Developing new methods for monitoring Double-crested Cormorant nesting colonies in the Strait of Georgia

by

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Declaration of Committee

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Abstract

Seabirds have historically been used as sentinel species for marine ecosystems. Double-crested Cormorants (DCCO) are blue listed in British Columbia and distributed throughout the Salish Sea. However, existing methods for monitoring DCCO fall short in some ways, including lacking time series throughout the breeding season and not having a way to determine nest success. I examined three DCCO colonies in the Salish Sea using GoPro and long-distance panoramic photography, as well as a drone. I also led the development of a machine learning model to count cormorants and their nests on the Ironworkers Memorial Bridge (IWMB) in Vancouver. My results show that one DCCO colony, Mitlenatch Island, failed to produce any offspring in 2021. The other two sites were more successful. The machine learning model was able to count birds at 69% accuracy and in a fraction of the time of manual counts. These methods have great potential for monitoring DCCO colonies as they provide opportunities to increase temporal resolution, reduce time and labour cost, and allow the examination of parameters not possible with traditional seabird monitoring methods.

Keywords: cormorants; GoPro; GigaPan; nesting colony; monitoring; machine learning

Dedication

This thesis is dedicated to my parents, who fostered a love of the ocean and the environment in me ever since I was born, and who are both ocean scientists themselves.

Acknowledgements

This research was conducted on the ancestral lands and waters of the Tsleil-Waututh, Squamish, Musqueam, Snunéymuxw, We Wai Kum, We Wai Kai, and Homalco First Nations, whose relationships with the land continue to this day.

I would like to thank my project partners, Ariel Lenske and Greg McClelland from the Canadian Wildlife Service, and Jenna Cragg from the Ministry Forests, Lands, Natural Resource Operations and Rural Development for their logistical, in-kind, and financial support, as well as their advice and expertise. Trudy Chatwin also contributed to many aspects of the project since its beginnings in 2020.

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Many types of data went into this project, and collecting it required the help of many different people and organizations. Data collection by drone would not have been possible without Eric Saczuk of InDro Robotics, Inc. and the BCIT RPAS Hub. The Gabriola Island GoPro was installed by Alex Harris. Derek Moore provided us with permits for the work on Mitlenatch Island.

I thank Sean Morris on Gabriola Island and Trident Navigation Ltd. in North Vancouver for their permission to enter their private property to take photos of cormorants.

Travel to and from Mitlenatch Island was an adventure each time, and it is with the help of Erica McClaren, Heather Steere, and Daniel Clark of BC Parks, Roger McDonnell, Greg Baldock, and Ruedi Pletcher of Ocean Fix Dive Centre in Campbell River, Rachel Sullivan-Lord, Bruce Paterson, Lindsey Nielsen, John and Bev Ford, the Mitlenatch Island Stewardship Team, and Rachel Stapleton that it was possible three times.

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List of Acronyms

BCIT	British Columbia Institute of Technology
DCCO	Double-crested Cormorant
DDT	Dichlorodiphenyltrichloroethane
FOV	Field of view
IWMB	Ironworkers Memorial Bridge
PECO	Pelagic Cormorant
RPAS	Remotely piloted aircraft system
SFU	Simon Fraser University
MIST	Mitlenatch Island Stewardship Team
MOTI	Ministry of Transport and Infrastructure

Chapter 1. Introduction

Seabirds are one of the world's most threatened groups of vertebrates as a result of habitat destruction, invasive species, fisheries bycatch, and direct persecution (Zydelis et al. 2009; Croxall et al. 2012; Paleczny et al. 2015). Almost half of all seabird species have declining populations, and one in three species is threatened with extinction (United Nations 2017).

Historically, the Double-crested Cormorant (*Phalacrocorax auritus*) has undergone major population declines in North America because of legal and illegal control activities by anglers and fish farmers (Adkins et al. 2014), who shot at breeding colonies and routinely destroyed nests. In addition, habitat was lost due to agricultural and water developments (Carter et al. 1995). By the late 1800s and early 1900s, the Double-crested Cormorant (DCCO) had experienced substantial decline and loss of breeding colonies along several portions of its Pacific Coast range (Carter et al. 1995; Hatch and Weselow 1999; Krohn et al. 1995; Weseloh et al. 1995, Wires and Cuthbert 2006). Due to widespread use of Dichlorodiphenyltrichloroethane (DDT) insecticide beginning in the 1940s, seabird nesting success further declined (Wires et al. 2001; Wires & Cuthbert 2006; Wires 2014). In 1972, the Double-crested Cormorant was Blue Listed in the United States by the National Audubon Society (Tate and Tate 1982) and added to the U.S. Migratory Bird Treaty Act protected bird list (23 U.S.T. 260 (1972)).

In the past few decades, the Double-crested Cormorant has made a remarkable recovery. The national designation of Double-crested Cormorants in Canada is currently ranked S4 (Apparently Secure) since March 2015. The status of the Double-crested Cormorant was reviewed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2016 and considered to be Not at Risk (NAR) at the federal level. Due to the species' abundant populations in other regions of Canada, the species is considered not vulnerable to extirpation or extinction at the global level and is thus designated as G5 (Globally common) (Kutner 2019, BC Conservation Data Centre 2021). In Ontario, Double-crested Cormorant recovery from mid-century numbers has been so successful that they are again coming into conflict with humans. At Presqu'ile Provincial Park in Ontario, a formally designated Important Bird Area, over 6,000 breeding cormorants were killed in 2004, allegedly to protect an old-growth forest (Ontario Parks 2005).

The Pacific or Western (or the Pacific Flyway) population of Double-crested Cormorants include those in Alaska, British Columbia, Washington, Oregon, Idaho, California, Nevada, Utah, Arizona, Montana, Wyoming, Colorado, and northern New Mexico (Wires & Cuthbert 2006; Adkins et al. 2014; Chastant et al. 2014). Since the 1980's in this Pacific region, Double-crested Cormorant numbers have increased substantially. This increase was largely due to one nesting colony on East Sand Island in the Columbia River estuary, Oregon (Adkins et al 2014). At 13,600 breeding pairs in 2010 (Lyons et al. 2014), the East Sand colony accounts for almost 40% of all breeding pairs in the western population. The East Sands Island population has been 'reduced' by lethal measures due to the perceived over-consumption of juvenile salmonids (Collis et al. 2002; Roby et al. 2003; Anderson et al. 2004; Clark et al. 2006), but little is known about the effect this had on the estuary ecosystem (Brown 2019).

Despite recovery in Double-crested Cormorant territories south and east of British Columbia, the numbers of breeding pairs estimated in coastal British Columbia and Washington have declined by approximately 66% since the 1980s (Adkins et al. 2014; Chastant et al. 2014). It is this declining subpopulation in British Columbia that I have chosen to focus my research on.

1.1. Double-crested Cormorants in British Columbia

The Double-crested Cormorant receives provincial protection under Section 34 of the British Columbia Wildlife Act and is currently a Blue-listed species in British Columbia (Adkins and Roby 2010, B.C. Conservation Data Centre 1995; Machmer 2008; Machmer 2017). This protection recognises the documented decline of coastal breeding cormorants, making it illegal under provincial law to harm, own, or destroy the species, egg, and nest, unless granted permission under the BC Wildlife Act. Between 1984 and 2001, there has been a two-thirds decline in the number of nests for this species (Machmer 2008), from 1607 pairs (Vermeer & Rankin 1984) to 602 pairs (Carter et al 2017). Thus, the Double-crested Cormorant continues to be considered as a bird of special concern in British Columbia.

Double-crested Cormorants are resident throughout coastal waters of British Columbia, but breeding occurs largely in the Strait of Georgia (Moul and Gebauer 2002). Double-crested Cormorants also breed in freshwater lakes throughout the province, such as Leach Lake in the Creston Valley (Van Damme & Colonel 2007), Osoyoos Lake in the Okanagan Valley, Stum Lake and Takla Lake in the Cariboo region, and at central and northern interior lakes located east of Smithers and Dawson Creek (Campbell et al. 1990; Moul & Gebauer 2002).

Double-crested Cormorants are fish-eating predators that are local foragers. Unlike other seabird species such as albatrosses, petrels, and frigatebirds that routinely travel more than 200 km to find food during the breeding season, cormorants only travel 5-10 km out to sea, staying much closer to home. Additionally, the species has shown itself to be sensitive to chemical pollution (especially organochorides such as DDT), and strongly affected by nest site harassment and disturbance from humans. Therefore, due to the species' dependence on local waters for food and its sensitivity to environmental conditions, the status of Double-crested Cormorant populations can be important indicators of local marine ecosystem health (e.g., Gress et al. 1973, Weseloh et al. 1995).

In the Salish Sea, there has been a shift in the nest site selection of cormorants from cliffs and offshore islets (Chatwin et al. 2003) to man-made structures like bridges, outflow dolphins and transmission towers (Butler 2015). These man-made structures are found within the City of Vancouver, a large urban centre of nearly 2.5 million people (Social Policy and Projects, City of Vancouver 2020). This proximity to the city may expose cormorants to anthropogenic stresses like commercial vessel transits, speedboats, and other small recreational boats (Chatwin et al. 2001) as well as higher ambient noise levels from vehicle, airplane, and train traffic, as well as noise from Vancouver's industrial port activities. On the other hand, these man-made structures may make breeding cormorants immune from terrestrial predators and less vulnerable to aerial avian predation by Bald Eagles and gulls and therefore less prone to nest abandonment (Hipfner et al. 2012).

As Double-crested Cormorants are indicators or sentinels of the local environment, the species' dependence on local waters for food and its sensitivity to environmental conditions, the status of Double-crested Cormorant populations can be important indicators of local marine ecosystem health, and in particular that of the local Vancouver coastline where these cormorants are foraging. The decline or the recovery of this species may have broader implications on management of local forage fish populations in urban estuaries and river mouths, and the degree of disturbance and disruption from humans and their noise and organo-chemicals they introduce to their environment. By monitoring Double-crested Cormorants, and following their nesting successes and failures, their population status could serve as an environmental health proxy that could lead to early management interventions that benefit cormorants and the coastal food web into which Double-crested Cormorants are interwoven.

1.2. Cormorant (Ecological) Restoration.

Vancouver is a large coastal city with extensive urban infrastructures including a number of bridges that span bodies of water providing suitable breeding habitat for marine piscivores (Rauzon et al. 2019). As these urban bridges are important for moving millions of cars a day into and out of the city (Public Sector Digest 2016), management for the safety and maintenance of these critical structures is a major concern for the Ministry of Transport and Infrastructure (MOTI) (Hemmera 2018a, b; Hemmera 2019) and the City of Vancouver’s engineering department. Exclusionary measures are being considered for limiting access to the bridge for breeding. The belief is that cormorants’ guano may affect activities like bridge inspection, maintenance, and management (Dorr et al. 2016). Huang & Lavenburg (2011) suggest that reactive chemicals and salts in cormorant guano could be potential factors that affect the structure’s integrity and longevity if the chemicals corrode the structures. Although their ammonia-rich droppings are proven to have detrimental impacts on vegetation, killing trees or ground vegetation at their breeding sites (Wires et al. 2001; Dorr et al. 2016), no studies have clearly established the effects of their guano on property and infrastructures (Wires et al. 2001), and little data has been collected on the health and life cycle of highway structures used for cormorant nesting (Huang and Lavenburg 2011). If Double-crested Cormorants were excluded from the Ironworkers Memorial Bridge (IWMB) through exclusionary netting and/or anti-bird architecture (such as spikes), this would result in up to half of the provincial population of this species of cormorants being excluded from their breeding colony. This could potentially have a catastrophic effect on current restoration efforts to recover this species in the province, as well as untold disruptions in the local food web and marine nutrient transport systems.

The first urban breeding colony of Double-crested Cormorants on human-made structures in British Columbia occurred at the Second Narrows transmission tower in 2009. The colony breeding site shifted to the adjacent IWMB between 2010 and 2014. The Double-crested Cormorant colony at the Second Narrows has increased gradually from 2010 to 2018 (Carter and Drever 2016; Halpin and Drever 2017; Hemmera 2018a; Hemmera 2018b). Following the development of a management framework for the Double-crested Cormorants in the Western Population by Pacific Flyway Council in 2012 (Pacific Flyway Council 2013), the Ironworkers Memorial Bridge was recommended as one of the monitoring locations (Carter and Drever 2016). Sampling and monitoring of the Ironworkers Memorial Bridge started in 2014.

1.3. Past Conventional Monitoring Methods

Breeding pairs of cormorants are difficult to census due to their remotely located and (sometimes) vertically oriented (e.g., seacliff) colonies. Conventional monitoring surveys of cormorants have been conducted using in-person observation using boat-based methods and binoculars. Studies on Triangle Island have been conducted in-person by using a viewing blind situated above the Pelagic Cormorant colonies so that the adult cormorants were surveyed when they were in standing postures (Hipfner & Greenwood 2009). The traditional census method for urban bridge occupancy involves looking up at near right-angles from a moving boat, making it difficult to observe all nesting and breeding birds. This lack of consistent census methods complicates interpretation of census data rendering comparisons among different breeding colonies problematic.

Conventional cormorant surveys at the Ironworkers Memorial Bridge and the Second Narrows transmission tower were boat-based and conducted from water under the bridge using an inflatable boat that carried three field surveyors – a boater, a counter, and a recorder (Carter and Drever 2016); except in 2018, when the survey was carried out by bridge maintenance crews using a ‘traveller’ (Hemmera 2018a, b; Hemmera 2019), a horizontal elevator that moved along the inner girders from the underside of the bridge. Additional challenges remain in counting cormorants from a boat as the proximity of humans during the census to nesting colonies may bias results. Human proximity can cause birds to exhibit a stress response that may lead to flushing from or abandonment of their nests (Chatwin et al. 2003).

Another challenge is the hazard of estimating chick survival in offshore-islet nesting species where the already difficult-to-access field location adds further risks to both birds and humans. Boat-based surveys can be challenging to account for tracking nests from a moving platform, particularly when nests or chicks are only partially observed (Carter and Drever 2016; Halpin and Drever 2017). These limitations have driven innovations for better ways to monitor breeding cormorants and their reproductive success in a part of their range where recovery and restoration of this population remains a significant objective in British Columbia.

1.4. Research Objectives.

This research targets the Double-crested Cormorants that nest in the Salish Sea at the two major breeding colonies and one minor breeding colony. The research focuses on nesting birds on the Ironworkers Memorial Bridge in the Metro Vancouver district that hosts up to half of British Columbia's Double-crested Cormorants (numbers derived from Chatwin et al. 2001; Carter et al. 2017). Monitoring was also focused on a major cormorant colony on the natural seacliffs of Gabriola Island, overlooking Northumberland Channel and the Duke Point Ferry Terminal. To cover the northern Strait of Georgia, we also put effort into monitoring the breeding rookery of Mitlenatch Island Nature Provincial Park. The focus was devising methods for monitoring these three very different nesting sites which collectively cover examples of an anthropogenic and urban vertical rookery, a natural and remote vertical seacliff rookery, and a remote horizontal rookery (Fig. 1-1).

Figure 1-1: A map showing the three DCCO colonies examined in this study.

This study addressed multiple objectives. The first was to monitor the nest phenology of Double-crested Cormorants at these three breeding sites. Through continuous monitoring, we aimed to gather evidence of how and when the cormorants are using the urban Ironworkers Memorial Bridge, and the two remote sites of Gabriola and Mitlenatch Islands. By using time-series of photogrammetric methods, we aimed to determine the basic biology and nesting phenology of Double-crested Cormorants in the region to provide baseline data for comparison of nest occupancy and fledging of juveniles across two years of monitoring. As the IWMB is being considered for managed exclusion of Double-crested Cormorants, this study aimed to inform best management practices for co-existing with cormorants on these highway corridors in the city of Vancouver. Our study did not aim to study effects of guano, but instead aimed at identifying when bridge maintenance activities could occur to minimize impacts on this blue-listed species. The research aims to provide a summary of cormorant activity highlighting the breeding success on this bridge to aid the decision-making processes for the Ministry of Transportation and Infrastructure (MOTI), particularly when compared to smaller more vulnerable populations such as that seen at Mitlenatch Island Nature Provincial Park.

As with many marine species, advances in technology have made it possible to change the way we monitor their breeding rookeries. Therefore, a second objective was to devise more efficient engineered solutions to monitoring breeding cormorants on nesting structures. Typical methods fall short in several ways, including lacking time series throughout the season and not having a way to determine nest success. In other words, they are insufficient for measuring the parameters of interest to this study. The aim was to build upon the spatial and temporal photogrammetry methods pioneered in Ong (2021) but reduce the processing time for counting cormorants in large images (1 to 4 GB in size). This work used GigaPan® software with a high-resolution Sony camera to create a time-series of panoramic images of the IWMB breeding colony as input to a set of neural net algorithms for detecting and classifying cormorants and their nests in these images.

The third objective of this thesis was to investigate new methods for monitoring cormorant colonies. In other studies, drones have been shown to be reliable tools for estimating colonial seabird numbers (Irigoin-Lovera et al 2019). As the drone approach distance has been tested to not disturb some species of cormorants at vertical distances of 50 m, the drone offers a much better aerial vantage point than a human at much greater approach distances and at oblique angles. We therefore wished to examine the benefits and costs of aerial drone photography in monitoring hard to access breeding colonies.

The tools will ultimately contribute to the long-term population evaluation, monitoring, and management of nesting and breeding cormorants in British Columbia. Monitoring and management of the urban colony is critical as its success within the metapopulation of Double-crested Cormorants in the province likely depends on this urban nest site. In addition, engineering new methods to monitor that are more rigorous and less open to observer or measurement bias will allow for comparisons across time and across cormorant breeding colonies.

Chapter 2. Methods

Photographs were taken of cormorant nests on the Ironworkers Memorial Bridge, Gabriola Island, and Mitlenatch Island throughout the nesting season. These image time series were used to examine phenology, or the timing of life cycle events (start and end date of nesting, hatching, and fledging). From these photos, counts were taken of the number of nests, chicks, and adult birds. Eggs were noted where possible but are almost always concealed by the parent incubating them. Three main methods were used for taking these photographs: long-distance photography, GoPro cameras installed close to the nests, and a drone equipped with a camera. Photos were also taken from a kayak at the bottom of the Gabriola Island seacliffs on June 30, 2021.

2.1. Long-distance photography

High-resolution panoramic photographs of the bridges in Metro Vancouver have been created using a GigaPan system (Lynch 2015) (Fig. 2-1). This software stitches together many photos into one high-resolution panorama (Fig. 2-2). Bird counts can be taken from these panoramas, but because of image quality identifying whether an individual is a juvenile or an adult can be difficult towards the end of the season when chicks near maturity and adult size. This is more of a problem for the Gabriola Island panoramas, as they are taken from 1,700 m away from the colony, whereas the panoramas of the IWMB are taken from 100-150 m away.

Figure 2-1: The author using the GigaPan system to photograph the IWMB (Ong, 2021).

Figure 2-2: Panoramic image showing the IWMB on July 7, 2021.

The equipment used to capture panoramic image tiles is as follows: GigaPan EPIC Pro robotic camera mount, Milano tripod, Sony α7R IV Digital SLT camera with 200-600 x zoom lens. The GigaPan is mounted on the tripod, and the camera is mounted on the GigaPan. The GigaPan then tilts the camera gradually, taking overlapping photographs that can be stitched together later. GigaPan has its own software that does this stitching, GigaPan Stitch. For this project, we used GigaPan Stitch as well as PTgui to stitch panoramas together, as GigaPan Stitch was unable to process some larger panoramas.

2.1.1 Ironworkers Memorial Bridge

Panoramas of the IWMB were taken from four locations (Fig. 2-3). Both the northern Span 2 and southern Span 1 were photographed from the east and from the west. This was for more accurate counts as some cormorants built nests in the corners of beams, where they were visible from one angle, but not both.

Figure 2-3: Photos of the IWMB were taken at four sampling locations around the bridge, shown as yellow pins in this aerial image of the bridge.

The marina sampling location at the northwest was the end of a private dock accessed with the permission of Trident Navigation. The Second Narrows Crossing location at the northeast was a rocky beach beneath the Second Narrows rail bridge. The Trans-Canada Trail location at the southwest was on a paved path leading under the IWMB. The Trans-Canada Trail location at the southeast was on a footbridge over the train tracks that lead across the rail bridge.

Panoramas of Span 2 were taken from both sides three times a week for the months of June and July, twice a week for August, and once each in late August and September. Panoramas of Span 1 were taken on May 18, 26, and 31, July 13, August 24, September 25, and October 26. The planned date for a Span 1 panorama in June was canceled because a major heat wave in the last week of June made fieldwork unsafe (Griffiths 2021). SFU and BCIT both suggested suspending fieldwork that week.

2.1.2 Gabriola Island

Panoramas of the Gabriola Island colony were taken from the northernmost point of Jack Point in Jack Point and Biggs Park, Nanaimo (Fig. 2-4).

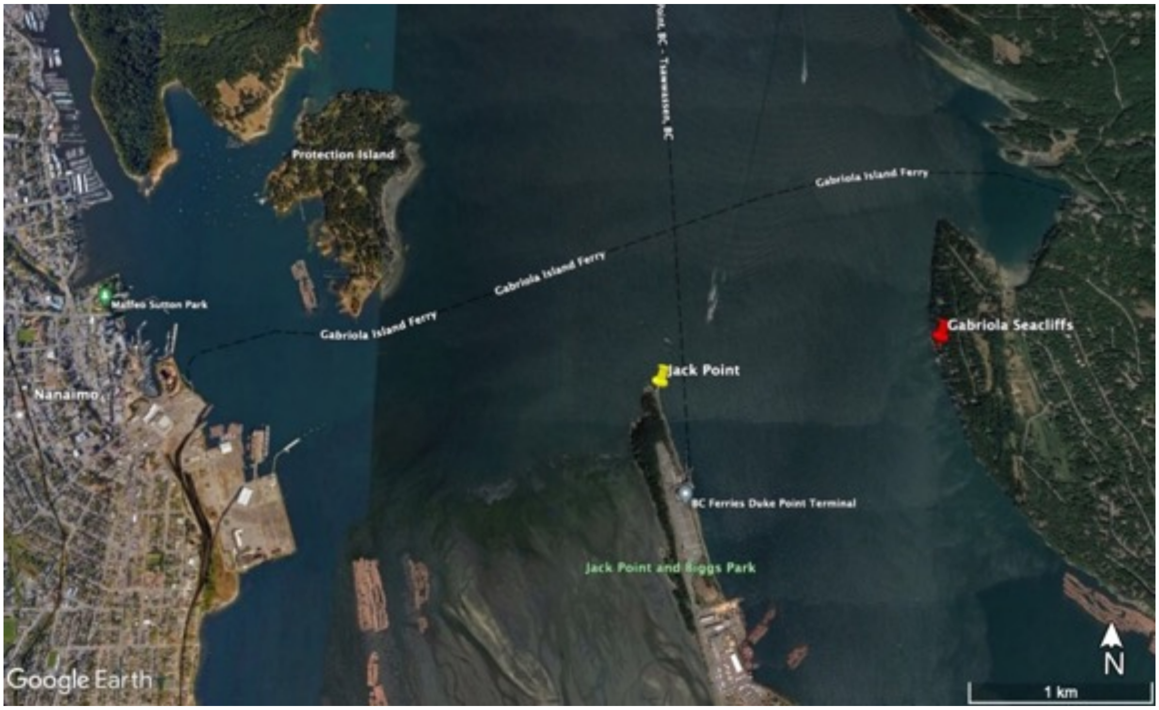

Figure 2-4: Panoramas of the Gabriola Island colony were taken from across the Northumberland Channel, at Jack Point.

In 2021, panoramas were taken at Jack Point on June 4, June 30, and September 6. On June 30, additional sampling was carried out at the Gabriola Seacliffs from kayaks in the water right below the colony. Photos were taken of all cormorants from the kayaks with the same Sony DSLT camera used to take the panoramas. These photos were then matched to their cliff locations on the June 30 panorama to ensure an accurate count.

2.2. GoPro cameras

GoPro photography has been used at seabird colonies to collect population data such as population size, breeding pairs, and breeding success, as well as to monitor nocturnal behavior of birds and their predators (Dilley et al. 2015).

GoPro cameras were used during the 2020 and 2021 breeding seasons to photograph the natural rookery site on Gabriola Island. In 2021, we expanded our regional coverage and installed a camera at the Mitlenatch Island colony. The camera setups consisted of a GoPro HERO7 camera, SD card, battery pack, and a BlinkX time lapse controller/Wi-Fi box inside a weatherproof case. A wire connected the battery pack to a solar panel outside the box. The solar panel and battery pack powered both the camera and the BlinkX device, which directed the camera to turn on every 30 minutes, take three photos 30 seconds apart, and turn back off. This pattern was designed to save power and ensure consistent photos. The camera on Mitlenatch Island was set to take photos every 30 minutes, 24 hours a day, from installation on April 26 until October 27. Packets of silica gel were included inside the box to protect the electronics from moisture.

A GoPro camera for the IWMB was also proposed, but the Ministry of Transport and Infrastructure (MOTI) declined to allow us to install one. The Ministry gave the reason as safety concern for workers doing maintenance on the bridge. This maintenance is ongoing and scheduled to last through spring 2023.

2.2.1 Gabriola Island

At Gabriola Island, the GoPro camera was fixed to the cliffside close to the colony, at an angle to photograph nests from above (Fig. 2-5). The camera was attached to the cormorant cliff by drilling and bolting the camera setup to the rock. The same field of view (and the same bolts) were used in 2021 as in 2020 by Macus Ong.

Figure 2-5: The Gabriola Island GoPro camera setup, pointing towards a ledge with nests on it (Wilkin, 2021).

2.2.2 Mitlenatch Island

On Mitlenatch Island, the camera was installed on April 26, attached to a post on top of a cliff near the southwest corner of the island (Fig. 2-6), looking down at nests right beside it. The post was made of metal rods held together with nuts and bolts. Eight holes were drilled into the rock with a hammer drill, and eight $^{3}/_{8}$ in expansion bolts were driven into them with a hammer. The four feet of the post were attached to these eight bolts with nuts and a rachet wrench. The weatherproof case containing the camera setup was screwed to the top of the post, and the solar panel was angled southward (Fig. 2-7).

Figure 2-6: A satellite image of Mitlenatch Island, showing the location of the DCCO colony in the yellow circle.

Figure 2-7: The Mitlenatch Island GoPro camera setup (Wilkin, 2021).

Double-Crested Cormorants at the site had built nests, but no eggs were present at the time of installing the camera. When we approached the site, all birds flew away from the nests. Only 20 minutes after we left the area, the cormorants returned to their nests (Fig. 2-8).

Figure 2-8: DCCO on Mitlenatch Island after returning to their nests following the GoPro camera installation (Joy, 2021).

On November 23, 2021, the Mitlenatch Island camera was retrieved. All pieces of the post and camera setup were recovered, and only the eight expansion bolts were left behind on the island. There were no cormorants remaining at the colony.

2.3. Drone photography

Additionally, a drone equipped with a camera was used to observe the colony on the IWMB up close. The drone was operated by a licensed drone technician, Eric Saczuk of InDro Robotics, Inc. and the BCIT RPAS Hub. A spotter watched the drone while the operator focused on the controller screen. Drone flights were staged on the rocky beach at the Second Narrows Crossing. Each flight began with the drone flying to the furthest beam of the northern span (Span 2) and photographing that beam. The drone then flew north beam by beam, stopping at each section to take photos of the cormorants.

Drone flights took approximately 40 minutes, and the drone had to be landed partway through for the battery to be replaced.

The drone used was a DJI Mavic 2 Zoom. The camera on the Mavic 2 Zoom is a 1/2.3 inch, 12 MP sensor (4000 x 3000 pixels) with up to 4x zoom (including 2x optical zoom 24 mm to 48 mm). Its Field of View ranges from 83deg at 24 mm to 48deg at 48 mm. Its aperture ranges from 2.8 (at 24 mm) to 3.8 (at 48 mm). Its ISO range is 100 to 3,200. Its shutter is electronic, ranging from 8sec to 1/8000sec. The camera's file format is either JPG or RAW (DNG).

In ideal conditions, the drone has a range of up to six kilometers from the operator and a battery life of 22 minutes (hence, the drone flights at the bridge requiring a battery change halfway through each session).

The drone was only flown on the east side of the IWMB as the west side of the bridge is in the drone flight exclusion zone associated with the Vancouver International Airport (YVR). The maximum altitude for drone flight is 122 m (Government of Canada, 2020), which is higher than the cormorant nests on the bridge.

In 2021, drone flights were done once per week from May to July, twice in August, and once in September.

2.4. Image processing

After photos were collected, numerical data was taken from them by counting cormorant nests, juveniles, and adult birds. Eggs were counted where possible, but they were almost never visible (because they are being constantly incubated, and it is rare to capture the exact moment of a parent standing up).

Counts were obtained from panoramas of the IWMB by manually counting birds and nests in the photos, beam by beam. This method is time consuming. Counts were obtained from GoPro photos of the Gabriola seacliffs by manually counting birds and nests.

2.5 Machine Learning Model Development

Starting with a pre-trained generalized object detection model, two machine learning models were developed: one trained on panoramas of the IWMB, and the other trained on panoramas of the Gabriola Island seacliffs. The models were pre-trained on the COCO train 2017 dataset, a dataset of everyday objects (Lin et al. 2015). All layers of the pre-trained model were then trained further on our data sets, meaning that even early steps of machine learning such as edge detection and gradients were trained on the cormorant panoramas. Our models were run on the Compute Canada clusters. This allowed for the remote use of a supercomputer, and for developers to run the models from anywhere, without needing a powerful personal computer.

The panoramas are broken up into 1000x1000 pixel tiles, with no overlap between tiles, and a subset of those tiles were annotated by me. Using the annotation side of the Label Objects and Save Time (LOST) interface (Fig. 2-9), I manually labeled each presented image. I was shown tiles one by one and annotated them by drawing boxes around nests and cormorants, then labeled the boxes accordingly from a drop-down menu. The LOST interface was chosen so that multiple people could work on annotations at the same time; LOST is a web-based framework for semi-automated annotation.

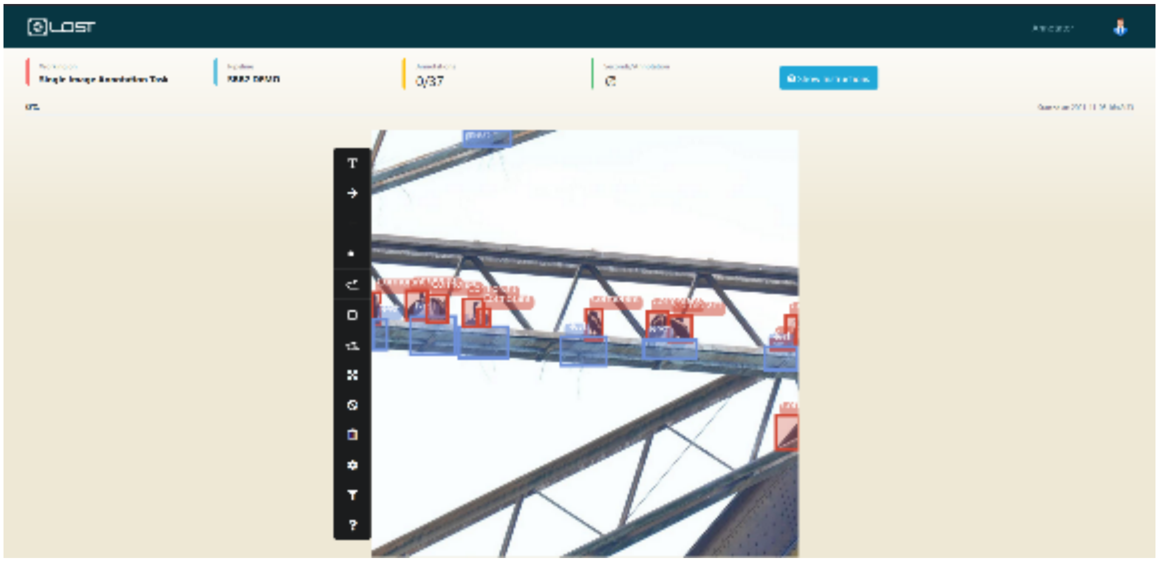

Figure 2-9: A screenshot of the LOST user interface for annotating images to be put into the model training pipeline.

The panoramas were divided into tiles with no pixel overlap because this way, manual annotations do not get cut in half. Additionally, the model being able to detect partial images of a cormorant or nest is beneficial in this case since birds and nests are often partially obscured by bridge beams.

All annotated tiles are split into training data (70%), validation data (15%), and testing data (15%). After the algorithm has trained itself with the annotations from the training data, it is run on the validation data, which it has not seen before. The validation data is used to calculate the mean average precision (mAP) of the model and guide decisions about continued model development. The final version of the model is later run on the test data to determine its performance when applied to real world data. For the IWMB model, training data was created from panoramas taken in June and July 2021, and validation data was created from panoramas taken in June and July 2020. Test data was from panoramas taken in May and June 2020. Test counts were compared with manual counts taken from those same panoramas in May and June 2020 rather than comparing model annotations to manual annotations (i.e., testing was done using entire panoramas rather than tiles). I evaluated the performance of the model by manually marking the annotations on the validation data as correct (true positives), incorrect (false positives), or missed (false negatives). This is not a direct interaction with the model. Rather, these corrected annotations are then added back to the beginning of the development pipeline as more training data. Hyperparameters (parameters that control the learning process) may be tweaked, then this cycle continues until the algorithm's performance is satisfactory. The main hyperparameter that was tuned was the learning rate, and the maximum number of boxes that can be detected per tile was also tuned. Since the intended application of the model is to replace manual counting, the most important measure of model performance is comparison to manual counts. A simplified flowchart of the model development pipeline is shown in Figure 2-10. The entire process was done separately for the Gabriola Island seacliff model, with data from panoramas taken on June 4, June 30, and September 6, 2021.

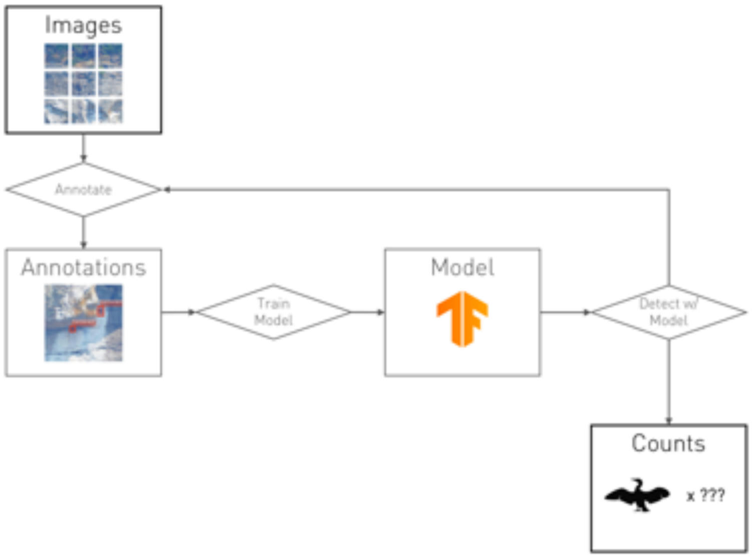

Figure 2-10: A simplified flowchart of the machine learning training pipeline.

In addition to the comparison to manual counts, other important measures of performance include mean average precision (mAP) and average recall. These metrics are derivatives of precision and recall, respectively. The mAP is generated from the precision, recall, and Intersection over Union (IoU) metrics. Precision is the number of true positives divided by the total number of detections (true positives plus false positives). The term “mean average” describes the average of averages across classes, or the mean of the average precision for cormorants and the average precision for nests. The recall is the number of true positives divided by the sum of the true positives and false negatives. The IoU is the area of overlap between an object detected by the model and an object annotated by a researcher (area of overlap), divided by the combined area of the boxes (area of union). In this model, a detection is considered a true positive if the IoU is greater than or equal to 0.5 (the standard threshold in the field of machine learning). If the IoU is less than 0.5, the detection is considered a false positive. If the model does not detect an object where one has been manually annotated, it is a false negative. A high recall indicates that a high proportion of objects were detected by the model. In other words, the model did not miss too many cormorants or nests. A high precision indicates a relatively low number of false positives. There is generally a trade-off between recall and precision. A model may have high recall but low precision by detecting many objects, which includes many true positives but also many false positives. It may have high precision but low recall by detecting few false positives while also missing many objects (having many false negatives). Because of this, the mAP is used as an important measure of model performance as it takes true positives, false positives, and false negatives all into account.

A desirable mAP is essentially the best we can get it to, that gives us a good/accurate count (close to manual counts) given a tradeoff between accuracy and efficiency. If the difference in model counts and manual counts is negligible, the model performance can be considered satisfactory even if the mAP is not high.

The models were trained to detect two types of objects: “cormorant” and “nest”. It was decided that given the difficulty faced even by researchers in telling adults and juveniles apart in the long-distance photos, that it would not be appropriate to train the models to try and do so. The same is true for Double-crested vs. Pelagic Cormorants in the Gabriola Island panoramas, which are taken from far enough away that the species of a bird is not always obvious.

The IWMB model was trained for 100,000 steps. This is enabled in part by data augmentation of the manually annotated tiles. This process creates repeats of the annotated tiles with the brightness, saturation, and/or contrast, etc. adjusted, or horizontally flipped. By augmenting the data, we were able to ensure the model can perform well on differently lit panoramas than the one that was tiled for training, which is important given panoramas were taken on days with different weather and different lighting. After training, developers adjusted the hyper-parameters of the model. For example, the learning rate was reduced to prevent overcorrecting.

After validation, in which the model makes detections on tiles it has not seen before, I look at its annotations in the LOST UI and “correct” them (although this is not a direct interaction with the model). This entails deleting detections that are false positives, annotating cormorants and nests that were missed, and adjusting the size and placement of some boxes. These corrected annotations are then added as additional training data, returning to the beginning of the loop (Fig. 2-10).

After finalizing the IWMB model’s methods including training, learning, confidence threshold, and post-processing using panoramas from 2020 and 2021, all 2021 panoramas were then processed by the model and post-processed using Python.

The models are interacted with through Tensorflow, an open-source machine learning platform. Tensorboard is the tool used to provide measurements and create charts during machine learning development.

Chapter 3. Results

3.1. Ironworkers Memorial Bridge

Before the beginning of the field season, I proposed creating a baseline for the cormorants' behaviour in response to a drone fly-by and determining a minimally disturbing distance before attempting to take photos. Based on the recommendations of Brisson-Curadeau et al. (2017), a distance of 20-25 m was predicted for this. However, on the day of the first drone flight (April 17, 2021), the cormorants appeared undisturbed by the drone, even at a distance estimated at 10 m or less. They did not stand up when the drone was nearby, a behaviour cormorants exhibit when predators circle overhead (Chatwin et al. 2013). Cormorants on the IWMB had no discernable reaction to the drone at any drone flight for the duration of the breeding season.

The first date chicks were observed in nests on the IWMB in 2021 was May 21. Almost all cormorants had left the bridge by September 24, and those that remained were not attending nests (most were juveniles). The number of birds present in each individual nest over the course of the season is shown in Figure 3-1.

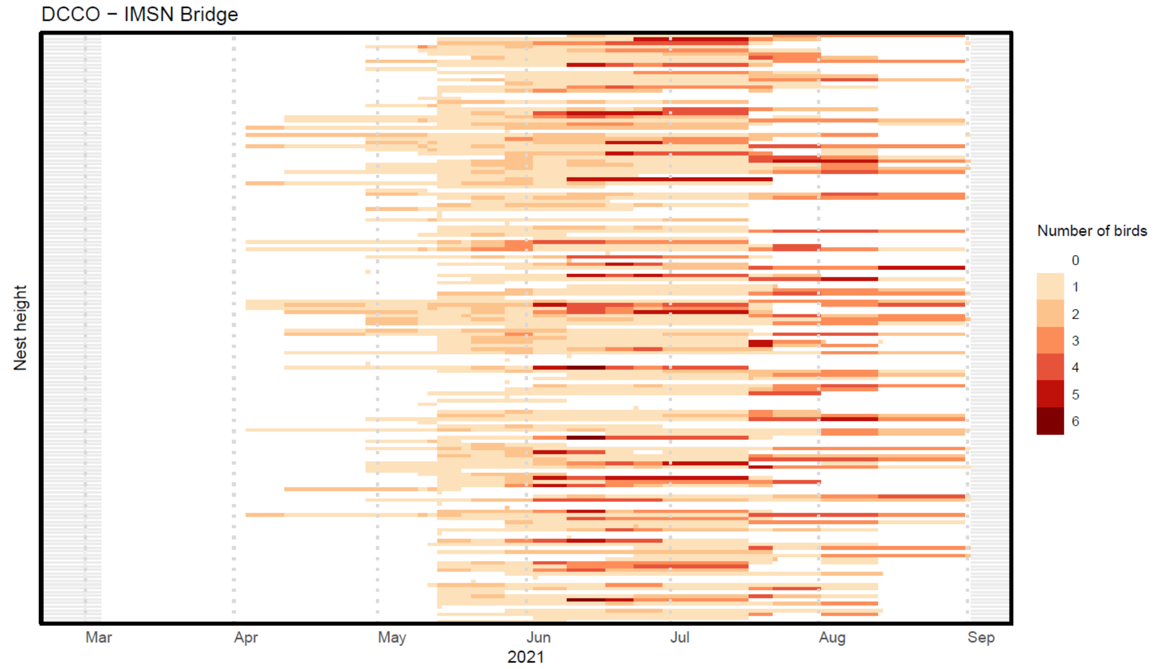

Figure 3-1: A heatmap showing the number of total birds present in each DCCO nest on the IWMB throughout summer 2021. Each row represents a single DCCO nest tracked across the monitoring period. Nest heights are relative to each other, with the origin at the cement foundation of the bridge.

A nest is “successful” if it produces at least one chick that survives to fledge and leave the nest. Although nest success is difficult to ascertain from these data, there was certainly some nest success at the IWMB, as fledged juveniles were observed around the colony (Fig. 3-2).

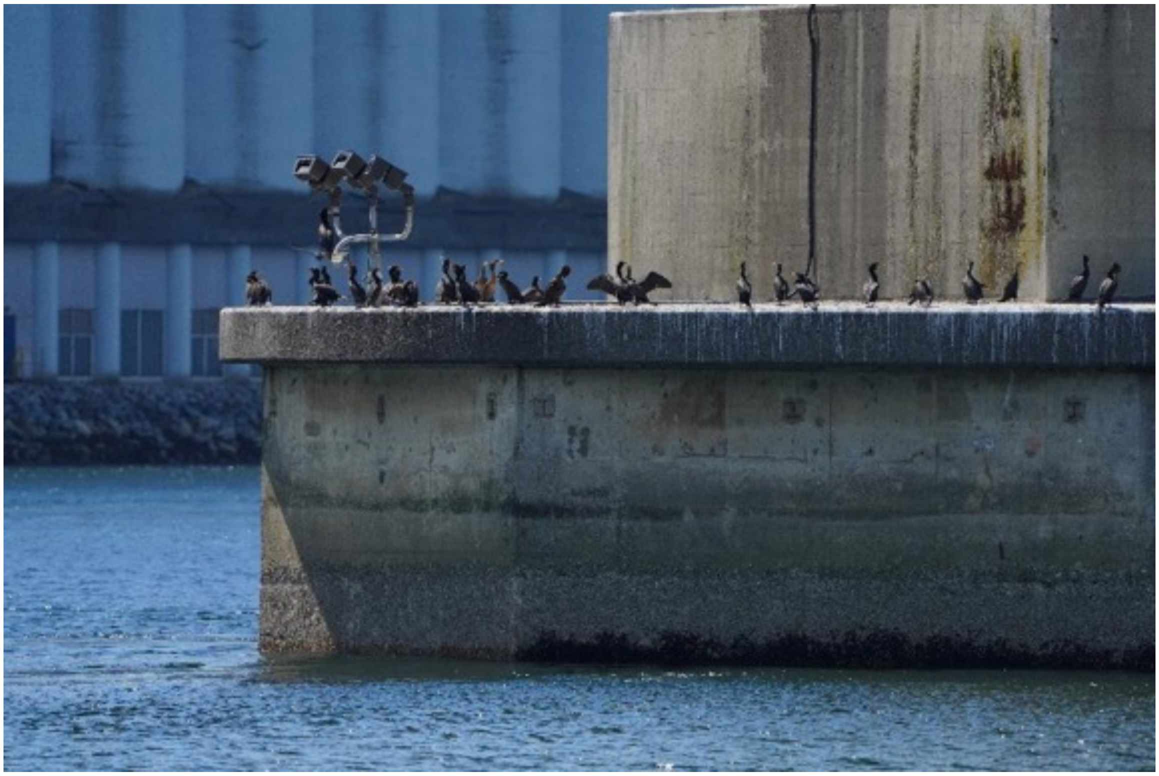

Figure 3-2: Recently fledged juvenile DCCO congregating on the IWMB's cement foundation on July 18 (Wilkin, 2021).

3.2. Gabriola Island

The day the camera was installed, March 27, 2021, DCCO were present in nests within the camera's field of view (FOV). The last date that cormorants can be seen in the Gabriola Island GoPro photos is August 27. In photos from September 1 and 2, no cormorants are present.

In May 2021, the GoPro camera on Gabriola Island malfunctioned. It took photos normally from installation on March 27 until May 7, and thereafter took only intermittent photos. The problem was a software issue where instead of storing all photos in the same folder, the camera created a new folder at every half hour interval, placing three photos in each. Once there were 999 folders on the camera's SD card, it was no longer able to create more folders, and instead stopped taking photos normally. For some reason, photos from after 999 folders were created were intermittently stored in apparently random existing folders.

The Gabriola Island GoPro had 34 nests in its field of view, 20 of which were close enough to count birds in. At least one nest, DCCO-CL1, failed. Because of the camera malfunction, the success of success of other nests could not be ascertained.

Several nests from 2020 survived the winter and were reused in 2021, and some 2020 nest sites where nests disappeared over the winter had nests rebuilt there in 2021 (Fig. 3-3).

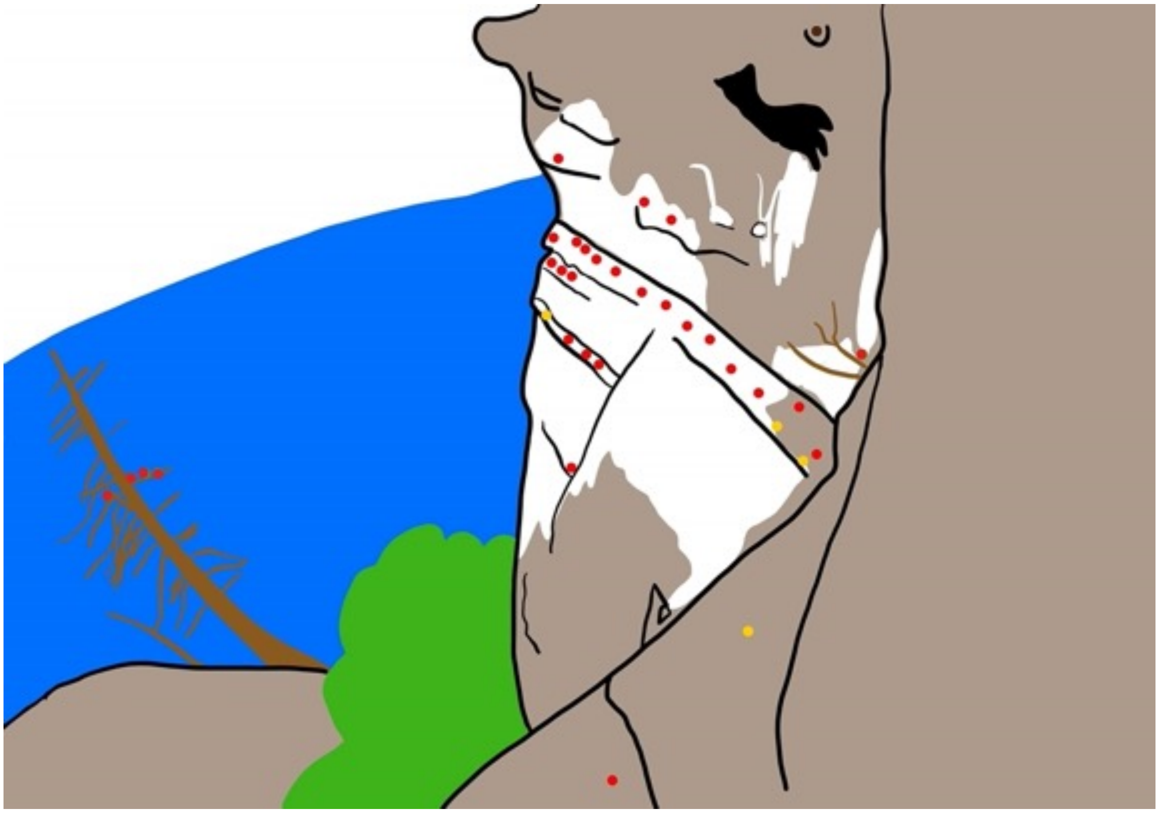

Figure 3-3: A diagram showing nest sites within the Gabriola Island camera's FOV. Red dots are nest sites that were used both in 2020 and 2021, and yellow dots are nests that were new in 2021. There are 4 yellow dots.

The number of birds present in each nest visible to the GoPro in both 2020 and 2021 is shown in Figure 3-4. Dates on which no photos were taken due to the camera malfunction have been interpolated with the number of birds from the last known date.

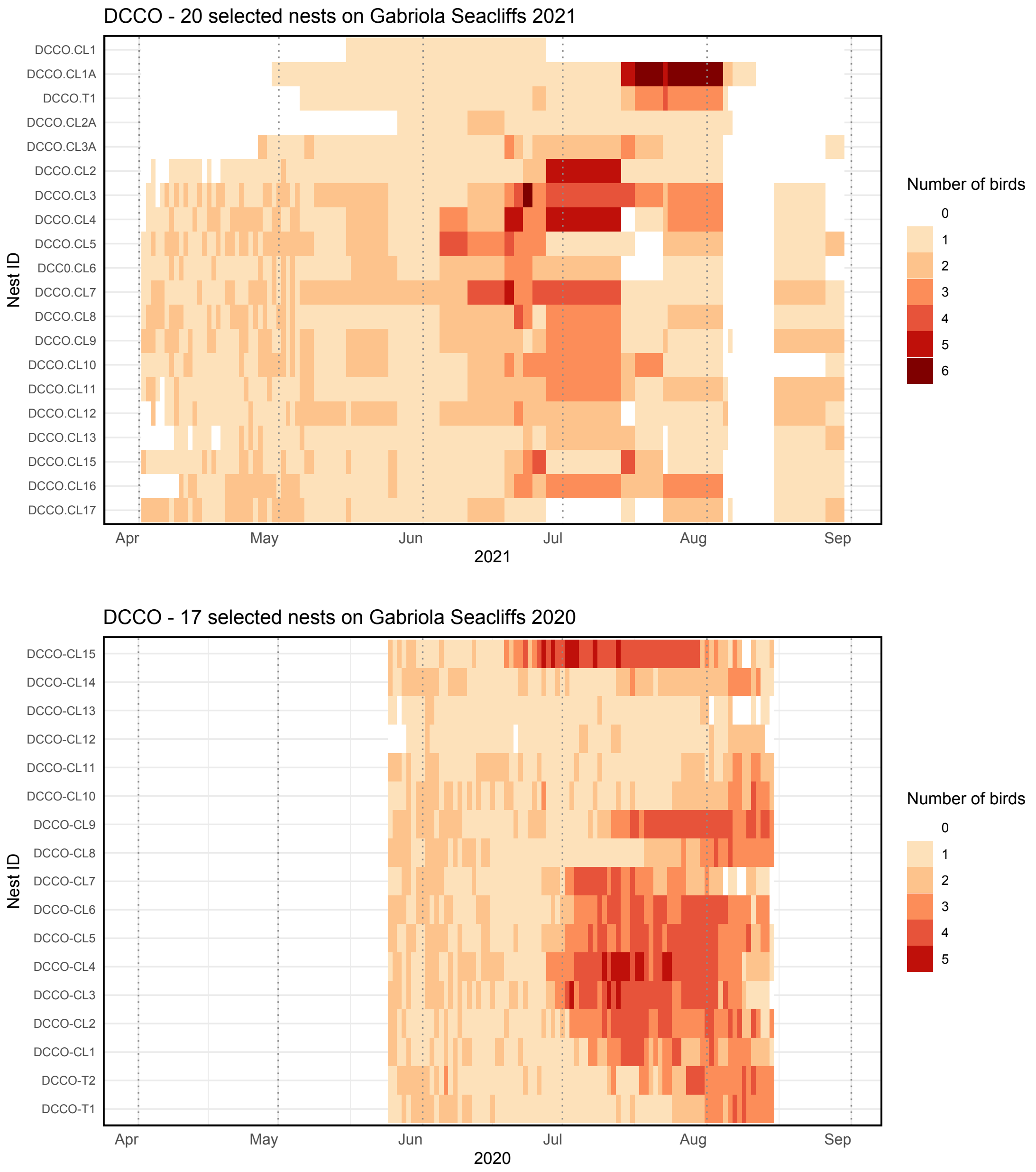

Figure 3-4: A heatmap showing the number of total birds present in each nest on the Gabriola Seacliffs throughout summer 2020 (top) and 2021 (bottom). Each row represents a time series of birds in a single nest.

The Gabriola Island seacliff is an example of a vertical natural seabird colony. There is evidence that it is a productive colony as fledged juveniles were present at the base of the cliffs during the June 30 kayak trip (Fig. 3-5). The GoPro camera set up saw multiple nests with juvenile cormorants in 2020 and 2021, which provided data on productivity. In 2020, the GoPro missed the start and end of the breeding season, while in 2021, the camera system malfunctioned. Monitoring methods should be further refined by ensuring the folder number (set by the image capture schedule) doesn't exceed 999, this would prevent the loss of data we experienced in this project.

Figure 3-5: A fledged juvenile DCCO that has left its nest is fed by a parent on a rock at the base of the cliff on June 30 (Wilkin, 2021).

3.3. Mitlenatch Island

When the camera was installed on April 26, 2021, nests had already been built, but none contained eggs. On August 14, there were no longer any birds present at the Mitlenatch Island colony. The last photo before August 14 was taken on August 3, and cormorants were still present. The GoPro camera captured the majority of nests at this colony, but at least five nests were outside its field of view.

In June 2021, the GoPro camera on Mitlenatch Island malfunctioned, with the same software issue as the Gabriola Island camera. It took photos normally from the evening of April 29 until early morning on June 4, and thereafter took only intermittent photos. The dates with useable photos after June 4 were June 8, 10, 12, 15, 16, and 27, July 1, 2, 13, and 18, August 3, 14, and 24, and September 11, 12, and 24. On days after and including August 14, there were no cormorants present in any photos. This is at least two weeks sooner than the Gabriola Island colony was also deserted.

The number of nests visible to the camera ranges from 14 to 22 over the course of the season as some nests were abandoned. The total number of sites in the camera's field of view that contained a nest at some point during the 2021 nesting season is 24.

No eggs, chicks, or juvenile cormorants are visible in any of the GoPro photos from Mitlenatch Island in 2021. Almost every day before the camera malfunction, there are photos of the colony apparently deserted, with no cormorants present (so the absence of eggs and chicks is certain). Of the 35 days where the camera was functioning correctly for the entire day, 34 of those days have at least one instance of the camera capturing this flushing of all cormorants from the colony. On 26 of those 35 days, one or more bald eagles are visible sitting amongst the empty nests (Fig. 3-6). Many photos of the colony while the cormorants were gone also include either Glaucous-winged Gulls or Northwestern Crows. After the camera malfunction, this flushing was also photographed on June 10.

When we went to collect the camera setup on November 23, 2021, I found several eggshells in the grass and bushes in the vicinity of the colony (other seabird colonies are on the other side of the island, so the shells were assumed to be cormorant eggshells).

Mitlenatch Island is an example of a horizontal natural seabird colony. I observed a Bald Eagle flying above Mitlenatch Island on the day of camera installation. Gulls were following the eagle and dive-bombing it.

Figure 3-6: Mid-breeding season image of Mitlenatch Island colony taken on June 2, 2021. A Bald Eagle, three gulls, and a crow are sitting amongst the empty cormorant nests.

3.4. Machine Learning

The final version of the IWMB model we named ‘version 3.1’. A version 4 was made, with more training, but its performance was poorer, so version 3.1 was used for analysis in the end. The learning rate for version 3.1 was 2.5 x 10^{-4}, which was the same as the warm-up learning rate. A model typically learns better if it is allowed to “warm up” with a slower learning rate. The default learning rate was 1 x 10^{-3}, but we found that decreasing it and forcing the model to learn slower had better results and stopped the model oscillating from overcorrecting. The maximum number of object detections per tile, including both nests and cormorants combined, was set to 70 (from the default of 100).

3.4.1. Post-processing and comparison with manual counts

Model counts were initially much higher than manual counts. Several post-processing steps were introduced to decrease the difference between model and manual counts. Manual post-processing was done on one panorama (Fig. 3-7) to determine what post-processing steps were needed and how to automate them.

Figure 3-7: A panorama that has been processed by the IWMB model. Yellow boxes denote nest detections, and red boxes denote cormorant detections.

Double counting can happen when a bird or nest is split in two by the tiling and counted in both tiles. This type of double counting is uncommon due to the distance between nests. In the panorama where post-processing was done manually, 43 out of

582 detections were duplicates, with 39 duplications of nests and 4 duplications of cormorants. Using pixel overlap in tiles can reduce duplication, but I chose not to use pixel overlap. The model detecting halves of birds has a benefit in that it can still detect birds and nests that are partly concealed by a beam of the bridge. De-duplication was automated for all panoramas. Automatic post-processing counted a nest annotation as a duplicate if two nest detections were within 20 pixels of each other (Fig. 3-8). This comparison is only done for tiles that share an edge. Because cormorant duplications were so rare, and cormorants in the same nest may have their detection boxes overlap, de-duplication was not done for cormorant annotations.

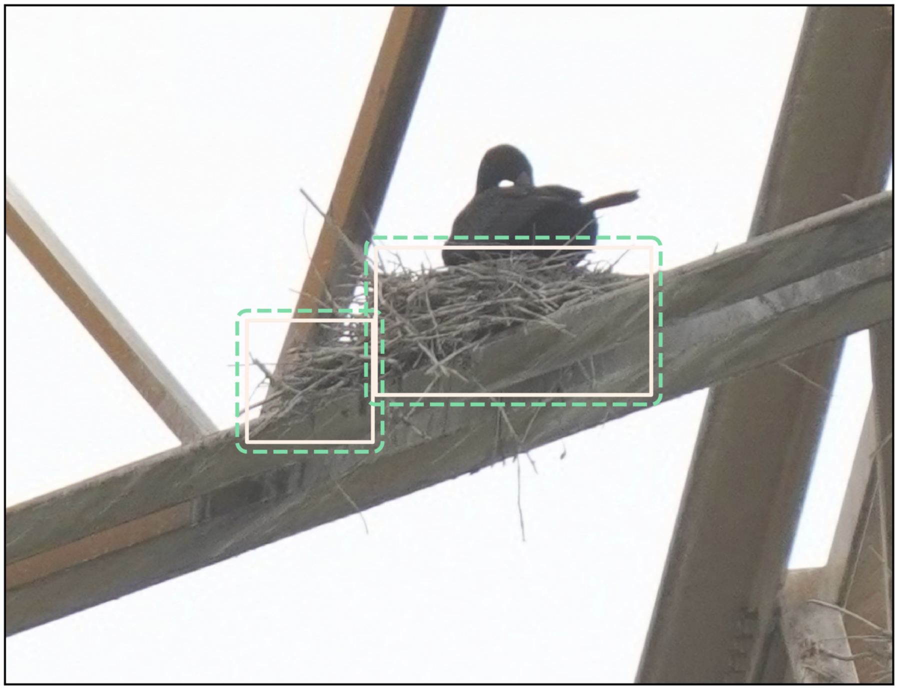

Figure 3-8: A duplicate nest count, in which two nest detections' 10 px buffer zones intersect.

Manual counters only counted cormorants that were at a nest, because the number of birds in each nest over the course of the season was a parameter of interest. To mimic this in automated post-processing, a 500 pixel radius "buffer" was placed around each nest. A buffer was also placed around each cormorant detection, the same height but twice the width of the cormorant detection box. If the two buffer zones intersected, the cormorant was counted (Fig. 3-9).

Figure 3-9: Green dashed lines indicate the buffer zone around each nest detection. The red box indicates a cormorant that was excluded from the final count as its buffer zone does not intersect a nest buffer zone.

Additionally, I noticed that many of the model's false positives were occurring in parts of the panorama that weren't on the bridge (e.g., boats in the water, people in New Brighton Park in the background), so we introduced a mask that would prevent the model from searching those areas of the panorama (Fig. 3-10).

Figure 3-10: The area of the panorama that the model searches is outlined in yellow. Red boxes are detections that were excluded by this step of post-processing, and green boxes are included detections.

Post-processing brought model counts much closer to manual counts (Fig. 3-11). Manual counts were taken from drone images of the same bridge region as the panorama as effort was prioritized for identifying when eggs hatched and fledglings appeared, GigaPan images were taken at the same time as the drone flew to capture the same nests from a different perspective, however due to this change in perspective, the 2021 manual counts are not expected to match the machine learning model count from the panorama as expected in the 2020 comparison.

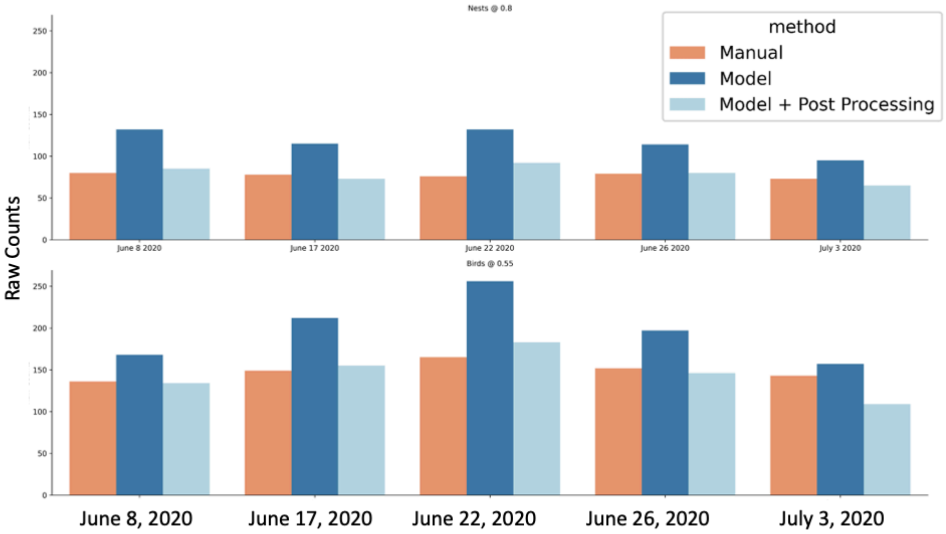

Figure 3-11: Comparison of the number of nests (top) and cormorants (bottom) found by manual counts of GigaPan images in 2020 (orange), the model count before post-processing (dark blue), and the model count after post-processing (light blue).

The machine learning algorithm will help overcome the image processing bottleneck of the number of panoramas taken of the bridge and enable a higher temporal resolution. The models have a much greater detection (processing) speed than manual counting, even considering the upfront time investment of training the models. It took two researchers an entire day to complete a manual count of a single panorama. The finished model can process a panorama in 30-45 minutes on a regular laptop computer (MacBook Pro).

3.4.2. Model performance

The precision of the model increased with the number of training steps, while validation loss decreased towards 0 with training steps (Fig. 3-12). We stopped the model at 100,000 steps. The final mAP was 69%.

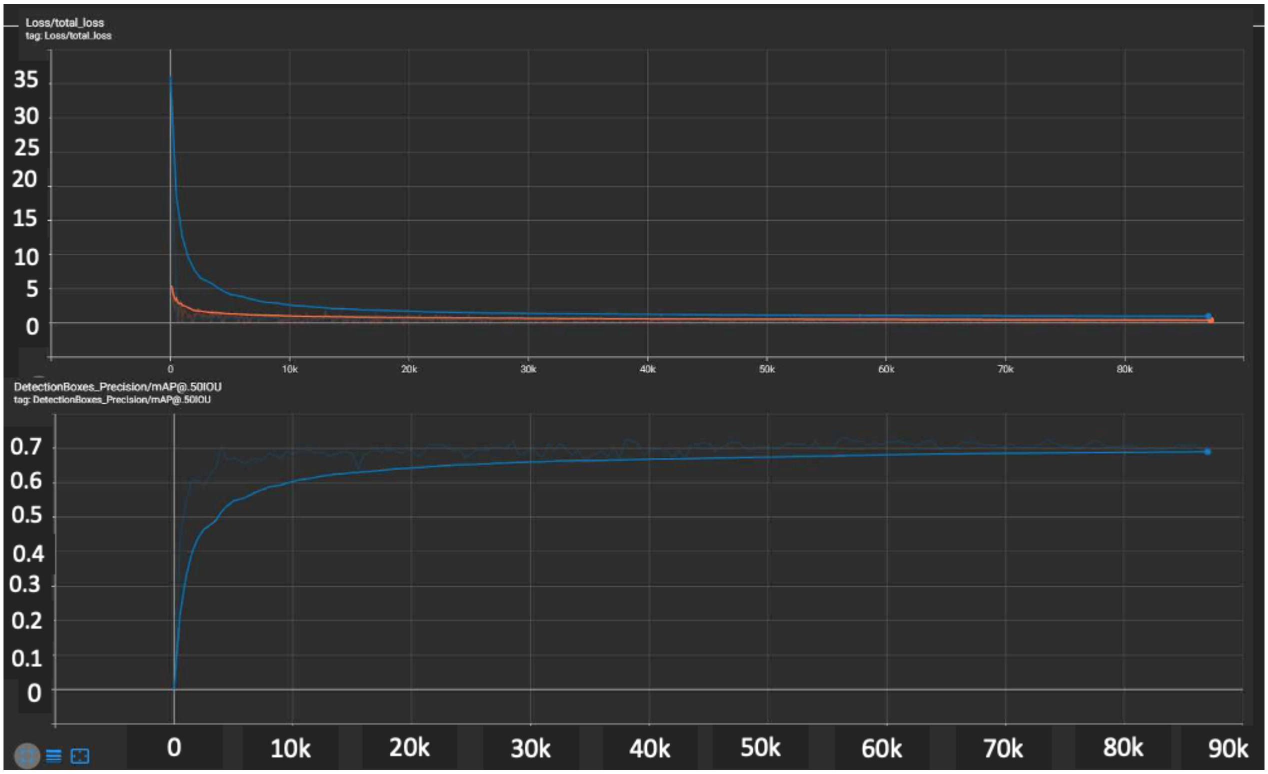

Figure 3-12: The IWMB counting model's loss (top) decreases with training steps, approaching zero. The model's mAP (bottom) increases with training steps, leveling off at around 0.7.

When a model detects an object, it assigns a confidence score between 0 and 1 for each detection. This represents how confident the model is that that annotation is correct. When a model is used to count objects, we set a confidence threshold. Any detections below that threshold are not counted. For the IWMB model, the confidence threshold for cormorant detections was 0.55, and the threshold for nests was 0.8. These values were chosen because they minimized the root mean square error (RMSE) of the model counts compared to manual counts of the same images (Fig. 3-13). Final model counts for 2021 are shown in Figure 3-14. The peak number of nests was 89 on June 16, and the peak number of cormorants was 208 on July 5 (Fig. 3-14).

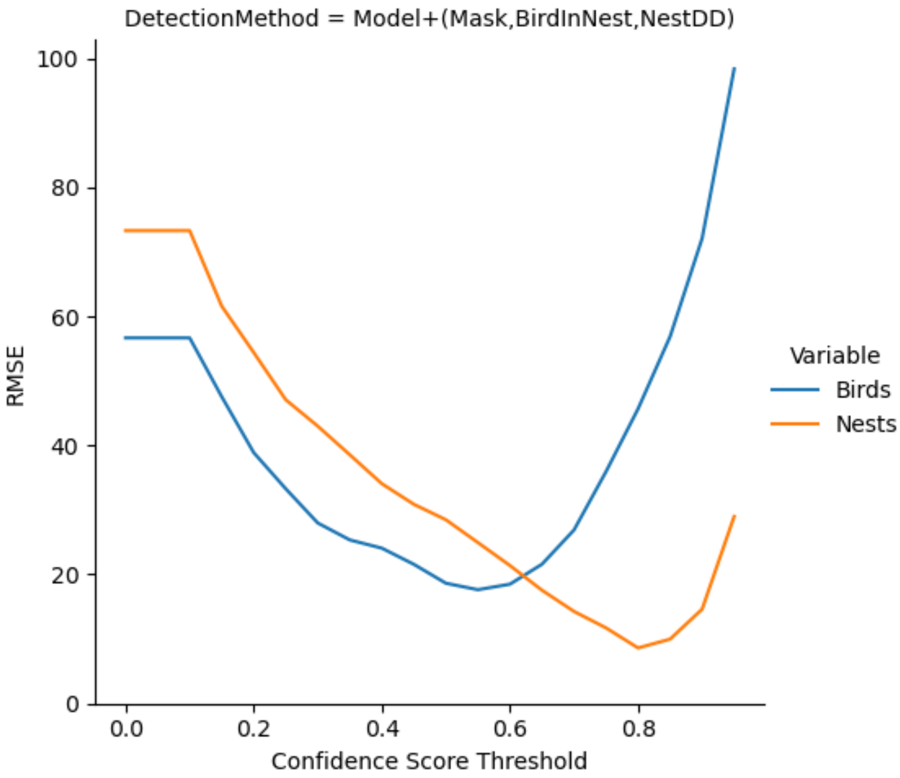

Figure 3-13: The root mean square error (RMSE) of the IWMB model with post-processing included at a range of confidence thresholds. We selected our confidence score threshold for detection-based object counting when the RMSE was minimized.

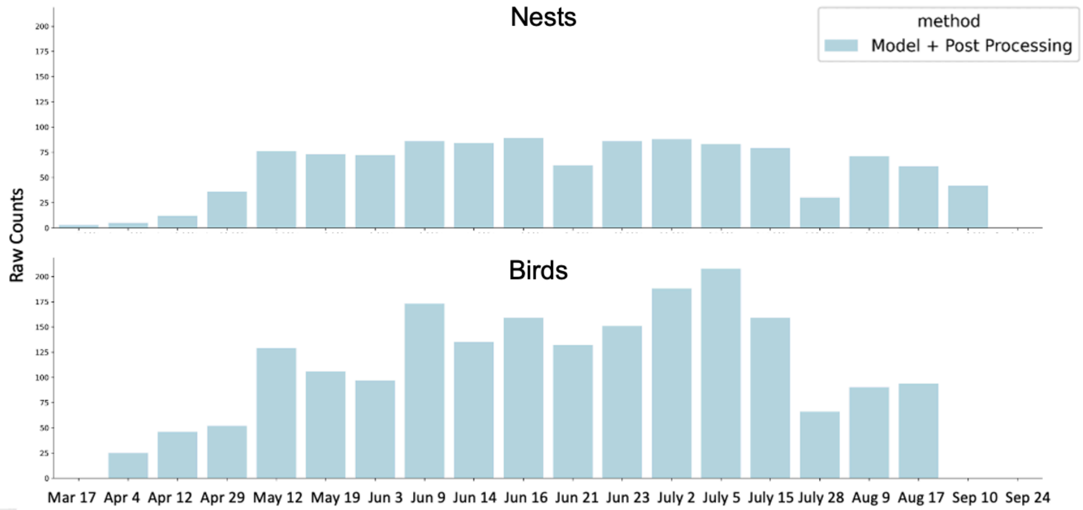

Figure 3-14: Machine learning model nest and cormorant counts using minimized confidence thresholds identified in Figure 3-13 for the IWMB Gigapan panoramas of the 2021 cormorant nesting season.

3.4.3. Common errors

Most final panoramas had dimensions of approximately 78,000 x 36,000 pixels and were between 2 and 2.3 GB in file size. However, several panoramas had smaller dimensions than most panoramas after being stitched. The abnormal panoramas ranged from 16,000 to 41,000 by 7,000 to 19,000 pixels and from 460 MB to 2.79 GB in size. When divided into tiles for training and testing, most panoramas produced between 2500 and 2900 tiles. The panoramas with abnormal dimensions produced 136 to 780 tiles. When the model ran these images, its counts for birds and nests were much lower than other panoramas, and post-processing dropped the counts below manual counts (at the same confidence threshold as the panoramas with typical dimensions). I assumed these images were compromised in some way and decided to exclude them from my analysis. There were also some panoramas that were unusually large, i.e., over 10 GB, and the model was not able to run with these file sizes. From the panoramas with small dimensions originally stitched with GigaPan Stitch, I selected two of these images to re-stitch in PTGui from the same photos. The re-stitched panoramas were over 10 GB. I stitched them each a third time with only the photos that contained parts of the bridge where birds were nesting, and the resulting panoramas were 4.08 and 6.43 GB. This time, they were divided into 2600-2800 tiles and the model was able to run them. There was not time to re-stitch, tile, and process all the panoramas with unusual dimensions and file sizes, but the two dates selected (June 3 and July 28) ensured even coverage across the season. With these two dates included, I avoided there being long periods (over three weeks) with no useable panoramas. The longest gap of time covering the main breeding season of May to July was 15 days.

Other common errors included background objects being detected as cormorants (false positives), which was addressed by masking out non-relevant (non-bridge) parts of the Gigapan panoramas. False negatives were much less common, with there being only eight in the manually post-processed panorama (compared to 98 false positives).

Chapter 4. Discussion

Each of the three cormorant colonies monitored in 2021 had distinct attributes and access challenges, meaning different photogrammetry methods were needed to answer questions about phenology and nest success. Mitlenatch Island is a remote site only accessible by small watercraft, which is impractical (and not permitted) for multiple visits. Additionally, it is not feasible to take long distance panoramas of the colony as there is restricted access to the island through provincial permit only. With less than 30 nests, the colony is easily monitored through a single GoPro camera field of view. Gabriola Island is a sheer cliff face overlooking Northumberland Channel (and Duke Point ferry terminal), also requiring access to private property to install a GoPro which could only capture 20 of the 305 nests. Panoramas can be taken of the cliffs, but from no closer than 1.7 km away, just north of the ferry terminal at Jack Point. The kayak trip enabled me to create a continuous spatial image that could be pieced together of all the cormorant nests from 100 m distance. This was extremely beneficial for counting the Gabriola Island colony. However, such a trip would not be possible to do frequently, and is therefore not a viable method for assessing colony success. Machine learning models of the Gigapan panorama could be built to automate the counts, and I have started to build these. The IWMB can be photographed with much greater frequency from a much closer distance (less than 200m) but getting a vantage point above the nests requires either an expensive drone, or authorization from MOTI to install a GoPro (which we were unable to obtain). Some nests are obscured from the vantage point where the panoramas are taken below the bridge at the Seymour River estuary. This population is so large that counting individuals and nests is a great time investment if done manually. Together these sites represent the full suite of logistical challenges of colony monitoring, and I've demonstrated that a variety of methods (and no single method) is required to monitor this metapopulation.

Each site also presents unique challenges for the cormorants that live there. Mitlenatch Island is a flat-topped cliff where DCCO experience severe predation pressure. I documented Bald Eagles, Glaucous-winged Gulls, and Northwestern Crows in the colony, and a Mitlenatch Island Stewardship Team (MIST) volunteer reported that the clifftop is also accessible to river otters and mink. Disturbance by Bald Eagles is one of the two main limiting factors on the growth of the western population (Adkins et al.

2014), the second factor being human disturbance. The IWMB did not appear to suffer from Bald Eagle or gull predation pressure (no predation nor flushing events were observed), and the steel structure is not accessible to climbing mammals. This and other man-made structures may make breeding cormorants immune from areal and terrestrial predators and therefore less prone to nest abandonment (Hipfner et al. 2012). However, DCCO are considered undesirable on this bridge by MOTI (Hemmera 2018a, 2018b, 2019, 2020), and on the Granville and Burrard bridges by the City of Vancouver (Engineering Services Department, City of Vancouver, personal communication), and therefore vulnerable to human management decisions.

The largest breeding colony of DCCO are at risk of being displaced if the province decides to exclude them from their breeding platforms on the IWMB, and of being scared away by construction and maintenance being carried out on the bridge planned for 2022. Consideration of the breeding biology of this vulnerable species needs to be incorporated into bridge management if this species is to locally recover from past population declines in the Georgia Strait (Machmer 2008, Adkins et al. 2014; Chastant et al. 2014).

Double-crested cormorants feed on a variety of benthic and mid-water schooling fish (Miller at al 2015) with sexual intraspecific segregation in foraging (Anderson et al. 2004). Based on diet differences and central place foraging theory (Mauer 1996), DCCO are likely maximizing their foraging efficiency by feeding in proximity to their nesting colonies. However, nothing is known about food sources for the IWMB cormorant colony, nor of those of DCCO from the Gabriola and Mitlenatch Island colonies. Future research is planned in 2022 to track cormorants to their feeding grounds.

Both the island colonies are south-facing and have either little (Gabriola Island) or no (Mitlenatch Island) shade. The record-breaking heat wave during the last week of June 2021 coincided with the failure of nest DCCO-CL1 on Gabriola Island. It is possible the heat contributed to the nest failure. Although it is common for DCCO to be exposed to direct sun, and adults are known to shade their chicks and bring them water in their beaks (Kuiken 2001), Bank Cormorants in southern Africa had limited nesting success under heat waves (Sherley et al. 2012). The resilience of coastal cormorants may be tested in the face of climate change if there are similar or more severe heat waves than the one seen in 2021. Climate change and associated thermal stress could restrict the recovery of DCCO in the Strait of Georgia, particularly for juveniles in colonies with little to no protection from direct sun.

The Mitlenatch Island colony failed to produce any offspring in 2021. The images showed repeated flushing of all the cormorants from their nests, likely a result of Bald Eagles or gull harassment. This would have allowed any eggs or chicks to be predated upon by the eagles themselves, or by opportunistic gulls or crows who can't flush the cormorants themselves. As of June 10, the last day that flushing was photographed, there were no cormorant eggs or chicks alive. This flushing and predation presumably continued for the rest of the season, as no juvenile cormorants can be seen in any photos later in the season. Eggs or chicks may have been hidden from view by parents incubating, but towards the end of the season they would have been visible if they were there, and the camera was close enough to identify birds as adult or juvenile with certainty.

The failure of the Mitlenatch Island colony underscores the importance of the IWMB colony to the DCCO metapopulation in BC. Colonies of breeding birds that form aggregations of individuals are likely driven by individuals seeking to minimize their exposure to danger by surrounding themselves with conspecifics (Emlen 1952, McDowall and Lynch 2019), and 95% of seabirds exhibit breeding coloniality (Wittenberger and Hunt 1985, Rolland et al. 1998). Many hypotheses have been proposed to explain why this strategy is so universally observed in seabirds despite the density-related costs to fitness through various mechanisms such as higher competition for prey, nest sites, and nest materials (Carascal et al. 1995, Hunter and Davis 1998), increased chances of disease (Rifkin et al. 2012) and likely at play at Mitlenatch, increased predation. The clifftop at Mitlenatch Island does not provide protection from avian predators and as shown by the number of GoPro images with avian predators, the breeding colony suffers from severe top-down pressure. Other reasons for the 2021 colony collapse cannot be ruled out, and monitoring in 2022 will provide more insights into whether 2021 was an anomaly, or if this colony serves as a sink to the metapopulation of cormorants in Georgia Strait.

The nests on Gabriola Island and the IWMB are much more difficult to access for predators as landing requires precision stalling to dead-point small ledges, something cormorants are adept at (I have observed cormorants having to circle around more than once to land on the beams, and to land on cliffside nests but never miss once committed to the landing). Glaucous-winged gulls are less successful at predating on seabird nests on steep cliffs than on nests in flat areas (Gilchrist et al. 1998), and the same may be true for other predatory birds. Unlike Mitlenatch Island, the IWMB is also inaccessible to otters and mink. In both the 2020 and 2021 seasons, no predation was observed at the IWMB colony, nor on the GoPro images from the Gabriola seacliffs. These vertically-oriented colonies are fledging new DCCO into the metapopulation of DCCO in the region. The proximity of this and other Vancouver bridges used by Pelagic Cormorants may expose cormorants to anthropogenic stresses unique to urban living. For example, physical (proximity) disturbance from commercial vessels and small recreational boats (Chatwin et al. 2001) and the associated additions to ambient noise levels in a highly industrial Port setting. Despite these challenges to urban living (nesting), the IWMB is a source of positive recruitment to the Strait of Georgia population, and to the marine food web of an urban ecosystem.

DCCO remain a blue-listed species in British Columbia. They have not recovered here the way they did elsewhere in North America or south of Washington after the banning of DDT. To monitor restoration efforts in this provincial population, new and better monitoring methods will be necessary. We built the machine learning models as one tool to address my objectives to monitor colonies throughout the breeding season. A standard boat drive-by survey of the Mitlenatch Island colony, for example, would not have detected the colony's failure (Mitlenatch Island Stewardship Team Workshop, personal communication, March 2022). This is evidence that monitoring colonies at multiple time points is necessary for assessing colony success, and the standard single-visit approach used for colonies in the Strait of Georgia is an error-prone and biased measure. Or worse, the single visit approach may fail to detect complete colony failure like at Mitlenatch Island in 2021 since birds are present at empty nests throughout the breeding season. Therefore, the robustness of site-specific population estimates depends on the extent of spatial and temporal coverage (Kemper et al. 2016), and the accuracy of the applied census technique.

4.1. Machine learning

I have worked to develop a new method that will contribute to this greater effort to understand the DCCO metapopulation in BC. The use of machine learning for monitoring seabird colonies in general is just beginning (Hayes et al. 2021), and I believe it has great potential. Seabird colonies can have millions of birds, and colony population sizes are estimated based on proxies such as burrow density or vocal activity (Reyes-Arriagada et al. 2006, Borker et al. 2014) if they are too large to be counted manually. But even colonies that are small “enough” to count manually have a high labour and time cost for doing so (Oro and Ruxton, 2001). If photography is possible at these colonies, machine learning could be a suitable method to make population and nest counts more accurate and less labour intensive. The upfront time investment of developing a model (in the case of this study, six months) must be considered in this. However, it is not atypical for developers of machine learning models to use a pre-trained model as a starting point as we did, and open source model training datasets are available (Lin et al. 2014). It is possible that a seabird colony training set could eventually be created, lowering the barrier for beginning the development process.

More work is necessary to fine-tune the machine learning model for the IWMB, and more training data is needed for the Gabriola Island model. However, the IWMB model has already been useful in enabling processing most of the 2021 panoramas in a fraction of the time it would have taken to count them manually. Due to time and labor constraints, manual counts were only done for days when there was a drone flight. Even with the dates that were excluded due to issues with image resolution and file size, the temporal resolution for the 2021 data is higher than it was when manual counting was the only option. The model was also applied to panoramas taken in 2020 and can in the future be applied to the Span 1 panoramas I took in 2021. A precaution I took when taking panoramas at Gabriola Island was to run the GigaPan 2 or 3 times, in case stitching later failed. Taking this precaution at the IWMB could help prevent the image file issues. As this project moves forward and our methods improve, the dataset will grow more consistent. Consistency and time series are key so that comparisons can be made year to year.

Given the importance of the IWMB as a nesting site for the metapopulation of DCCO in BC, accurate monitoring of its community is essential. Whereas in 2020 and

2021 counts were taken of only the cormorants and nests on Span 2, with the amount of time saved by the model the entire colony could be counted, enabling a proper census and a better understanding of the whole community. In the face of climate change and heat domes like the ones seen in 2021, the recovery of DCCO here is not guaranteed despite their recovery elsewhere. The increased accuracy and extent of monitoring enabled by machine learning will help detect changes in population size and the timing of nesting milestones as the environment continues to change.

Machine learning also has the potential for wider application to seabird colony monitoring. The panoramic images taken from beside the bridge, or across the Northumberland Channel from Gabriola Island, are easier, less expensive, and less invasive to perform than drone surveys. If our models can be used to reliably count cormorants from panoramas, then population data can be collected with high temporal resolution but a low labor cost. This is true for other colonies, other species, in other parts of the world as well. Some studies have already used machine learning to count seabirds (Hayes et al. 2021) but used drone images rather than long-distance panoramas for their analysis. This is useful for a colony with no suitable vantage point to take panoramas from. But for the IWMB, it would have been unsafe for the drone to fly directly under the bridge. If I had attempted to make a panorama from the drone images, some of the beams with nests would have been obscured by the outermost beams. There are some possibilities to get around this problem with tile overlap, but this has not yet been explored.

4.2. Further work

Monitoring is an essential part of Ecological Restoration. To restore the population of a blue listed species such as DCCO, it is necessary to have monitoring methods that provide time series. Without the time series from the Mitlenatch Island GoPro, the failure of the DCCO colony there would have remained undiscovered. MIST surveys of the colony include a nest count only, and as they are conducted from a boat at the base of the cliff, could not possibly detect the lack of eggs and chicks.

More work is needed on this project to advance our techniques and our understanding of BC’s DCCO metapopulation. The creation of the two machine learning models is a big step, but they could both benefit from further fine-tuning, and still leave the question of nest success. With the malfunction of the island GoPro cameras in 2021, we only know that the Mitlenatch Island colony's nest success was zero, and that the other two sites' nest success was nonzero. This is ecologically significant, but more precision is needed for a long-term monitoring project.

More work is needed to make the GoPro monitoring more consistent. For the upcoming 2022 season, I programmed the camera setup to take photos less frequently (every 3.5 hours rather than every half hour) so that if the same software malfunction occurs, the season will be over before the camera reaches 999 folders. Eventually a fixed version of the software may be available and this will not be necessary, although it is unclear whether the issue is caused by the GoPro camera firmware or the CamDo BlinkX firmware.

Another future possibility for the IWMB model to analyze images even with reduced dimensions could be to explore tweaking the tiling process. In the IWMB model, the panoramas are divided into 1000x1000 pixel tiles, then the resolution is changed to 500x500 before the model searches them. It might be possible to improve the counts if this compression is not done, and the smaller dimension panoramas are divided into 500x500 tiles right off the bat.

There are many ways to improve this novel method, and many directions for this project to move forward. Live capture and tagging of DCCO is being planned for the 2022 season, and we may soon have information on the location of DCCO feeding grounds, which can be tracked in real-time. Understanding the needs of this population may help the City of Vancouver and MOTI manage the bridge nesting site to ensure human safety without severely disrupting the largest DCCO nesting colony in BC, a site potentially vital for the BC metapopulation's survival.

4.3. Recommendations

This work highlights the importance of the IWMB not only to Vancouver's local population of cormorants, but to the whole metapopulation of DCCO in BC. It underscores the necessity of providing alternative nest sites if MOTI and the City of Vancouver decide to exclude cormorants from nesting on the IWMB as well as other bridges in Vancouver, including the Granville and Burrard Street bridges.

The City of Vancouver has the beginnings of a plan for alternative nest sites, but it is early in development. I would recommend, for these “cormorant condos,” that protection from predators should be a major element of the structural design, because top-down pressure can clearly be a severe restriction on breeding success. Shade may also be important, and I would recommend that as well.

Hopefully my work, as well as the continuation of this project in 2022 and into the future, can guide management solutions for this vulnerable population. My objective to develop and improve DCCO monitoring methods is one step towards this goal.

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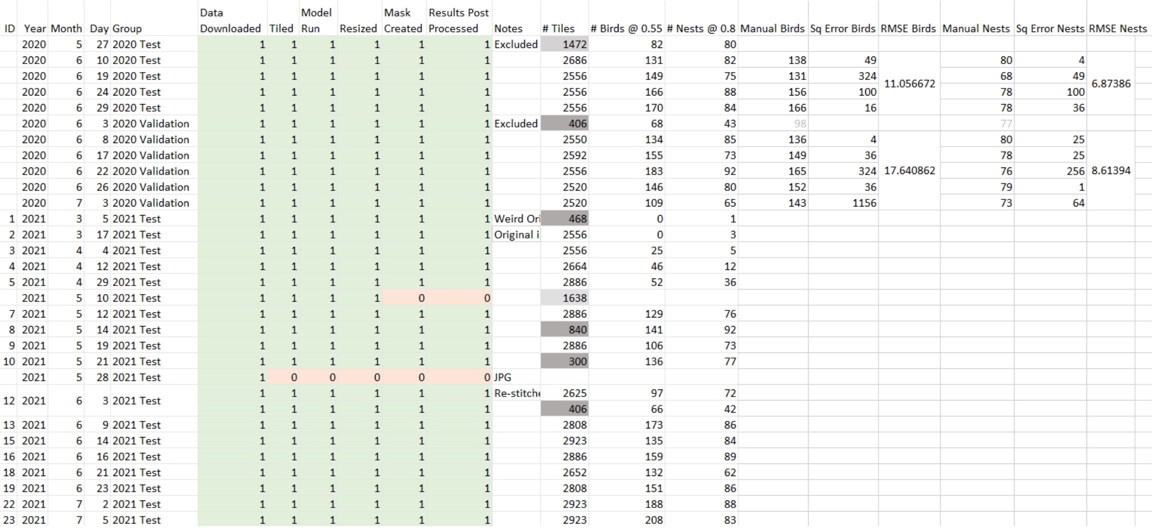
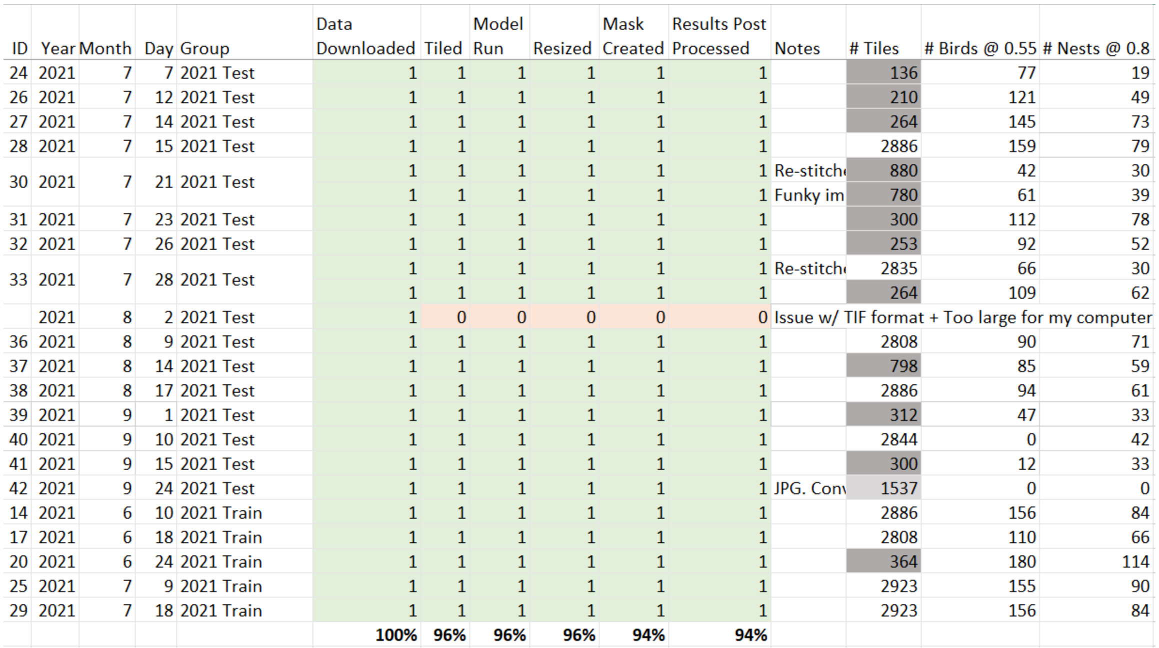
Appendix A.

Ironworkers Memorial Bridge Machine Learning Model Progress (training, validation, and testing)



ID	Year	Month	Day	Group	Data Downloaded	Tiled	Model Run	Resized	Mask Created	Results Post Processed	Notes	# Tiles	# Birds @ 0.55	# Nests @ 0.8	Manual Birds	Sq Error Birds	RMSE Birds	Manual Nests	Sq Error Nests	RMSE Nests
	2020	5	27	2020 Test	1	1	1	1	1	1	Excluded	1472	82	80						
	2020	6	10	2020 Test	1	1	1	1	1	1		2686	131	82	138	49	11.056672	80	4	6.87386
	2020	6	19	2020 Test	1	1	1	1	1	1		2556	149	75	131	324		68	49	
	2020	6	24	2020 Test	1	1	1	1	1	1		2556	166	88	156	100		78	100	
	2020	6	29	2020 Test	1	1	1	1	1	1		2556	170	84	166	16		78	36	
	2020	6	3	2020 Validation	1	1	1	1	1	1	Excluded	406	68	43	98			77		
	2020	6	8	2020 Validation	1	1	1	1	1	1		2550	134	85	136	4	17.640862	80	25	8.61394
	2020	6	17	2020 Validation	1	1	1	1	1	1		2592	155	73	149	36		78	25	
	2020	6	22	2020 Validation	1	1	1	1	1	1		2556	183	92	165	324		76	256	
	2020	6	26	2020 Validation	1	1	1	1	1	1		2520	146	80	152	36		79	1	
	2020	7	3	2020 Validation	1	1	1	1	1	1		2520	109	65	143	1156		73	64	
1	2021	3	5	2021 Test	1	1	1	1	1	1	Weird Ori	468	0	1						
2	2021	3	17	2021 Test	1	1	1	1	1	1	Original i	2556	0	3						
3	2021	4	4	2021 Test	1	1	1	1	1	1		2556	25	5						
4	2021	4	12	2021 Test	1	1	1	1	1	1		2664	46	12						
5	2021	4	29	2021 Test	1	1	1	1	1	1		2886	52	36						
	2021	5	10	2021 Test	1	1	1	1	0	0		1638								
7	2021	5	12	2021 Test	1	1	1	1	1	1		2886	129	76						
8	2021	5	14	2021 Test	1	1	1	1	1	1		840	141	92						
9	2021	5	19	2021 Test	1	1	1	1	1	1		2886	106	73						
10	2021	5	21	2021 Test	1	1	1	1	1	1		300	136	77						
	2021	5	28	2021 Test	1	0	0	0	0	0	JPG									
12	2021	6	3	2021 Test	1	1	1	1	1	1	Re-stitch	2625	97	72						
					1	1	1	1	1	1		406	66	42						
13	2021	6	9	2021 Test	1	1	1	1	1	1		2808	173	86						
15	2021	6	14	2021 Test	1	1	1	1	1	1		2923	135	84						
16	2021	6	16	2021 Test	1	1	1	1	1	1		2886	159	89						
18	2021	6	21	2021 Test	1	1	1	1	1	1		2652	132	62						
19	2021	6	23	2021 Test	1	1	1	1	1	1		2808	151	86						
22	2021	7	2	2021 Test	1	1	1	1	1	1		2923	188	88						
23	2021	7	5	2021 Test	1	1	1	1	1	1		2923	208	83						



ID	Year	Month	Day	Group	Data Downloaded	Tiled	Model Run	Resized	Mask Created	Results Post Processed	Notes	# Tiles	# Birds @ 0.55	# Nests @ 0.8
24	2021	7	7	2021 Test	1	1	1	1	1	1		136	77	19
26	2021	7	12	2021 Test	1	1	1	1	1	1		210	121	49
27	2021	7	14	2021 Test	1	1	1	1	1	1		264	145	73
28	2021	7	15	2021 Test	1	1	1	1	1	1		2886	159	79
30	2021	7	21	2021 Test	1	1	1	1	1	1	Re-stitch	880	42	30
					1	1	1	1	1	1	Funky im	780	61	39
31	2021	7	23	2021 Test	1	1	1	1	1	1		300	112	78
32	2021	7	26	2021 Test	1	1	1	1	1	1		253	92	52
33	2021	7	28	2021 Test	1	1	1	1	1	1	Re-stitch	2835	66	30
					1	1	1	1	1	1		264	109	62
	2021	8	2	2021 Test	1	0	0	0	0	0	Issue w/ TIF format + Too large for my computer			
36	2021	8	9	2021 Test	1	1	1	1	1	1		2808	90	71
37	2021	8	14	2021 Test	1	1	1	1	1	1		798	85	59
38	2021	8	17	2021 Test	1	1	1	1	1	1		2886	94	61
39	2021	9	1	2021 Test	1	1	1	1	1	1		312	47	33
40	2021	9	10	2021 Test	1	1	1	1	1	1		2844	0	42
41	2021	9	15	2021 Test	1	1	1	1	1	1		300	12	33
42	2021	9	24	2021 Test	1	1	1	1	1	1	JPG. Conv	1537	0	0
14	2021	6	10	2021 Train	1	1	1	1	1	1		2886	156	84
17	2021	6	18	2021 Train	1	1	1	1	1	1		2808	110	66
20	2021	6	24	2021 Train	1	1	1	1	1	1		364	180	114
25	2021	7	9	2021 Train	1	1	1	1	1	1		2923	155	90
29	2021	7	18	2021 Train	1	1	1	1	1	1		2923	156	84
					100%	**96%**	**96%**	**96%**	**94%**	**94%**				

Appendix B.

Gabriola Island 2020 nest diagram