frąckiewicz, 2023, Jiménez Lopez & Mulero-Pázmány, 2021). Studies have shown that disturbance can lead to increased heart

rates and corticosterone levels in birds that do not appear to react behaviorally (Vas, Lescroël, Duriez, Boguszewski & Grémillet, 2015). Low altitude flights, noise, and the frequency of drone use contribute to the degree of disturbance, an extreme example is the 'swarms' of drones being trialed to survey forest fires (Wallace, Martin & White, 2018).

Establishing efficient protocols for seabird monitoring that minimize distress is therefore crucial to reduce the risk of disturbance and particularly, nest failure. (Gallego & Sarasola, 2021). More research on the impacts of different types, sizes and noise levels of drones on a range of bird species, is recommended by Valle & Scarton (2019). They state that to reduce disturbance: launch at least 100m from nest sites; restrict drone flights over nests to less than one minute; monitor predators near temporarily unattended nests; and immediately suspend flights when required.

However, there are mixed reviews about how drones are launched and minimum distances from distances species (Mapes et al. 2020). Some agree 100m is a safe distance to ensure target species aren't disturbed during flights, while others suggest that being closer and allowing the target species to see and become used to the drone can reduce disturbance.

Collins et al. (2019) discuss how parents and other adults of different species may react to drones. They suggest that low altitudes don't allow sufficient time to assess threats and may cause panic. Seabirds are strongly influenced by the actions of other adults. They often use the behavior of neighboring groups and individuals as a warning cue of predation risk. This can occur even in small groups of birds. At locations like Raine Island, with thousands of roosting and nesting seabirds, hundreds of birds may leave the ground temporarily for even minor events. Around the boat landing area and research facility some birds have become accustomed to the presence of humans. However, responses are highly variable for different species under different conditions and are not easily predicted.

2 Methods

2.1 Survey area

Raine Island is a small, coral cay situated south-east of Cape York, the northern most point of Australia. The much larger Raine Island Reef (Figure 5 and Figure 6) lies east of a large channel through the outer line of ribbon like barrier reefs that enclose the large northern lagoon dominated by deltaic reefs (Figure 5a) subject to strong tides and currents from the Torres Strait between Australia and Papua New Guinea. To the north of Raine Island lies Moulter Reef, and Moulter Cay which has less vegetation, less turtle nesting and fewer seabirds (Figure 5b). These have been mapped in previous drone surveys using methods like those used at Raine Island. There are other cays important for wildlife on the deltaic and inshore reefs of this region and scattered along the Great Barrier Reef 1500 km south to islands such as Heron, Lady Elliot, Lady Musgrave and other cays in the southern Capricorn Bunker Group.

The study area used to assess the response of the island's seabirds to drone flights lies at the northwestern end of Raine Island (Figure 6) and was chosen to include a range of representative habitats and seabird species by field scientists from the Queensland Department of Environment and Science (DES) and the Great Barrier Reef Marine Park Authority (GBRMPA). These researchers manage long term monitoring of the island's fauna and acted as observers for the ground-based counts of seabirds to compare with the video-based counts made in this study.

2.2 Data sources

Videos and photos used in this study and bird counts from ground observers were acquired during surveys flights conducted by AUT staff (Lorenzo Fiori, Dan Breen) and scientists from the Great Barrier Reef Marine Park Authority (Mark Read), Queensland Department of Environment and Science (Graham Hemson and Andrew Dunstan), Biopixel Ltd (Richard Fitzpatrick) and Aboriginal and Torres Strait Indigenous Owners. The surveys analysed here were conducted in December 2015 during hot dry weather before the onset of the Wet Season.

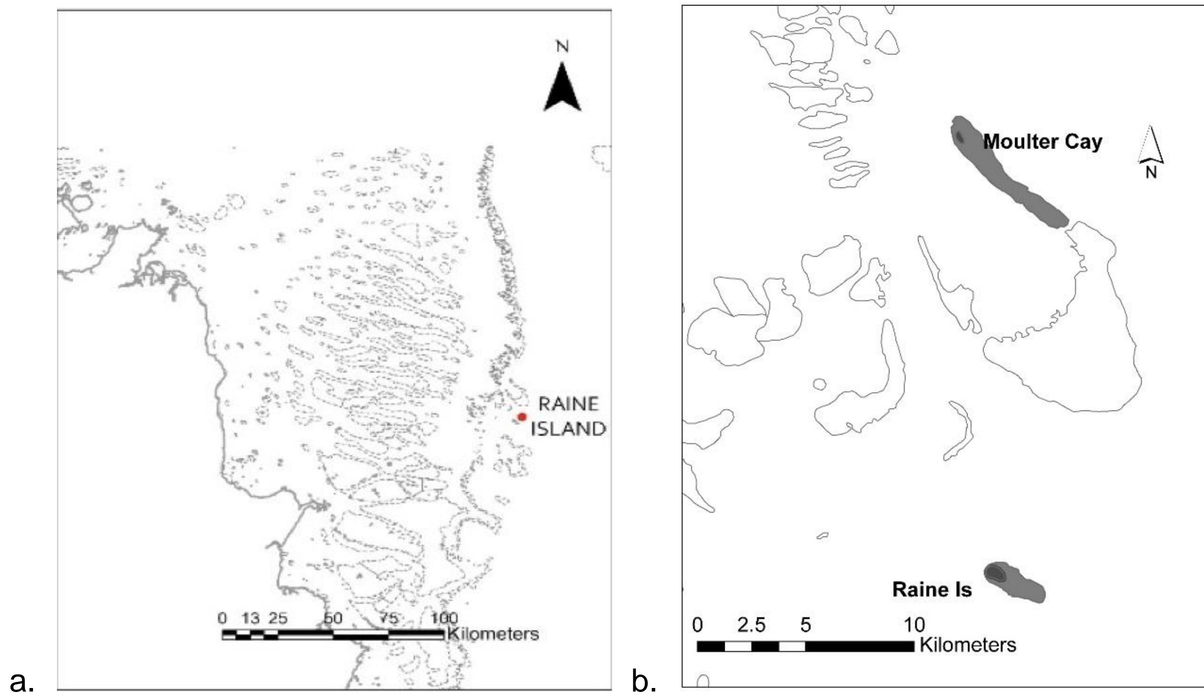

Figure 5. Location of Raine Island a. on the outer Great Barrier Reef, east of Cape York Peninsula b. in relation to surrounding reefs.

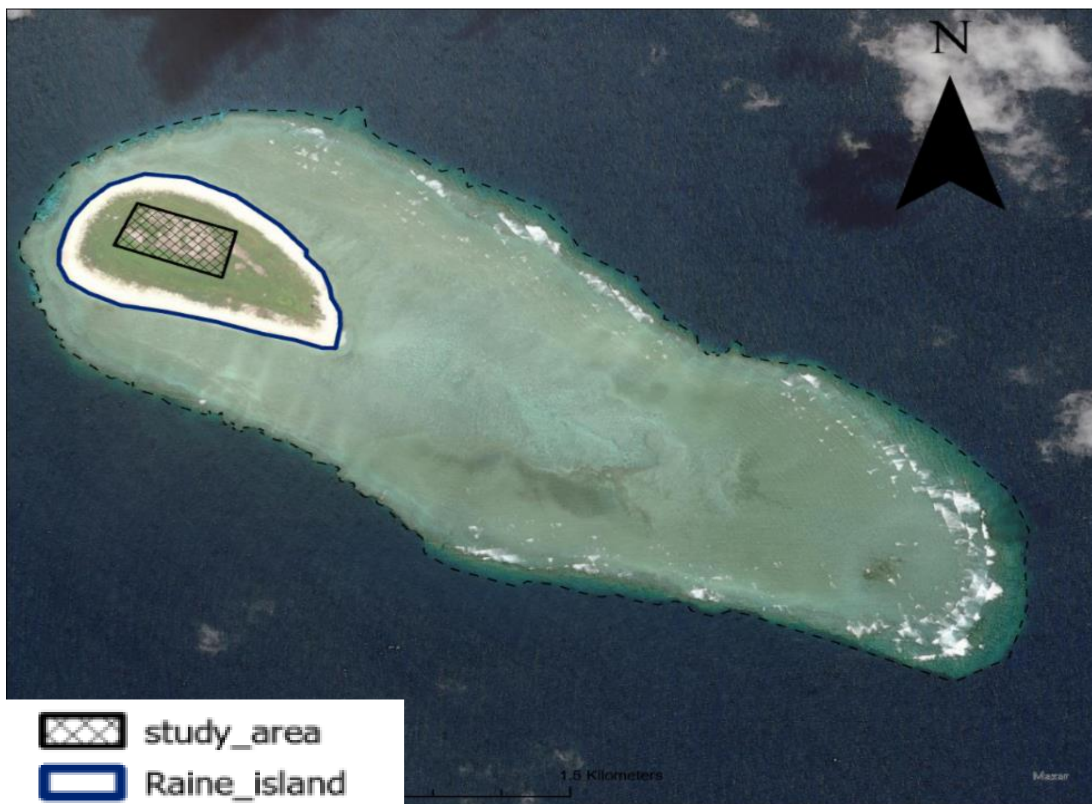

Figure 6. Location of study area on Raine Island on Raine Island Reef.

This work complements a broader investigation mapping island morphology, vegetation, turtle nesting, seabird abundance, diversity and breeding and disturbance from drones and other monitoring and management interventions.

2.3 Equipment, flight paths and observers

Video from a HexH20 waterproof hexacopter (Figure 7) was used to determine whether an unmanned aerial vehicle could effectively monitor behavioral disturbances in the Island's seabirds. This was one of four different drones used in previous analyses. The HexH20 was operated from a DJI Naza-M V2 controller, for maximum flight times of less than 12-15 minutes to allow for flying and landing in strong winds.

Figure 7. HexH2O hexacopter drone by QUADH2O Ltd

The drone has a waterproof compartment and viewing port which carried a Sony A5100 24-megapixel camera to record multiple overlapping photographs to build high resolution photomosaics and digital surface models of the Island. The drone video imagery used in this study on seabird disturbance was recorded on a slightly forward-facing GoPro video to record birds flying ahead and directly below the drone. Video was recorded as Codec: H264 - MPEG-4 AVC, with a resolution and buffer dimensions of 2704 x 1520 and a frame rate of 25. The drone was launched from a 1m^2 plywood platform in the outer dune swale adjacent to the beach and research facility. The latter comprised two steel containers at the north-west end of the island providing equipment storage, electronic surveillance monitoring, satellite communications, solar power and shade (Figure 8).

Figure 8. Launching a DJI Phantom drone from the dune swale adjacent to the research facility and beach where the ship's tenders routinely land.

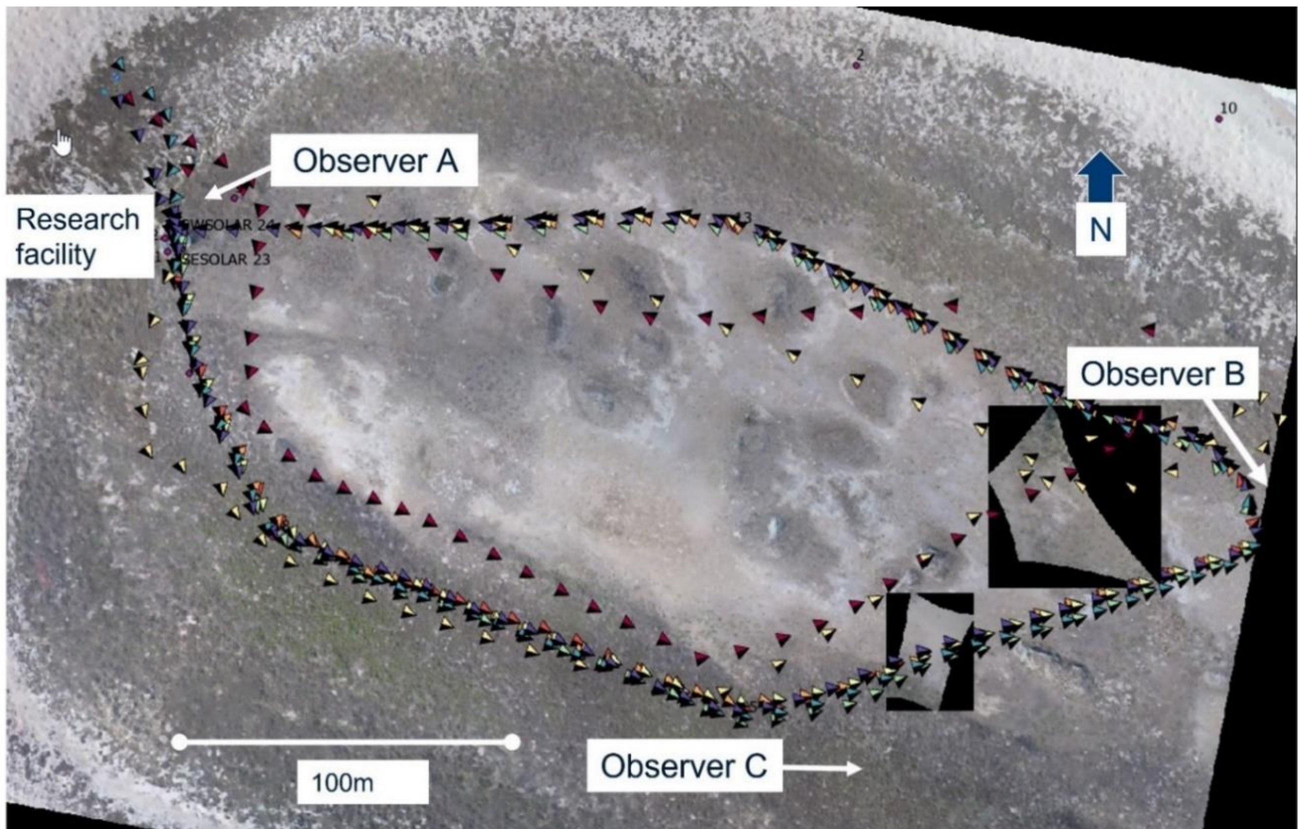

Figure 9. Positions of ground observers, drone tracks and video images for flights at 8 different heights flown anti-clockwise (From Observer A to C to B to A).

After launch, the drone was flown 100m out over the reef before slowly ascending, flying at 3 m per second without sudden changes in direction or altitude. A roughly triangular, anti-clockwise, 1km course was flown at 8 randomly ordered heights (20, 30, 40, 50, 60, 80,100, 120 m). Observers at fixed vantage points sat at the end of each course segment facing the oncoming drone at positions 400 m (Observer C), 550 m (Observer B) and 700 m (Observer A) from the start. The observers, drone and video operators, maintained radio contact to coordinate flights and record flight details. Automated navigation software was used to pre-program flight paths, but strong winds caused some deviation. Flights over the survey area generally took around 5 minutes to complete.

Observers identified flying birds to species, whether they were nesting with eggs or chicks visible and whether birds left the ground or showed other signs of disturbance (head turning, flapping wings) during and in between drone flights. Ten-minute recovery periods and control counts of birds flying and the total number of birds on the ground were made between each flight within set areas along the drone course.

Flights were supervised by Great Barrier Reef Marine Park and Queensland Department of Environment and Science officers and scientists in accordance with ethical guidelines developed by the recovery project. Initial trial flights were flown at 120m with the intention of discontinuing the trials if disturbance was judged to be excessive.

2.4 Analyses

2.4.1 Image processing and pilot study

The video processing software FFmpeg was used to extract still images from the drone videos at 3 second intervals (Hock & Lingxia, 2014) for flights at 8 different heights. The aerial images from the drone flights were georeferenced and corrected for camera tilt and two seconds of video immediately preceding each image linked to each aerial photo in the ArcPro (ESRI version 3.1) Geographic Information System (GIS) to assist in identifying flying birds and avoid counting bird shadows and other artefacts (Figure 12).

A 20 x 20 m square tessellation was generated in ArcPro and overlaid on georeferenced photos to count birds systematically and avoid recounts and misses. Each flying bird was saved into the ArcPro geodatabase as a point feature to retain information on the spatial distribution of disturbance (Figure 13). Where possible seabird species and other information were recorded but this was not always possible. All data was entered into ArcPro GIS and exported to statistical and other software where necessary.

As the method could require counting birds in many photos, and potentially resample the same birds, a pilot study was conducted to estimate the minimum number of photos required to achieve a reasonable level of precision. At least 65 still images were sub-sampled from videos captured from each flight at 20m, 30m and 40m. Counts of flying birds from drone images flown at 20m, 30m and 40m were randomly selected for subsample sizes of n= 10, 20, 30, 40, 50, 60, 70 still images and used to compute standard errors and precision where:

Equation 1. $$SE_{\bar{x}} = \frac{S}{\sqrt{n}}$$

Where SE is the standard error, S the standard deviation and n the number of observations and where:

Equation 2. Precision= SE/Mean (Andrews and Mapstone 1987 pp.37-27).

Values were randomly subsampled each time with replacement for each combination of drone height and subsample size and the statistics graphed in Microsoft Excel. The change in standard error and precision for random subsamples of n= 5, 10, 20, 30, 40, 50, 60 and 70 photos were plotted for drone flights at 20m, 30m and 40m to help determine a representative number of subsamples for subsequent bird counts.

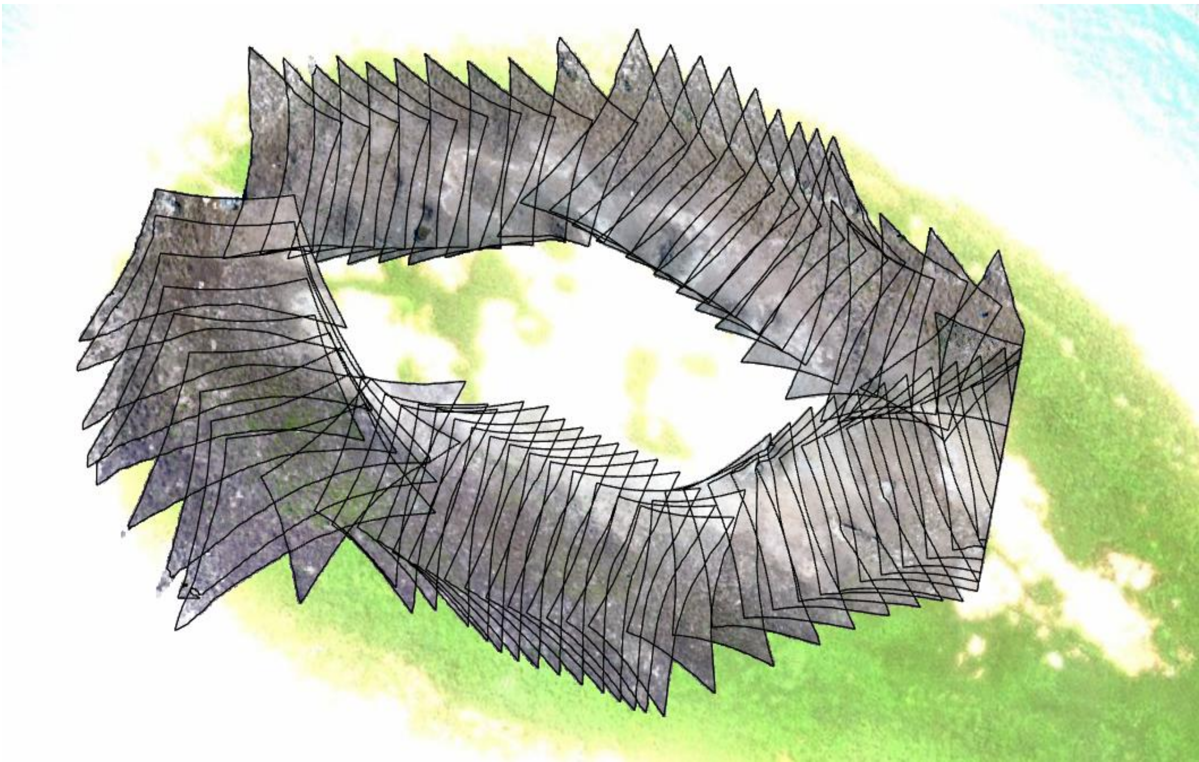

Figure 10. Shapes and positions of multiple orthorectified georeferenced individual aerial photos extracted from video imagery taken from one drone flight.

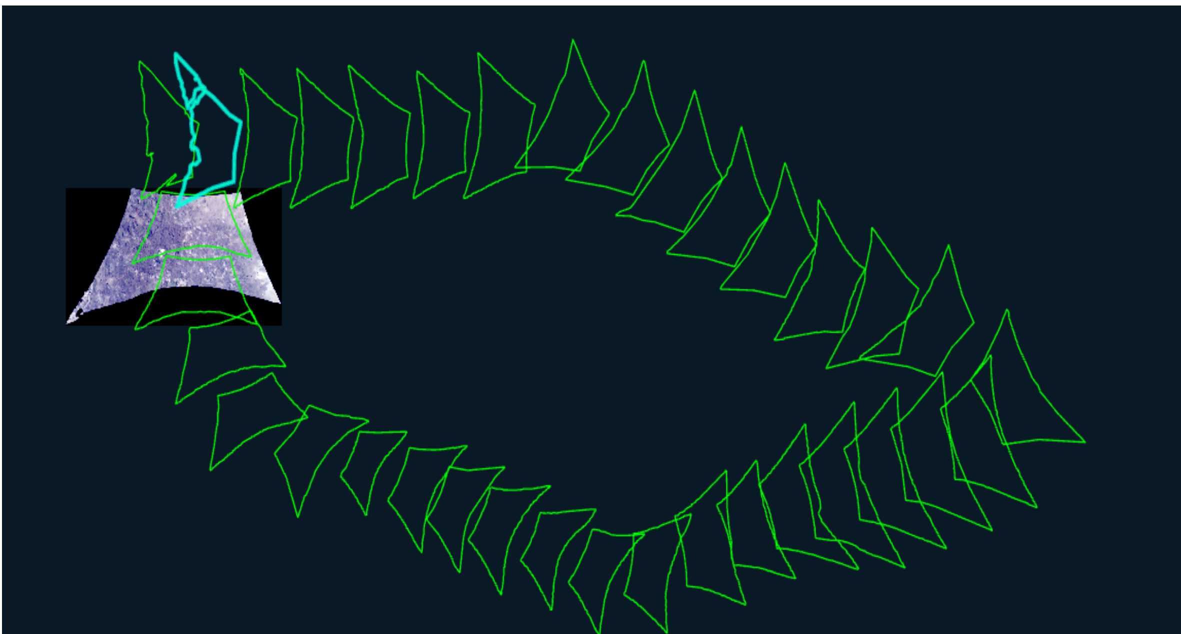

Figure 11. Locations of 30 georeferenced aerial photos sub-sampled from one drone flight.

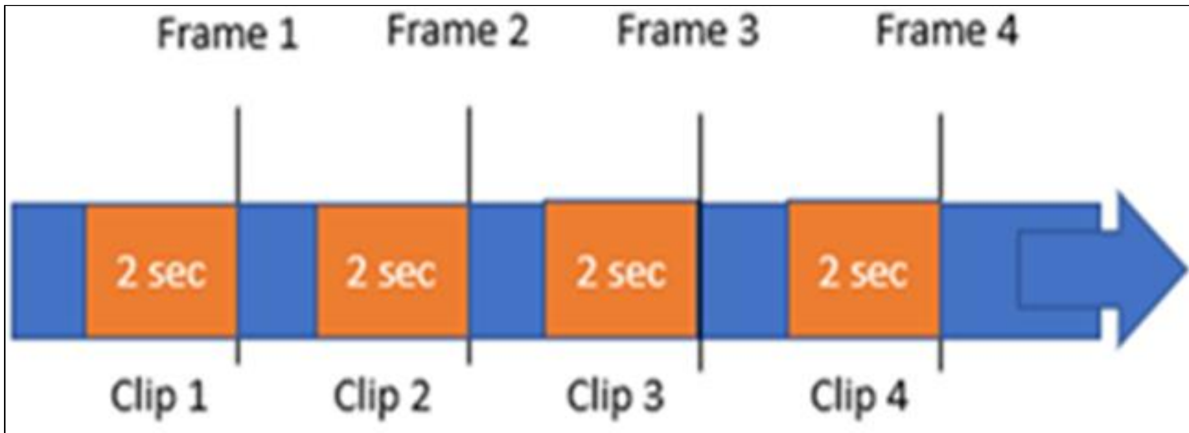

Figure 12. Two second videos preceding each still image integrated in ArcPro to assist in identifying flying birds and avoid counting bird shadows and other artefacts.

Figure 13. Point features created in ArcPro GIS mapping flying birds.

2.4.2 Orthophoto mosaic and digital surface model

The photogrammetry software Agisoft Metashape was used to georeference and combine 1479 still images from the drone video flown at 50m. This created a high resolution ortho-mosaic and a digital surface model (DSL) of the study area mapping the relative topography of the ground, surface vegetation and distribution of roosting, nesting and flying birds over the entire study area.

2.4.3 Correction for increasing field of view with increasing drone height

To compare the number of flying birds counted on drone images collected at different heights, the increasing areas of ground visible within photos taken from higher altitudes had to be accounted for. ArcPro GIS was used to create polygon features for the perimeter of each georeferenced photo extracted from videos taken at 20m. The polygon outlines for the photos taken from 20m were then overlaid on georeferenced still images from videos flown at 30, 40, 50, 60, 80, 100 and 120m. Only flying birds within the 20m polygon were counted so that a similar area was sampled at each height.

2.4.4 Ground based video of birds flying in the study area

A tripod mounted, professional quality RED video camera with zoom lens was located 20m south of the research facility and used to follow and record each drone flight and the responses of roosting and nesting birds to the drone. Flying birds were counted on 30 still images randomly sampled from a ground-based video of each flight flown at 20, 30 40, 50, 60 ,100 and 120 m. The video covered most of the study area but included birds from nearby up to 500m away and there was likely to be some overlap and non-independence of areas counted.

2.4.5 Comparisons between survey techniques

The mean numbers of birds of flying birds from 30 drone and 30 ground-based still video images for eight drone flights between 20 and 120m were graphed against drone height and against the total number of flying birds counted by ground observers for these flights. General linear models (GLM) based on poisson distributions and log link functions were used to describe relationships between flying bird counts, drone height and survey method using the paleontological statistics software PAST (Hammer et al. 2001) .

3 Results

3.1 Photogrammetry

Georeferenced images corrected for lens distortion, 3-dimensional yaw (x), roll (y) and pitch (z) of drone and their effect on field of view in images from the drone video are mapped in Figure 10 for one flight. These show the difference in shape and areas viewed when compared to an unprocessed rectangular image. An example of 30 sub-sampled images from the above data is shown in Figure 11.

Comparisons between video counts at different drone heights were compromised by the effect of increasing drone height increasing the area of ground and the number of birds within view. Figure 14 shows samples of imagery taken at different drone heights overlaid with a polygon representing the extent of the corresponding image for the 20 m flight so that flying bird counts could be made within similar areas. Counts of flying birds were made for 240 images subsampled in this way and are presented in the following analyses.

A georeferenced aerial photomosaic and a digital surface model of the study area built from still images extracted from the 50m flight video are shown in Figure 15 and Figure 16.

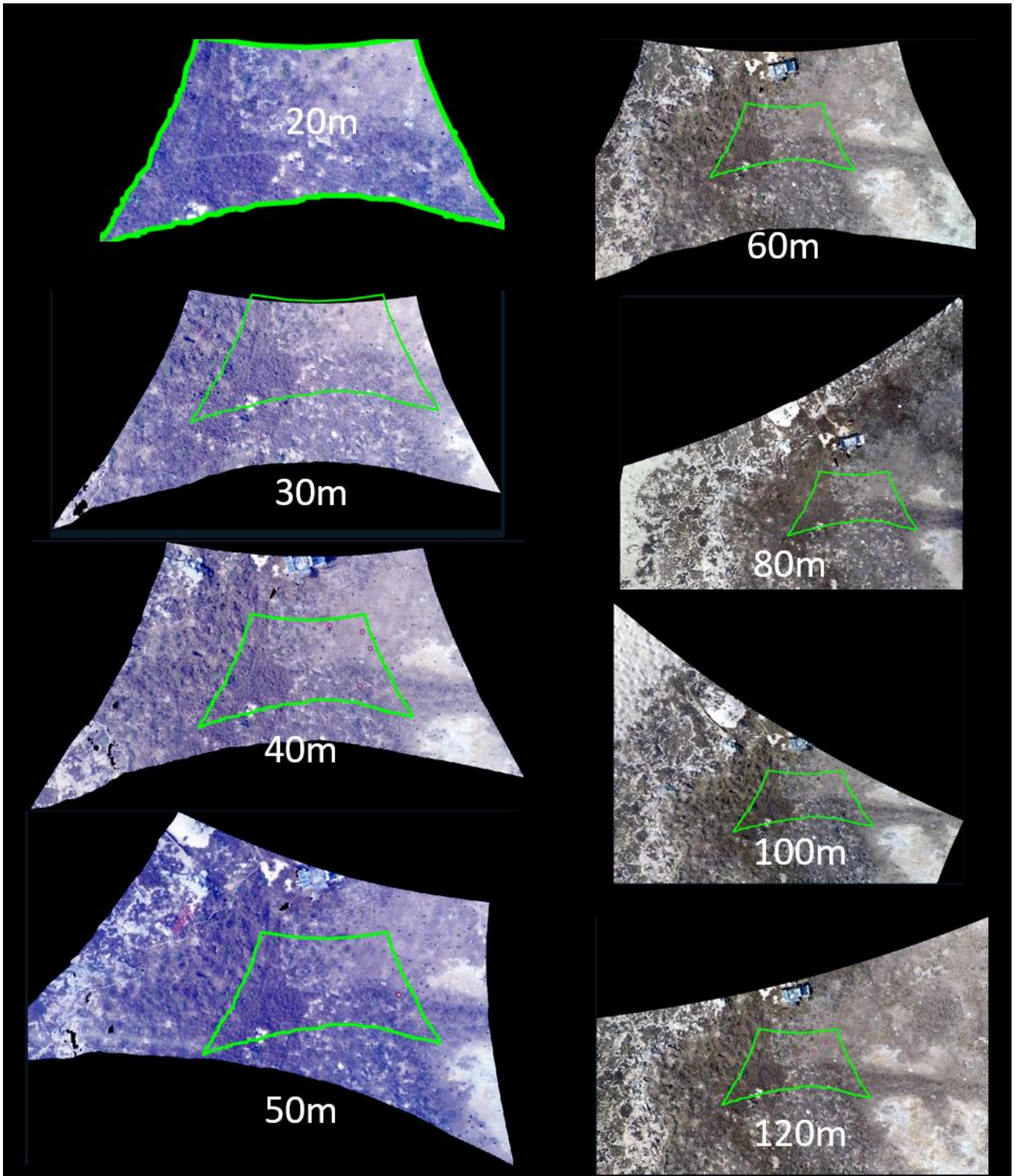

Figure 14. Georeferenced images of the same area cropped to the field of view of the 20m flight from videos flown at heights ranging down the page on the left-hand side, at 20m, 30m, 40m, 50m and on the right-hand side at 60m, 80m, 100m, 120m.

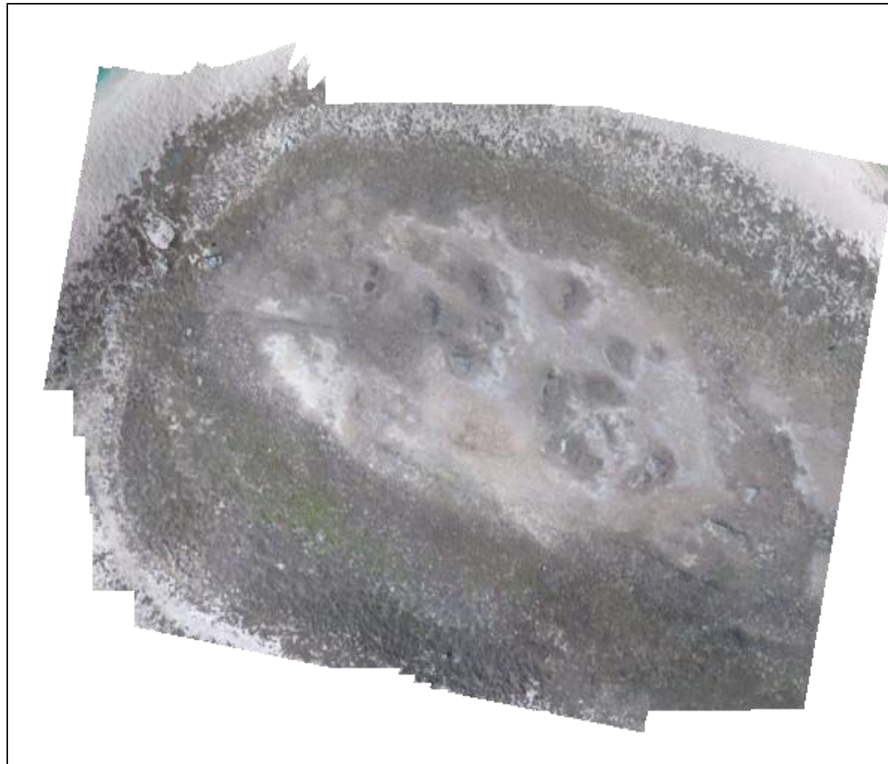

Figure 15. Aerial photomosaic of study area generated from images from drone video.

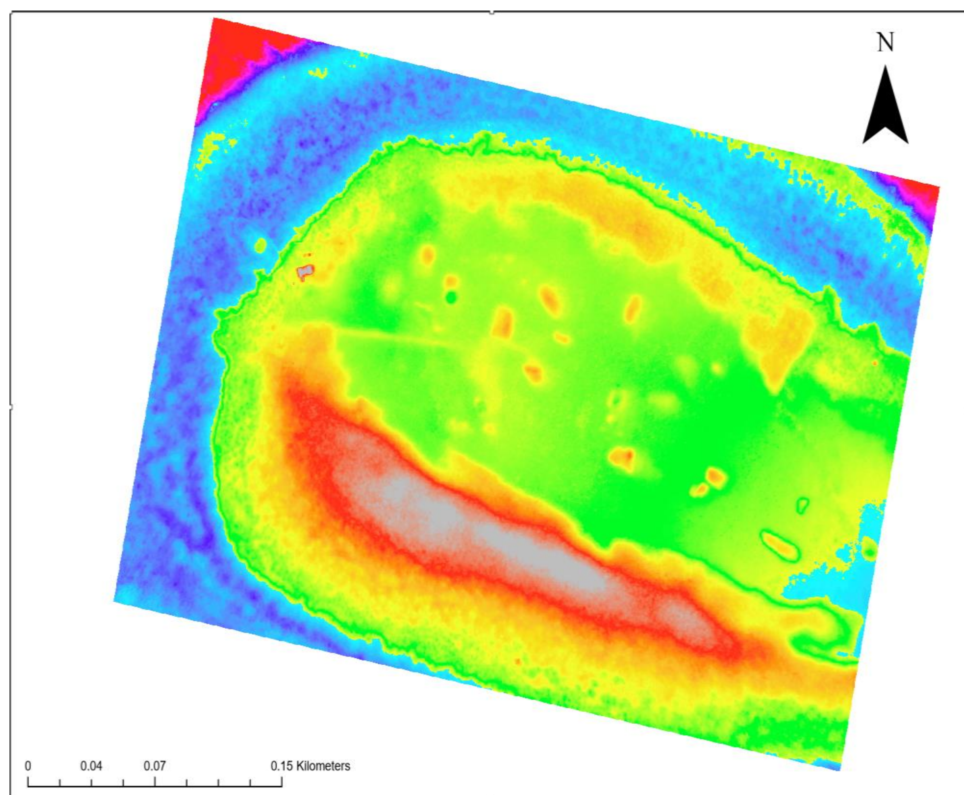

Figure 16. Digital Elevation Model (DSM) of study area from images from drone video.

3.2 Statistical analyses

3.2.1 How many images are required to subsample videos of each flight?

Standard errors of the mean number of flying birds for increasing sub-sample sizes between 5 and approximately 70 images per flight are shown in Figure 17. The errors decrease rapidly between sampling 5 to 20 images, then level off or slowly decrease from sampling 30 to 70 images per flight.

Standard errors varied substantially with drone height but there was no trend in error size with the height of the flight and precision, as measured by the standard error/ratio, was similar for different heights (Figure 18).

In both figures, the curves level off at a sample size of approximately 30 images from each flight. This sample size could therefore provide a relatively representative estimate of behavioural disturbance while minimising sampling effort and avoiding resampling.

While the standard errors are relatively large, precision was less than 0.3 for 30 subsamples which is reasonable given the natural heterogeneity in bird distributions and their flocking behaviours, and so this sample size was adopted for subsequent counts.

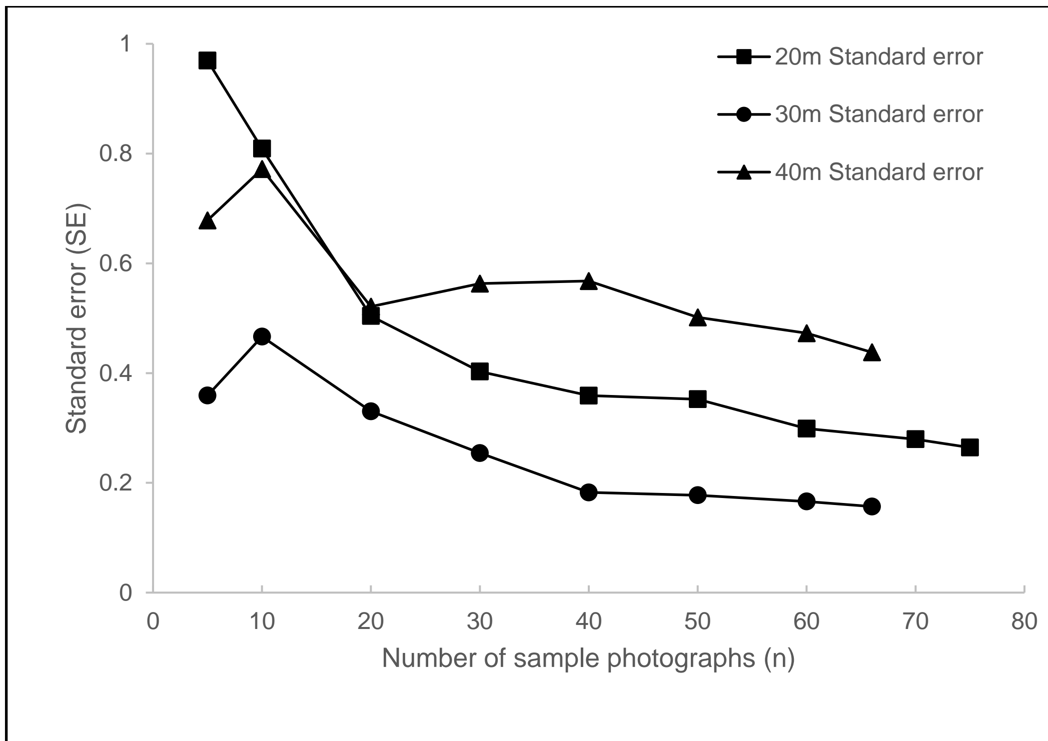

Figure 17. Standard errors of mean counts of flying birds from three drone heights with increasing numbers of still photos sampled from each flight.

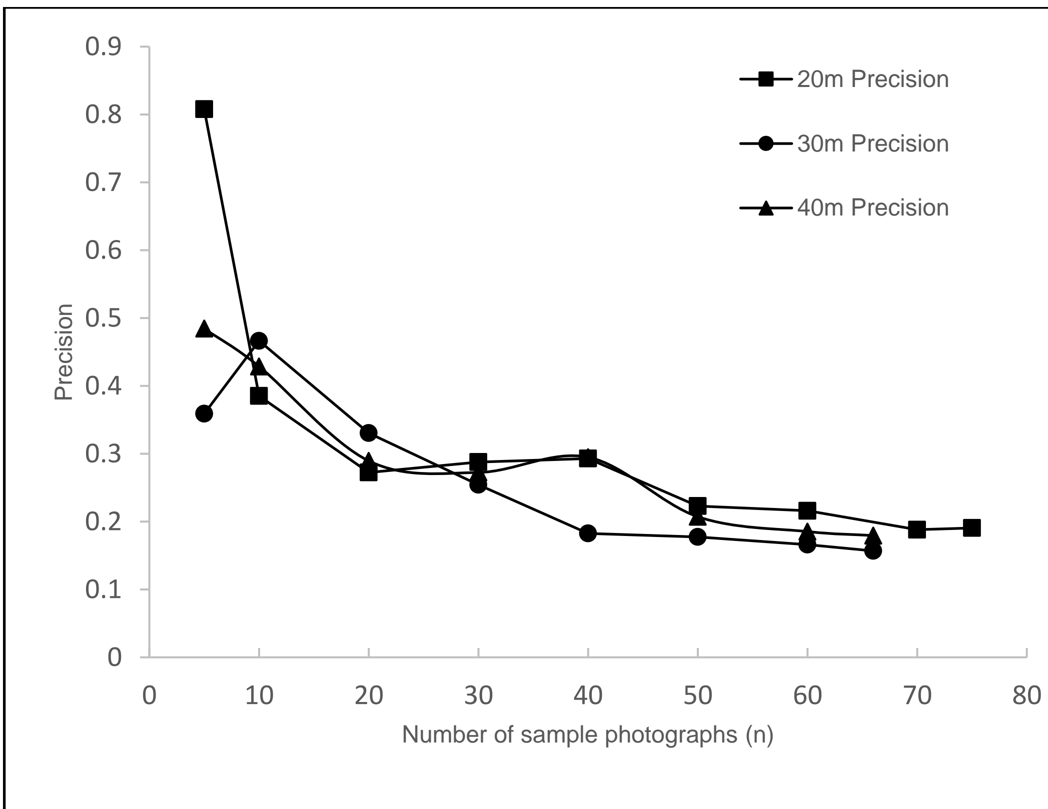

Figure 18. Precision (standard error to mean ratio) of mean counts of flying birds from three drone heights with increasing numbers of still photos sampled from each flight.

3.2.2 Do counts of flying birds by ground observers vary with drone height?

The total sums of flying birds counted by the three observers assigned to three sections of the flight are plotted against increasing drone heights in Figure 19. There is a general, but highly variable decrease in the number of flying birds with increasing drone height. The log-linked Poisson General Linear Model fitted ($P<0.001$) supports this (Table 2).

The number of birds taking flight ranged from around 140 birds at 20 m and 50 m to 23 birds at 80 m. No nesting birds (from 340-440 nesting birds counted between each flight) were observed to take flight during these trials and most ‘roosting’, non-nesting seabirds returned to the ground within two minutes.

The percentage of birds flying compared to the total counts of birds on the ground before each drone flight ranged from 2% for the 80m flight to 11% for the 50m flight (Figure 20) and there was a weak negative relationship ($P<0.1$) between drone height and the percentage of the birds on the ground taking flight.

3.2.3 Do counts of flying birds from video images vary with drone height?

Mean counts of flying birds from drone video varied significantly, but variably with drone height ($P<0.001$, Table 2, Figure 21) ranging from 72 birds at 50m to 11 seabirds at 120m. Mean video counts were for most heights, between 28 and 75% of the corresponding total observer counts noting that the video images only subsample the flight video, while observers make counts throughout the entire flight.

3.2.4 Do counts of flying birds from a ground-based video vary with drone height?

There was no relationship between the ground-based video counts and the total observer counts of flying birds ($P>0.6$, Table 2, Figure 22). The video provided a large field of view along a horizontal plane clearly showing the degree of disturbance at most camera angles tracking the drone. However, on the final leg of the flight, with the drone directly approaching the video at ground level, the images sometimes repeatedly sampled the same disturbance of roosting frigate birds, artificially inflating the number of birds disturbed.

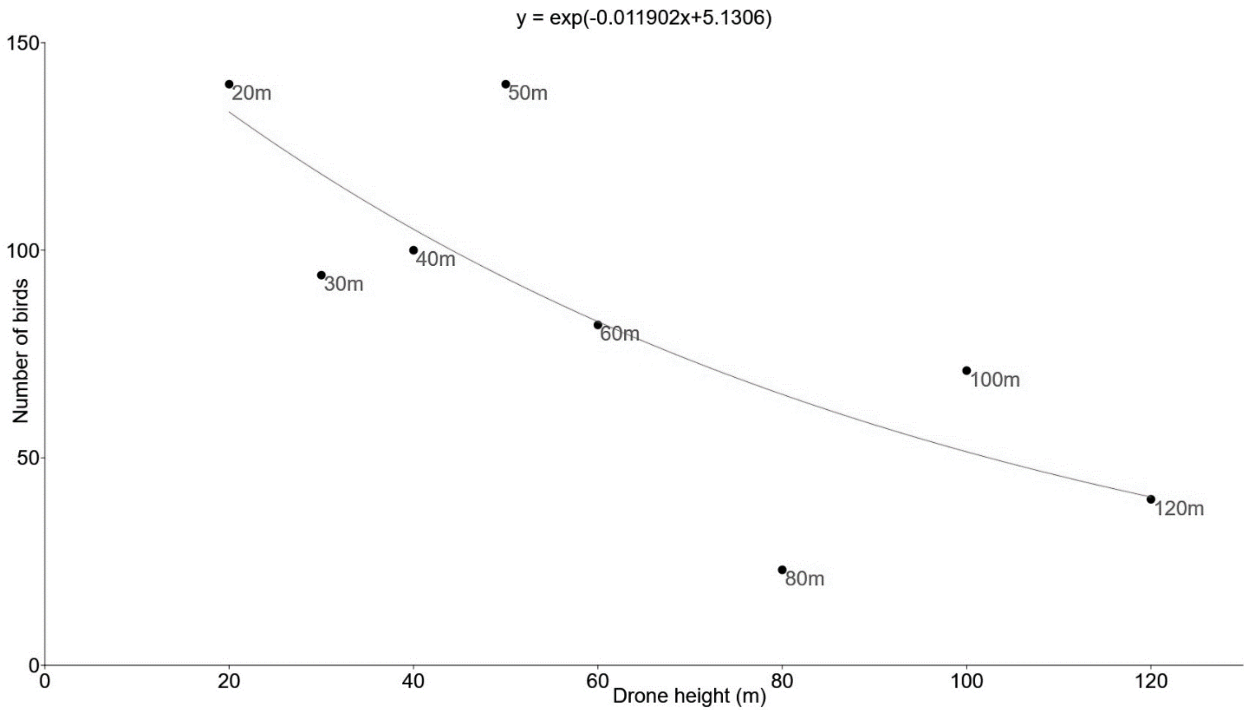

Figure 19. Total ground observer counts of flying birds at increasing drone heights.

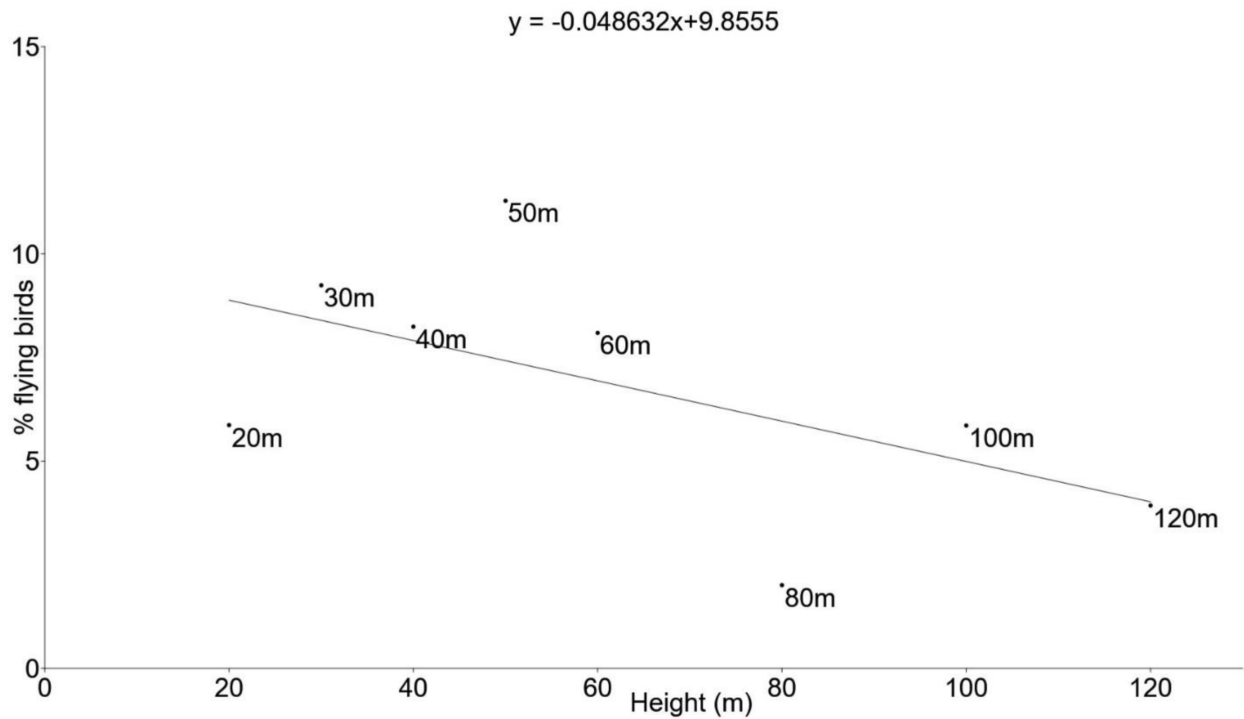

Figure 20. Flying birds counted by ground observers as a percentage of the total number of birds counted on the ground between drone flights.

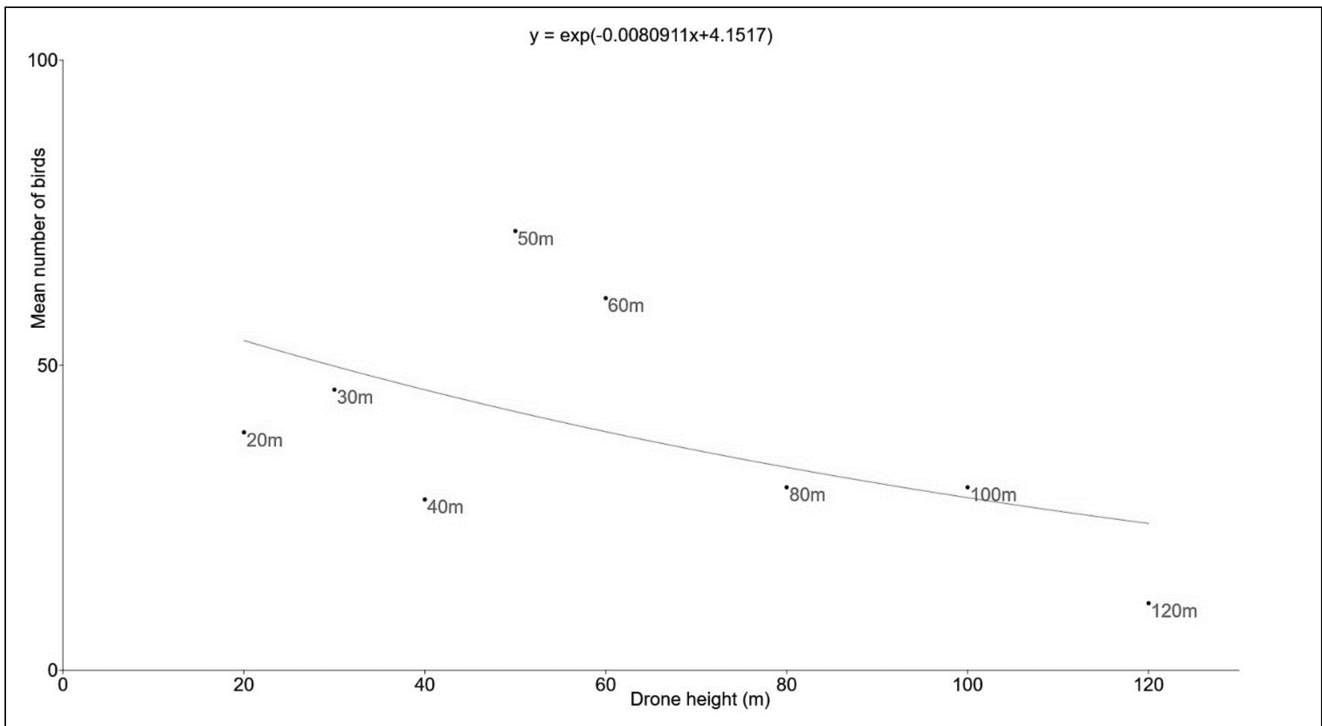

Figure 21. Mean (n=30) counts of birds taking flight from drone video taken at increasing heights.

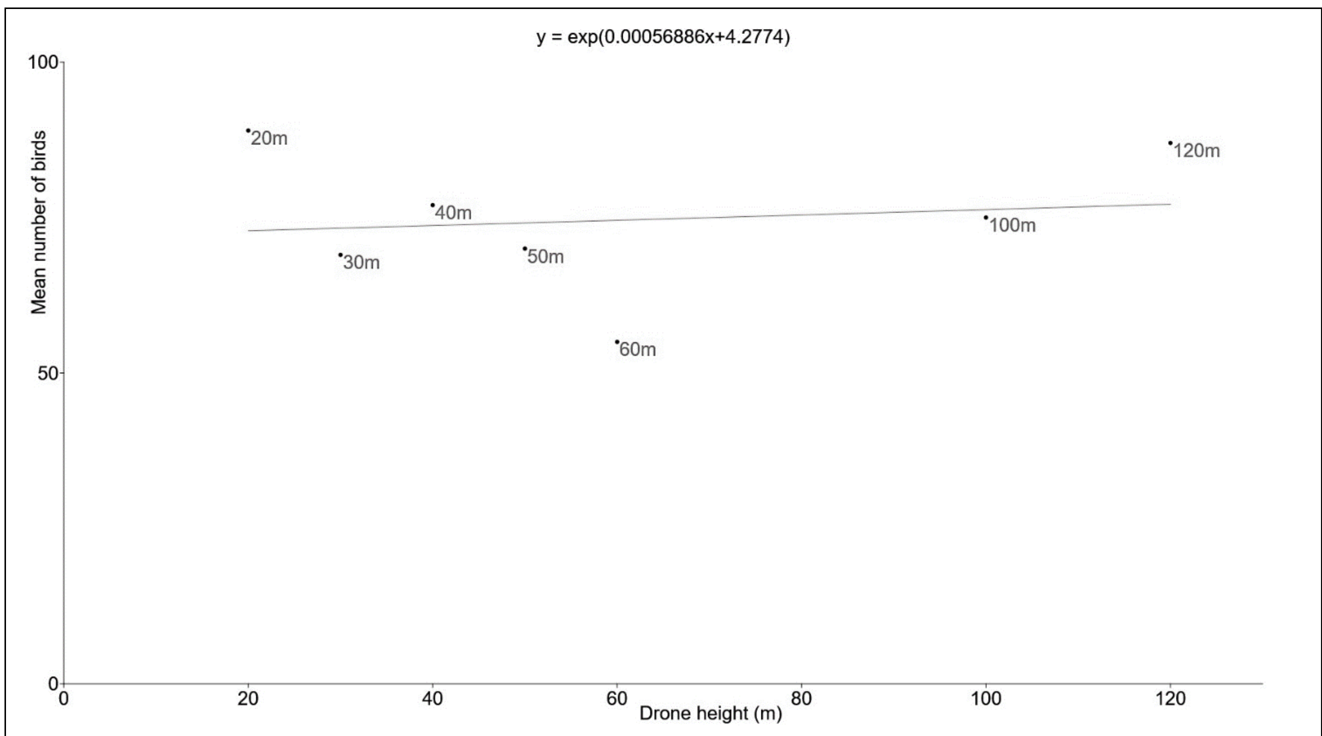

Figure 22. Mean (n=30) ground-based video counts of flying birds with a drone at increasing heights.

3.2.5 How do counts of flying birds from drone images compare to counts by ground observers?

There was a significant positive relationship between drone video counts and counts of flying birds made by ground observers (P<0.001,Table 2, Figure 23). Observer counts of flying birds were generally higher than counts made from the drone videos, especially for the 20m drone flight, but observer counts for the 80m were slightly lower than the counts made from the drone video.

3.2.6 How do counts of flying birds from ground video compare to counts by ground observers?

There was no apparent relationship between the ground video counts of flying birds with counts made by human ground observers and counts from the ground video were similar at all heights with no consistent relationship (P>0.09, Table 2, Figure 24).

Table 2. Results of general linear model analyses of variation in counts of flying birds with drone height, ground observer, ground video and drone video methods compared.

Source	Log likelihood	G	p-value
Ground observer counts with drone height	-34.7	89.4	P<0.001
Drone video counts with drone height	-24.9	20.1	P<0.001
Ground video counts with drone height	-5.4	0.2	P>0.6
Drone video counts versus ground observer counts	-52.4	54	P<0.001
Ground video counts versus ground observer counts	-43.4	0.06	P>0.9

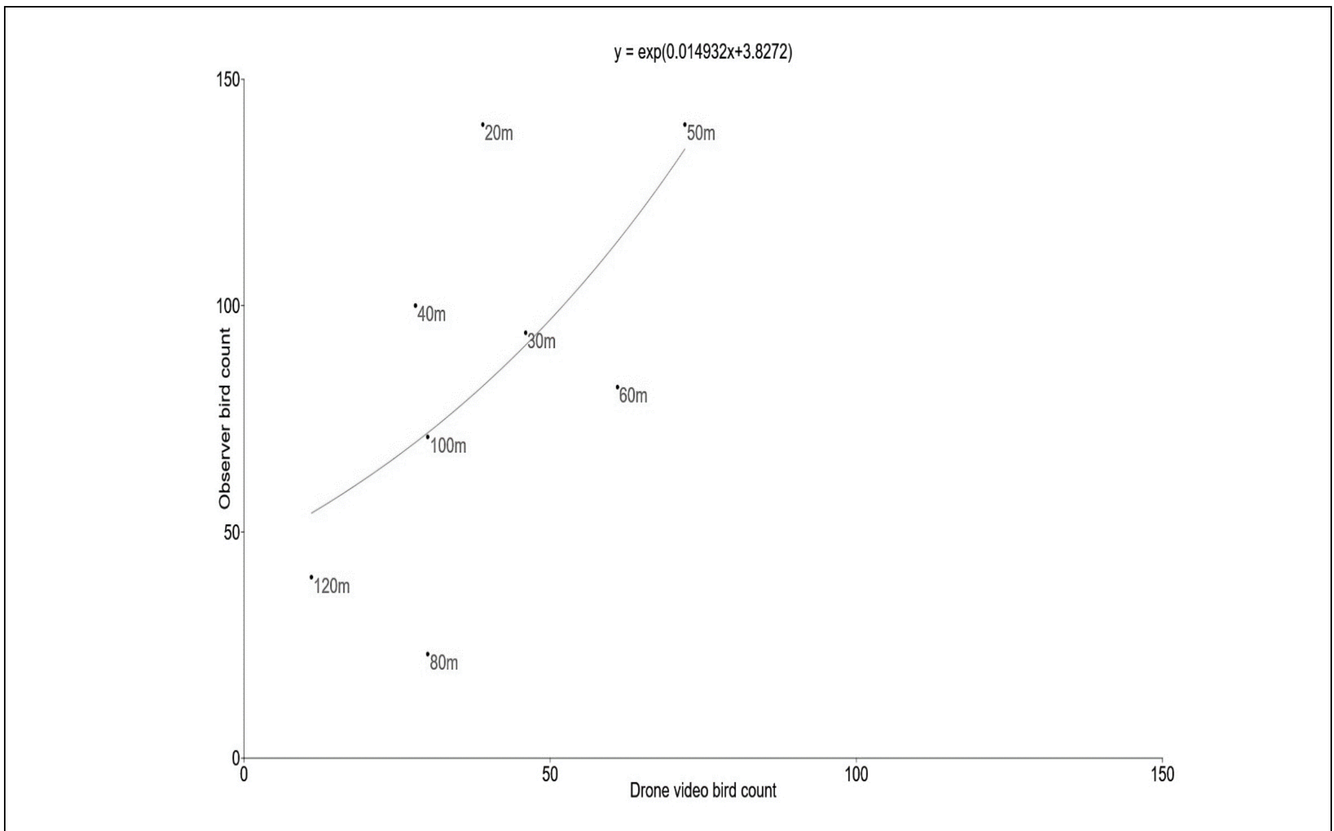

Figure 23. Mean counts (n=30) of flying birds from drone videos compared with total counts by ground observers.

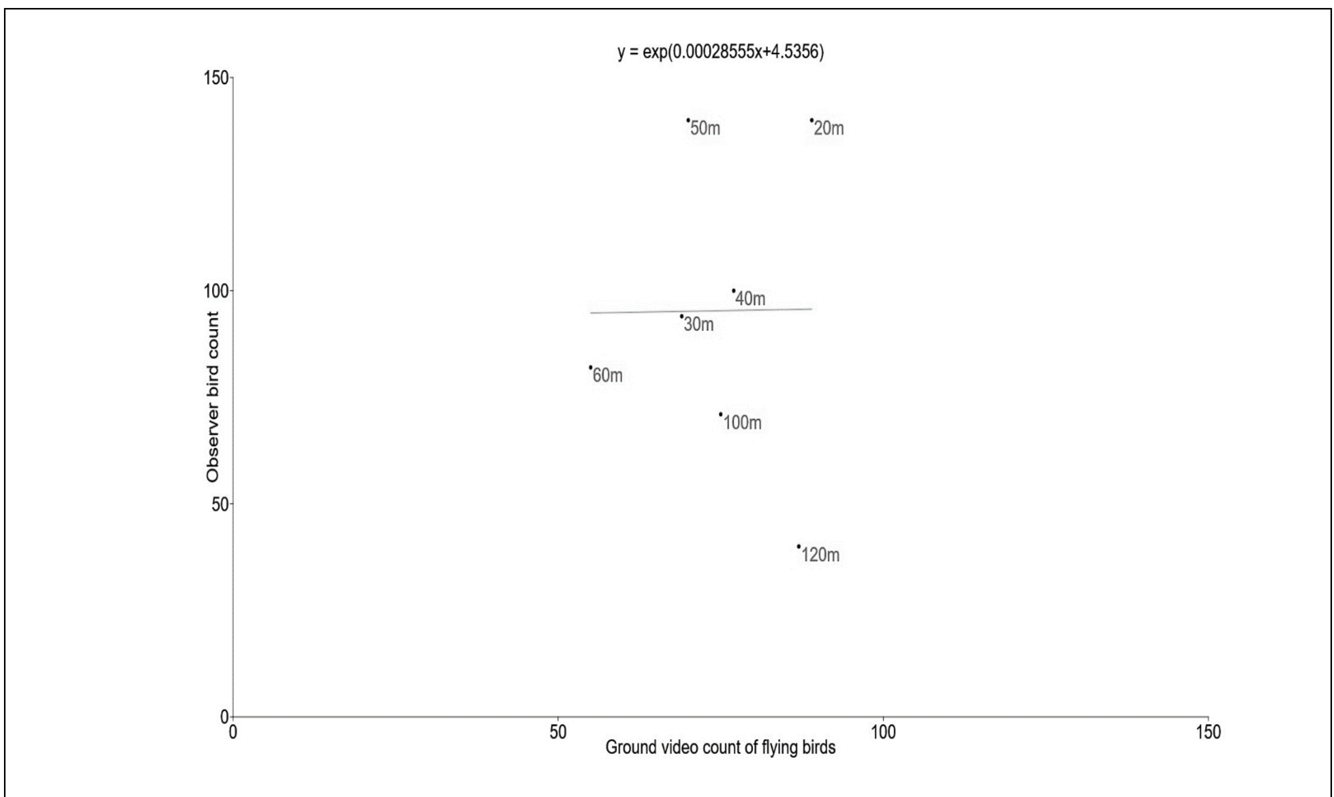

Figure 24. Mean counts (n=30) of flying birds from ground video compared with counts by ground observers.

4 Discussion

This study has demonstrated that still images from videos recorded by drones can be used to monitor their disturbance on roosting seabirds. A related study on the effect of drones on roosting and nesting seabirds was required as part of the ethics approval for research using drones at Raine Island (Fiori et al 2016). Fiori's study gave the insight needed for understanding the effects drones can have on the island. Furthermore, the study counted birds that were flying and roosting including chicks, while this study counted only flying birds. There were two different drones, flown for two seasons at 8 heights between 20 and 120m along three transects, ground observers recorded comparable numbers of roosting (non-nesting) birds taking flight with a drone overhead. In one season, a few birds left eggs or nestlings temporarily, although parents returned to their nests within 2 minutes. It is important that birds do not leave nests exposing eggs and nestlings to extreme heat and predation by silver gulls, but no mortalities were observed and any parent birds that did leave, returned to the nest within minutes. The study showed significant differences in the effects of drones on seabirds for different drone types, seasons, flying heights and species and demonstrated the inherent unpredictability in potential effects under varying conditions.

Monitoring seabird disturbance in real time from downward and forward-facing onboard video provides an additional check on adverse effects on wildlife not anticipated by guidelines to avoid disturbance. The approach can also be a fast, nonintrusive, and cost-effective way to survey population densities, especially in remote, difficult-to-access, and sensitive conservation areas like Raine Island.

4.1 Resolution and precision of video estimates

While the study demonstrated that imagery obtained from drone video can be used to monitor the flight response of roosting seabirds to disturbance, the results were highly variable. While variability is an intrinsic characteristic of spatial and temporal heterogeneity or 'patchiness' in plant and animal distributions, there are also systematic biases and a lack of precision associated with different methods of observation.

The images captured by the HexH20 drone and Go-Pro camera were of a resolution high enough to count flying seabirds at different heights and in many cases, identify seabird species, although this became difficult as height increased and almost impossible at 120m.

Being able to replay 2 seconds of integrated video immediately before each still image improved the ability to distinguish flying birds from shadows and other artefacts.

There was a strong tendency for flocks of seabirds to collectively respond, or not, to disturbance events and other triggers. This meant that the variability in the counts of flying birds among the still video images captured throughout each drone flight was relatively high. Comparing the change in standard errors and precision (standard error to mean ratio) using the 30m flights as an example shows that with increasing sample sizes, sub-sampling 30 still images from each flight could decrease standard errors to around 30% of the mean, but that this proportion decreased more slowly to around 20% for sub-sample sizes ranging from 50 to 70 images per flight. This is an important consideration in estimating the level of observer effort required for different methods, especially where a greater number of flights are sampled.

4.2 Ground observations of seabird responses to drones

A general decrease in the total number of flying birds counted by ground observers when the drone was flown at increasing heights might be expected. However, the responses were quite variable and reflect that in this study, data from only one flight at each height was surveyed. The number of flying birds represented between 2 and 11% of the total number of birds on the ground along each flight path.

Weston et al (2020) explained how increasing the distance between birds and drones was less likely to disturb birds. It has also been highlighted how birds may perceive a drone as a raptor or other predator and that different birds' species vary in their sensitivity to drone disturbance (Weimerskirch, Prudor & Schull (2018). In some surveys, observers on the ground caused more seabirds to take flight than a drone flying 100 m overhead (Edney and Wood 2020) but in others the response depended on the type of drone, take off, speed, height and species (Brisson-Curadeau et al., 2017). In this study, most birds returned to the ground within two minutes and no nesting birds took flight.

The HexH20 drone used in this study was the largest, most conspicuous and loudest of the three drones tested, but the way the drone was flown was also likely to affect seabird responses. Taking off from near the beach, ascending and descending over water beyond the island, maintaining relatively low speeds and avoiding sudden changes in direction or height over seabirds appears to reduce the level of disturbance. Hovering and changing direction over seabirds, with associated increases and changes in engine noise appeared to increase seabird disturbance and flight responses (Fiori et al. 2016). Such information

has been incorporated into guidelines used by the Queensland Government for research permits to use drones on other coral cays, some of which also have commercial airstrips and heliports.

Seabirds near the field station appeared to become more accustomed to human presence and counts of birds flying nearby, were almost zero for trial drone take-off and landings from the adjacent dune swale for 8 different heights. There was also a tendency for seabird responses to drone flights to decrease with time although this has yet to be confirmed statistically (Fiori et al. 2016).

Approximate counts of birds leaving the ground is an obvious but incomplete evaluation of seabird disturbance. They do not account for less conspicuous physiological, breeding, feeding, growth and survivorship responses not addressed in this study. Even if there aren't behavioral changes, there can be delayed physiological responses triggered such increased heart rates, elevated metabolic rate, a decline in condition and higher rates of nest abandonment and breeding failures (Borrelle and Fletcher 2017).

Nesting and roosting are only a part of the life history of seabirds which spend many days at sea and travel thousands of kilometres of open ocean subject to variable winds, currents, food, storms and threats such as fisheries by-catch, plastics and climate change. Research on the oceanic behaviour of seabirds and identifying ecologically important areas of ocean as dedicated marine protected areas for seabirds (Miller et al. 2023) is a major priority complementing island and mainland protection and research.

The decrease in flying birds at greater drone heights suggests that flying above 60m may be an appropriate minimal height to conduct drone surveys, when necessary, at Raine Island. However, there is also the potential of using increasingly powerful zoom lenses and other methods such as the video and sound recordings from fixed installations around the island. These collect and transmit data continuously throughout the year. An important link since only a few short field trips to this remote location are feasible each year.

4.3 Drone photogrammetry

In order to accurately map the spatial distributions and densities of objects from drones, it is desirable to correct for lens distortion, the orientation and altitude of the drone and to georeference imagery so that results such as counts of flying birds can be directly compared among different locations, and in this study, different drone heights. A novel approach to compare counts of flying birds at different drone heights used georeferenced

images captured from 20m as a template to delimit areas on images taken at greater heights to sample an equivalent area and location.

Still images from the drone flights were also used to build an aerial georeferenced photo mosaic and digital surface model of the study area. Similar models have been built for Raine and Moulter Cay and it would be interesting to see how counts of flying birds in those photo mosaics compare to this study.

4.4 Drone video counts of flying birds

Mean counts of flying birds from drone images were lower than field observer counts as the former were averages of subsampled images and the ground observers recorded total counts from a different field of view. However, video counts of flying birds also tended to decrease with drone height although the counts of flying birds at 20, 30 and 40m were relatively low when compared to counts for other heights and to counts made by ground observers for these heights.

One possible explanation for this is that birds flying at similar or higher altitudes to the drone would not be visible to the video camera. Another is that with a smaller field of view, a drone at low altitudes would capture less imagery in front, and to each side of the drone, and would not include birds flying off the ground well ahead. This might occur especially where birds responded rapidly to the sight and sound of the drone and to the chain reactions of their neighbors.

This effect was observed particularly when a drone and its associated sound travelled downwind toward seabirds. There is therefore, the potential for counts from video flown at lower heights to underestimate levels of seabird disturbance. This might be partially mitigated by adjusting the angle of view to facing more forward than down. The latter, however, will have an effect on calculating the area of ground surveyed and on the detectability of birds at greater distances.

In a study by Zhang et al. (2021), they found it was easy to miscount when the objects are extremely crowded, when drones flew close to the birds and when birds flew in and out of the camera's field of view, especially at lower heights. They suggest this led to confusion and double counting. A study by Schroeder et al. (2020), describes the high variability in their bird counts and false positive (detecting objects where there are none) and false negative (not detecting objects where there are there) observer errors. In addition, Berni et al. (2020) found that when participants looked at images their attention waned but maintained concentration when viewing video of the same point of interest.

In this study, grids were overlain on images to avoid missing or double counting and the bird's positions were recorded as a GIS point feature which could be checked independently. Previewing two seconds of video before each still image also assisted in identifying moving birds and avoiding counting shadows and other artefacts.

Despite differences, there was a strong relationship between the drone video counts and the ground observer counts of flying birds. Given that there are biases and variability in most field estimates, the correlation between drone video and ground observer counts suggests the potential to use drone video estimates as an approximate index of disturbance, particularly where ground observers are unavailable or have difficulty in accessing dangerous or sensitive sites.

Consideration of the field of view of videos facing from directly down to directly ahead, and how this, and the height of the drone, affects the area surveyed and bird counts needs further investigation. In this study, using the georeferenced 20 m images as templates to select the same areas from images taken at greater heights resolved some of these issues and demonstrated how photogrammetry using data from flight logs and GPS can improve spatial accuracy.

4.5 Ground video counts of flying birds

The RED video camera on a tripod at the start of the drone flight path provided by Biopixel Ltd was an opportunity to explore another option to monitor disturbance to seabirds from drones. The method is promising as it doesn't require an additional video to be carried on the drone especially when the main objective of the flight is to carry other types of sensors. In addition, looking horizontally through flocks of birds can provide a more synoptic, broader and intuitive view of seabird disturbance.

This was apparent in viewing these videos, but quantifying the number of flying birds was complicated by repeated images of the same birds on the final leg of the flights which approached the camera from directly in front. This was unavoidable under the circumstances but consideration of the position and viewing angles of ground-based video would make this a useful and cost-effective tool. There was no relationship between the mean ground video counts and the total ground observer counts. Reviewing counts for just the first two legs of the flight path may show a closer relationship given the oversampling on the final leg during the head-on approach to the ground-based video camera.

In the ground-based videos, there also appeared to be a halo of clear airspace with a few birds around the drone itself as it moved around the flight path. This may be a behavioral

response to the drone. Mapping the relative positions of the drone and flying birds in randomly selected images from ground-based videos could be used to test this idea on a larger dataset.

4.6 Limitations and recommendations

Drone photogrammetry survey can be a fast, nonintrusive, and cost-effective way to survey the extent and spatial distribution of habitats and species especially in remote, difficult-to-access and sensitive conservation areas like Raine Island. However, no matter what methods are used, there is no guarantee that data will be collected without issues or observer bias.

Diefenbach et al. (2003) found that ground-based counts to be a source of error for most methods including fixed transects. Nichols et al. (2000) recommend using two observers to test for bias and to provide training and Frederick et al. (2003), found considerable differences in counts among trained biologists. Differences in experience and visual impairment were discounted, but the results were more unpredictable than expected. Erwin (1982) suggests that observers may either underestimate or overestimate counts depending on the overall flock size of birds.

While using drone video to monitor seabirds may be feasible, there are issues with differences in the size and shape of the field of view with height, lens distortion and the orientation of the video (roll, pitch, yaw on x, y and z axes). There may also be miscounting errors, especially at lower heights, where birds may fly in and out of images or above or behind the drone. Another issue is where it becomes impossible to see birds clearly at high altitudes, even when zoomed into high resolution images.

Schroeder et al. (2020) explain how further training of observers in the use of digital image recognition tools can decrease counting errors and reduce the effort required by manual counts. Deep learning algorithms or neural networks can also learn to recognize features from training data and extract similar features from new larger data sets (Hayes et al., 2021). For example, Hong et al. (2019) used a convolutional neural network to detect whales using satellite images. Automated analysis of remotely sensed data using advances in technology such as deep learning algorithms to recognize, count and track moving organisms is a research priority. This study provides training data and a baseline to evaluate the performance of these methods.

5 Conclusion

The Great Barrier Reef is an ecologically and culturally significant ecosystem and is known for its rich marine biodiversity, which includes breeding populations of 20 seabird species. Marine ecosystems also provide many services including fishing harvests and other economic, social and cultural resources that support livelihoods (Barbier, 2017). To implement ecosystem-based management plans requires information on the status and behaviour of ecosystems (Piatt, Sydeman & Wiese, 2007) and their component species, habitats and processes. The ability to identify and understand environmental issues can help prevent or mitigate declines in biodiversity (Browning et al, 2018) and there is an urgent need to limit human impacts on wildlife and natural habitats (Stokes et al., 2020). Understanding the population biology and spatial ecology of wildlife populations can help inform better management decisions (Hodgson et al, 2018, Rush et. al, 2018).

While drones are still relatively new in conservation science, there is much potential in their application in environmental research and management. Careful use of drones in ornithology and many other fields can have positive benefits for species conservation and ecosystem protection (Vas, Lescroël, Duriez, Boguszewski & Grémillet, 2015) but the impact of the monitoring itself can be an issue in itself. To avoid this, this study recommends closely monitoring drone flights in areas with wildlife present, making use of drone data collected incidentally as triggers for management, and continuing investigation into other factors and less obvious signs of seabird distress.

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