Multi-event modelling shows variable breeding success for the at-risk Double-crested Cormorant population within the Strait of Georgia

by

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Abstract

During the last two decades, the Double-crested Cormorant (*Phalacrocorax auratus*; DCCO) experienced a significant loss of its population within the Strait of Georgia and is a listed species of 'special concern' within British Columbia. To study the DCCO, remote, time-lapse photography captured nesting seasons at three locations within the Strait of Georgia from 2020 to 2022. With the image data, a multi-event model was created to estimate probabilities of chick detection and survival. From these, overall nest success was estimated, an important indicator of colony health. Results showed that natural nesting locations produced variable breeding success while a colony located on an urban bridge, and the largest DCCO nesting colony in the province, experienced the highest productivity. The provincial government is currently discussing excluding the DCCO from the bridge, however, low to variable nest success at natural nesting sites show that the overall DCCO population will likely experience populations declines as a result of this management action.

Keywords: Double-crested Cormorant, multi-event model, hidden Markov model, breeding, nest success, mark-recapture

Dedication

This work is dedicated to my parents, Anne and David. Thank you for your unwavering support. Because of you, I know no limits.

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I would like to acknowledge that this research was conducted upon the unceded traditional territories of the Coast Salish peoples, including the səl̓ilw̓ətaʔɬ (Tsleil-Waututh), kʷikʷəƛ̓əm (Kwikwetlem), Sḵwx̱wú7mesh Úxwumixw (Squamish) and xʷməθkʷəy̓əm (Musqueam) Nations.

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Throughout this project, I was grateful to share the ups and downs with my classmate and roommate, Jen Rogers. Jen’s infectious optimism and can-do attitude inspired me to achieve my goals. And finally, I would like to thank my supervisor, Ruth Joy. Ruth allowed me to experience countless opportunities throughout my master’s degree from presentations to nominations and unforgettable field work. Thanks to Ruth’s endless support, I feel confident and prepared to continue my career in environmental science. Words cannot describe how immensely grateful I am to have had Ruth as a supervisor.

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List of Acronyms

DCCO	Double-crested Cormorant
PECO	Pelagic Cormorant
IWMB	Ironworker Memorial Bridge

Chapter 1.

Introduction

Methods in monitoring nesting sea birds have greatly improved over the last decade. With advances in technology, monitoring has become less invasive and more robust through the use of remote photography. In this study, applications of remote photography are taken further by applying a multi-event model to photographic data sets to determine nest success and breeding parameters of the Double-crested Cormorant (*Phalacrocorax auritus*) (DCCO) at multiple locations within the Strait of Georgia, British Columbia.

The DCCO, sub-species *P. a. albociliatus*, can be found along the coastlines of the Pacific Ocean in North America, with the northern boundary located in the Strait of Georgia, British Columbia (Carter et al. 1995). Although DCCO inhabits many regions, its populations are variable across each, with Oregon and Washington state containing the majority of nesting pairs at 20,000 in 2009 (Wires & Cuthbert 2006; Adkins et al. 2014). In 1987, the Strait of Georgia contained almost 2,000 breeding pairs, however, the population experienced intense declines over the next 20 years, resulting in 600 pairs remaining in the province in 2014 (Carter et al. 2018). The DCCO is currently blue listed under British Columbia's ranking system, meaning it is a species of special concern (Cannings 1994; Moul & Gebauer 2002). It is unknown what led to the decrease in population and subsequent suppression within the Strait of Georgia, however, species of special concern are known to be particularly sensitive to anthropogenic activities and changes to their environment (B.C. Conservation Data Centre 2022).

DCCO in British Columbia are year-round residents of the Strait of Georgia and Juan de Fuca Strait (Moul & Gebauer 2002). Within the Strait of Georgia, DCCO have historically nested on seacliffs and islets between their breeding months of April and September (Chatwin et al. 2002). In 2014, Carter et al. (2018) documented that DCCO nested on a total of five cliff sites within the Strait of Georgia.

Since 1983, Pelagic Cormorants (*Phalacrocorax pelagicus*; PECO) have been nesting at the Ironworkers Memorial Bridge (IWMB), followed by DCCO in 2009 (Carter et al. 2018). The IWMB is currently the largest nesting ground of the DCCO in British Columbia with 296 nests documented in 2020 (Ong 2021). These bridge nesting cormorants have raised the concern of the Ministry of Transportation and Infrastructure due to concern that their guano could potentially impact the structural integrity of the bridge (Hemmera 2018). This has led to discussions around excluding the cormorants from the bridge (Hemmera 2018). The IWMB is likely the most important nesting ground for this sensitive species in the province, therefore, inhibiting access of the cormorants to this breeding ground could lead to population-level impacts.

This study is built upon prior Strait of Georgia cormorant research by Ong (2021) and Wilkin (2022) whose results show that nest success within the DCCO's natural cliff environment may be poor, while the IWMB could produce the highest number of offspring. In order to examine this hypothesis, parameters of nest success through the progression of breeding season will be determined for Gabriola Island, Mitlenatch Island, and the IWMB for the years 2020, 2021, and 2022 through the creation of a multi-event model (Pradel 2005). Results from this study will also guide restoration suggestions for the DCCO who is currently experiencing threats to their largest and potentially most successful breeding ground, and possible low nest success at their natural nesting sites.

1.1. The decline of the Double-crested Cormorant within the Strait of Georgia

The DCCO within British Columbia experienced a 68% decline in the number of nests present, falling from 1,900 to 600 nests between the years of 1987 and 2009 (Carter et al. 2018). Since then, DCCO have failed to recover to their original extent prior to 1987 (Carter et al. 2018). PECO, a species of cormorant that often nests within the same colony as DCCO, also experienced a decline in the same time period falling from approximately 2,300 pairs to 1,100 before the population recovered back to 1,400 pairs (Carter et al. 2018). The cause of this decline is currently unknown, although, it is hypothesized to be related to increases in urban expansion along the coastlines, fluctuations in prey availability, and/or an increasing pressure from Bald Eagle (*Haliaeetus leucocephalus*) predation (Harris et al. 1994; Adkins et al. 2014; Carter et al. 2018; Goulet et al. 2021).

1.1.1. Urban expansion

Although the Coast Salish Peoples have resided in the region of the Strait of Georgia since time immemorial, recent dramatic increases in human population and the resulting urbanization have altered local coastlines (Sobocinski 2021). With an increase of 1 million people in the last 20 years, the southern coastal population of British Columbia is now at 3.8 million and is projected to reach 4.6 million by 2030 (Sobocinski 2021). This quickly expanding urbanised area has led to losses in cliff-nesting habitat for cormorants in the form of industrialized transformation of coastlines for commercial and marine vessel use, loss of native habitat after the construction of residential sites, and the overall loss of undisturbed nesting locations. For example, a breeding colony of PECO abandoned their nesting site at the Siwash and Prospect cliffs in Stanley Park while construction for a bicycle lane occurred, dropping from 93 nesting pairs to 12 in the year 2000, followed by complete nest abandonment by 2014 (Carter 2014). In the year 2000, PECO were also formally detected for the first time nesting at the Burrard and Granville Bridges, and the Second Narrows Bridge and Power Tower, followed by DCCO in 2009 (Carter et al. 2018). This may show a movement of cormorants nesting in their natural habitat to man-made sites after being displaced by anthropogenic activity at Stanley Park. Other instances of nest abandonment include colonies at Passage Island and Gordon Island, which no longer held PCCO after the year 2000 when houses were built above their nesting grounds (Carter et al. 2018). The Bare Point colony also became abandoned after log booming activity began, leading the colony to decline from 373 PCCO breeding pairs in 1982, to complete colony abandonment in 2000 (Carter et al. 2018).

Other instances of disturbance include commercial and tourism vessels travelling in proximity to nesting colonies, direct human presence near nesting grounds, and increases in noise pollution. Cormorants are most sensitive to human disturbance during their nesting season while eggs and nestlings are present as human-caused flushing can facilitate predation (Ellison & Cleary 1978). As well, flushing events can expose chicks to the elements, for example, if newborn nestlings are left for more than 11 minutes, they may desiccate due to over-exposure from the sun (Moul & Gebauer 2002).

1.1.2. Increase in predator pressure

The most problematic predator on cormorants within the Strait of Georgia is the Bald Eagle. Bald Eagle populations have been increasing within the province of British Columbia, even surpassing historical populations in some areas, and are likely the main cause of disturbance to nesting cormorants (Chatwin et al. 2002; Goulet et al. 2021). Bald Eagles predate on each life stage of cormorants from egg to adult, and facilitate predation by crows (*Corvus caurinus*) and gulls (*Larus sp.*) (Therriault et al. 2009). Repeated flushing events caused by Bald Eagles can contribute to full colony failure as seen on Protection and Smith Islands in the state of Washington between 1990 and 1992 (Moul & Gebauer 2002). Additionally, high levels of nest failure occurred in 1994 at Mandarte Island within the Strait of Georgia, when flushing caused by Bald Eagles and humans led to further predation by crows and gulls (Sullivan 1998). One predation event in Manitoba documented by Hunt et al. (1992) describes a Bald Eagle facilitated flushing event on nesting DCCO that resulted in over 200 nests exposed to heavy gull predation, reducing the colony to two remaining nests with eggs (Hunt et al.1992).

1.2. Double-crested Cormorant ecology

1.2.1. Nesting habitat

The natural nesting habitat of cormorants within the Strait of Georgia is among rocky cliffs adjacent to water and islets (Léger & McNeil 1985). However, in 2009, DCCO began to nest upon the beams of the IWMB in Vancouver (Carter et al. 2018). In 2014, it was determined that DCCO are currently nesting at six locations within the Strait of Georgia including the bridge (Carter et al. 2018). These locations are the Shoal Islands, Gabriola Island Cliffs, Galiano Island Cliffs, Mandarte Island, Mitlenatch Island, and the IWMB (Carter et al. 2018). The study sites for this research include Gabriola Island, Mitlenatch Island, and the IWMB, and are known to each have unique nesting structures and are hypothesized to be related to nest success as it may control the level of access by predators.

It has been observed that PECO are able to nest as a single species in a colony while DCCO prefer to nest with PECO in the Strait of Georgia (Vermeer & Rankin 1984). When DCCO and PECO nest within the same cliff colony, they remain separate. DCCO prefer open ledges, positioned at the top of the colony while PECO prefer to nest below (Moul & Gebauer 2002). On man-made structures, it has also been reported by Ong (2021) that DCCO and PECO remain separated within the colony. The IWMB is currently the only bridge within the Vancouver area to contain both DCCO and PECO, while the Granville Street and Burrard Bridges contain only PECO.

The IWMB is maintained by the Ministry of Transportation and Infrastructure, a provincial agency that is concerned about the impact cormorant guano has on the bridge's structures due to the level of acidity. In response to these concerns there is ongoing talk about the potential exclusion of the cormorants from the IWMB (Hemmera 2018). However, there have been no studies that have tested this theory. Exclusions have already occurred for the Burrard Street Bridge where a net was installed in 2015 while bridge maintenance occurred and then was removed in 2019 (City of Vancouver 2019). As well, the Granville Street Bridge exclusion net was installed in 2019 while seismic upgrades occurred on the bridge (City of Vancouver 2019). The use of exclusion nets at the IWMB is a high-risk measure for the Strait of Georgia population of DCCO as the IWMB colony contains the greatest number of provincially listed breeding DCCO. This exclusion of nesting birds could have substantial negative consequences for the species, forcing breeding individuals to relocate to an unknown and potentially less conducive nesting location.

1.2.2. Nest attendance and chick care

On average, DCCO produce three to four eggs in a clutch (Stenzel et al. 1995) When clutches contain a greater than average number of chicks (>4), growth rates for young decrease, and the rearing period increases, likely due to increases in foraging effort by the parents (Sullivan 1998; Moul & Gebauer 2002).

Nest attendance post hatching varies across the range of DCCO. In tree nesting DCCO found in Quebec, adults are present at the nest for 100% of the time for the first 31-35 days after hatching (Léger and McNeil 1985). The average time DCCO incubate eggs was reported to be 28 days in Utah, USA, as documented by Mitchell (1977) and 25 to 28 days in the Strait of Georgia by Moul & Gebauer (2002). The chick care period of DCCO has also been reported to be 25 to 42 days by Moul & Gebauer (2002). Both male and female parents are equally attentive, attending DCCO nests through the sharing of roles in foraging and feeding (Léger and McNeil 1985).

1.2.3. Nest phenology

DCCO within the Strait of Georgia have been known to exhibit breeding behaviour between the months of April and September, however, the timing of laying of eggs and incubation period is variable throughout colonies and years. For example, in 1993, the DCCO colony at Five Finger Island began laying eggs around April/May while the DCCO colony at Mandarte Island, 70 km south of Five Finger Island, was delayed for over one month (Sullivan 1998). This was likely caused by repetitive flushing by Bald Eagles which led to predation of young and the need to relay clutches (Sullivan 1998). Furthermore, in 1993, the Fraser River DCCO colony was delayed three months for similar reasons, with eggs being seen in late July and early August (Sullivan 1998). Such delays in nesting may result in lower breeding success due to conditions outside the optimal breeding time (Hällfors et al. 2020; Shipley et al. 2020).

1.2.4. Nest success

In this study, the definition for nest success outlined by Armstrong et al. (2002) was followed and define as the proportion of nests that hatch at least one successful egg that survives to fledge. Nest success is related to the level of fitness for a bird, which is a measure of the species ability to successfully reproduce in order to promote population stability and/or growth (Orr 2009; Streby et al. 2014). For this reason, nest success can be used as an indicator of population persistence for the DCCO (Reed 2005). Nest success contributes to continued understanding of population trends for the DCCO and provides justification for management interventions that could support conservation and restoration of the species, particularly at the industrial bridge sites that are used by cormorants and managed by the provincial Ministry of Transportation and Infrastructure.

There are known variables that can increase the likelihood of nest success for DCCO. It has been demonstrated that DCCO located higher within tree nesting colonies are able to produce a greater number of young in their clutch (Léger & McNeil 1985). It has also been shown that early breeders are able to produce significantly more successful nests than late breeders.

Nest success for the DCCO throughout the Strait of Georgia has not been well documented in recent years. However, some nest success and hatching success rates (the probability of eggs hatching into chicks) have been determined for multiple colonies in the past at Mandarte Island, Five Finger Island, and the Fraser River colony (Table 1) (Sullivan 1998; Moul & Gebauer 2002).

Table 1. Past nest success values determined for the DCCO within the Strait of Georgia, British Columbia.

Author	Year	Colony location	Nest success (%)
Sullivan 1998	1993	Five Finger Island	86
Sullivan 1998	1993	Fraser River	77
Sullivan 1998	1993	Mandarte Island	80
Sullivan 1998	1994	Five Finger Island	81
Sullivan 1998	1994	Fraser River	81
Sullivan 1998	1994	Mandarte Island	0.005

1.2.5. Double-crested Cormorants' role in the ecosystem

Seabirds are considered to be sentinel species within their ecosystems (Mallory et al. 2010). They have been used to detect and monitor stressors including pollution, depleting fish stocks, fluctuations in ocean productivity, and climate change (Mallory et al. 2010). This is due to seabird vulnerability of pollutants and from prey that bioaccumulate toxins, changes to the food web structure, and changes in their nesting conditions (Burger & Gochfeld 2004). Seabirds are also widespread, visible, and well-studied in some cases, making their life histories more transparent then other marine species who carry out their life history entirely in the ocean (Grémillet 2020). Seabirds show the impact of negative environmental effects through a reduction in reproductive effort, nest success, and overall survival (Mallory et al. 2010).

Dias et al. (2012) suggests that the Great Cormorant (*Phalacrocorax carbo*) can be used as an indicator of fish species diversity off the Iberian Coast through collection and analysis of cormorant pellets. DCCO in the Great Lakes (*P. a. auritum*) have been monitored as biomarkers for developmental toxicants (Fox et al. 1991). Kushlan (1993) also suggests that DCCO can be a bioindicator for environmental change through the collection of live samples and monitoring in the USA.

By studying nest success of the DCCO within the Strait of Georgia, we can gain knowledge on the current level of ecosystem health from the direction of population change. Through the field-based research on nest success, we can begin to understand the DCCO's relationship within the Strait of Georgia ecosystem and what factors could be limiting population increases. Limitations found may also offer clues into how other populations of seabirds, and potentially other marine species, are being impacted.

1.3. Multi-event model

Monitoring vulnerable populations and species at risk is an important aspect of conservation and restoration. However, monitoring can often be overlooked, intermittent, and disruptive to the species being studied (Edney & Wood 2020). In the case of nesting seabirds, limiting factors include traveling to remote nesting sites and causing disruption to colonies such as exposing juveniles to predators after flushing events. Advances in technology have allowed monitoring to become autonomous and non-invasive. Through the use of solar powered cameras and time-lapse camera technology, records of the entire nesting season for the DCCO were captured. This type of monitoring also offers more complete and long-term data, allowing for new factors to be studied such as nest success and demographic parameters of breeding (Cam et al. 2003).

Breeding parameters can be determined through the collection of daily photos at seabird colonies by using a mark-recapture framework where each photo taken is a new capture event (Cam et al. 2003; Lorentzen et al. 2011). A multistate model can then be applied to the capture data. This is a statistical model that describes the transitions between multiple states. Possible states for during the breeding season for the DCCO that were considered in this study included the presence of an incubating adult, a chick, and the occurrence of death. There is uncertainty in the presence of an egg or chick when an incubating adult is present.

Multi-event models extend multistate models through 7an observation process that describes the probability of imperfectly observing the underlying state (Pradel 2005; Nichols & Kendall 2010; Lorentzen et al. 2012). When using distance photography for nesting seabirds, the state of the nest in an image is not always certain and this uncertainty is modeled through an observation process. For example, an incubating adult may conceal the presence of an egg or nestling and the timing of the transition from egg to nestling would be uncertain as well (Pradel 2005). A time-dependent multi-event model is a type of Bayesian hidden Markov model, where inferences on time dependent state transitions are made accounting for the state observation uncertainty (McClintock et al. 2020; Pradel 2005). Hidden Markov models are useful in studying ecology as they consider underlying, dynamic, ecological processes that are not directly observed (Tucker & Anand 2005; McClintock et al. 2020). In my thesis, I use a multi-event model to estimate probabilities of observing chicks and chick survival for the DCCO breeding colony on Gabriola Island.

1.4. Study goal and objectives

The goal of this study is to gain an understanding of DCCO nest success at natural nesting sites within the Strait of Georgia in order to determine population level effects that could occur if the IWMB is to be excluded. In order to understand nest success, time-dependant breeding parameters were modelled using a multi-event model which offers probabilities on DCCO nest states and state transitions including chick presence, egg and chick survival, and the transition from egg to chick or death. Chick care and predator presence at natural nesting sites will also be determined in order to understand the model's results. Natural nesting site results will also be compared to overall nest success at the IWMB. To accomplish this, remote photography was used to determine weekly states of all visible nests at Gabriola Island and Mitlenatch Island, and a portion of nests at the Ironworkers Bridge, for the years 2020, 2021, and 2022. Results from this study can inform suggestions for restorative interventions for the species to support future population stability and growth.

Chapter 2. Methods

2.1. Photo monitoring

Three cormorant nesting sites within the Strait of Georgia were photo-monitored including Gabriola Island, Mitlenatch Island, and the IWMB (Figure 1). These sites were chosen to continue the work of Macus Ong (2020) and Rose Wilkin (2021). As well, each site is representative of a unique DCCO nesting structure within the Strait of Georgia. Photo-monitoring began in April and ended in September from 2020 through 2022, encompassing the entirety of the DCCO nesting season.

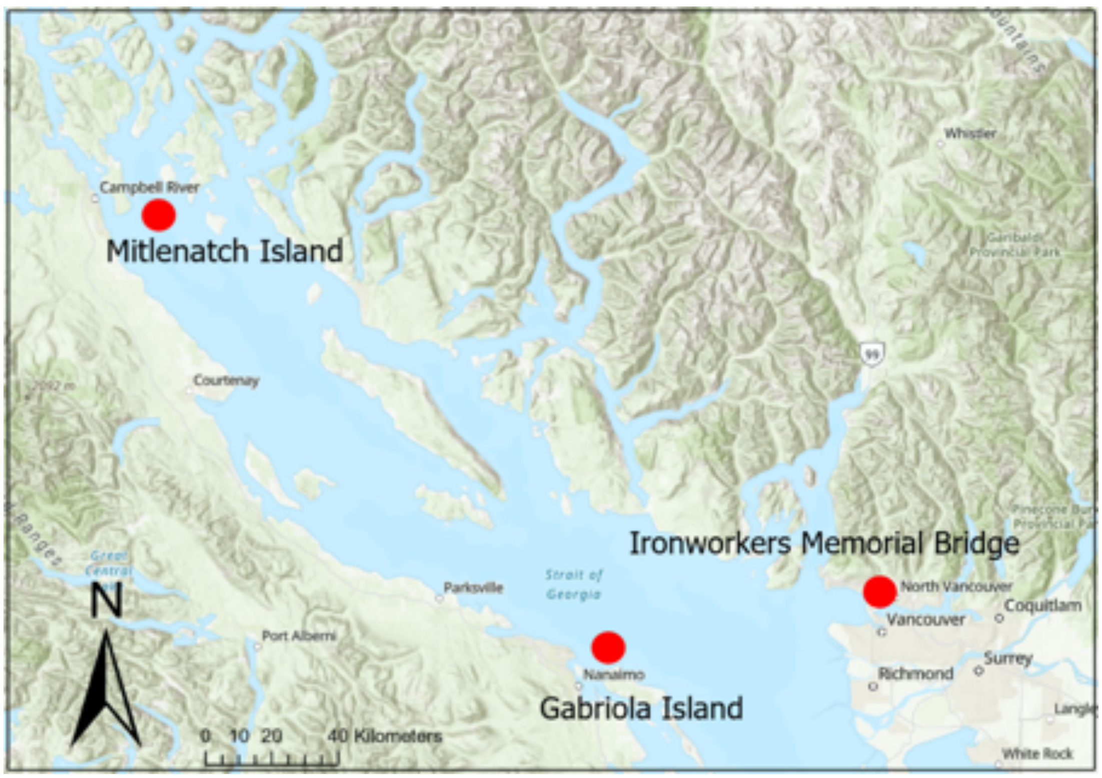

Figure 1. Study site locations within the Strait of Georgia, British Columbia including Mitlenatch Island, Gabriola Island, and the Ironworkers Memorial Bridge used in the 2020, 2021, and 2022 data collection.

2.1.1. Photo monitoring at Gabriola Island

Gabriola Island is located five km east of Nanaimo and currently has a population of 4,500 people (Government of Canada 2017) . Both PECO and DCCO nest along the western side of the island on a cliff face that is approximately 40 m high and composed of sandstone. The nesting DCCO are located in the upper half of the sheer cliff face and the PECO in the lower half within crevasses. The most recent nest count for Gabriola Island was reported at 64 DCCO nests in 2014 (Carter et al. 2018). To monitor the entire nesting season at Gabriola Island, a GoPro camera was installed on the upper tier of the seacliff during the DCCO nesting season in the years 2020, 2021, and 2022 (Table 2). Powered by a solar panel and controlled by Blink X technology, the GoPro camera was able to take real-time photos of a subset of up to 29 nests each day (Figure 2).

Table 2. Components used to set up the GoPro camera at Gabriola Island on April 15th, 2022, and Mitlenatch Island on April 2nd, 2022, British Columbia.

Item	Description
GoPro camera HERO7	Placed inside the weatherproof box and connected to BlinkX box
Memory card size 64 GB	Micro SD
Portable battery pack	Connected to solar panel and to Blink X box
Silica Gel Packets	Used to decrease moisture inside box (x5)
Blink X box	Time lapse control of the camera
Solar panel	9W Solar Kit by CamDo, attached to battery pack
Weatherproof box	DryX Weatherproof Box by CamDo
Arm w bracket	Made by RAM
Expansions bolts ⅜	Used to hold weatherproof box in place (x4)

For my research, I monitored the 2022 DCCO nesting season at the centre of the Gabriola Island seacliff colony. I compared the 2022 breeding colony at Gabriola Island to the same GoPro camera's field of view collected in 2020 (Ong 2021) and 2021 (Wilkin 2022). In 2022, I set the BlinkX time lapse box to trigger the GoPro camera system to capture photos every 2.5 hours starting at 6:00, followed by 9:30, 13:00, 16:30, and 20:00. Each photo session produced 11 photos, spanning a time of 5 minutes per session, taking a total of 55 photos each day. Photos were taken throughout the day to capture multiple aspects of each nest to reduce uncertainty of nest states. For example, nestlings are often hidden by the incubating parent, therefore more photos will result in a higher chance of seeing their young. The camera was retrieved on September 18th, 2022. GoPro images from the nesting seasons at Gabriola Island for the years 2020 and 2021 were also included in this study (Table 2). In the year 2020, the GoPro malfunctioned leading to the loss of 11 days intermittently across the nesting season. Additionally, in the year 2021, the GoPro camera also malfunctioned, leading to missing session dates with a total of 17 days' worth of data across the nesting season (Appendix A). These malfunctions did not affect the analysis, as the analysis resolution was weekly, and therefore, nest sites monitored for each week for the duration of the analysis period for each year (Table 3).

Table 3. Dates and photo coverage from the GoPro at Gabriola Island, British Columbia, for the years 2020, 2021, and 2022. * For the year 2020, the GoPro camera malfunctioned and was unable to capture images for 11 days intermittently throughout the nesting sea

Year	Start date of photo capture	Day of camera removal	Frequency of images captured per day
2020*	May 23rd	August 15th	Three photos taken every 2 hours 24/hrs a day
2021*	April 26th	October 27th	Three photos taken every 30 minutes 24/hrs a day
2022	April 15th	September 18th	11 photos taken every 2.5 hours beginning at 06:00 and ending at 20:00 each day.

Figure 2. Labelled diagram of numbered nests for Gabriola Island, British Columbia. The number order is based on the addition of new nests added between the years 2020, 2021, and 2022. Red numbers indicate a nest was not made in 2022 where there was one in a previous year. Nests labelled with a *T*, mean they are tree nesting sites, whereas the cliff site denotation of “CL”, used by Ong (2021) and Wilkin (2022), was omitted in this figure, see Appendix C for complete labelled diagram.

In addition to the time series of GoPro camera images, a count of the entire Gabriola Island colony occurred on July 5th, 2022, using a series of high-resolution images of the Gabriola Seacliffs. I used a Sony a7R IV DSLR camera equipped with a 200-600x zoom lens with the images taken below the cliffs floating in a double kayak.

Additionally, I took a panoramic image of the Gabriola Seacliffs from 1.7 km away from land at the tip of Jack Point, Nanaimo. The panoramic image was captured using the Sony a7R IV DSLR camera equipped with a 200-600x zoom lens along with a GigaPan Epic Pro. The panoramic orthomosaic photos helped provide an overview of the entire natural breeding colony at Gabriola and a full count, while the high-resolution images taken from the kayak helped to determine which species each nest belonged to.

2.1.2. Photo monitoring at Mitlenatch Island

Mitlenatch Island is located 20 km southeast of Campbell River, British Columbia. Mitlenatch is a small rocky island, 155 ha in size with shrubs as the dominant vegetation type (British Columbia Parks n.d). It is designated as a Provincial Nature Park and is not accessible by the public, however, the Mitlenatch Island Stewardship Team completes regular activities upon the island, such as ecological surveys and invasive species control. DCCO were first found nesting upon Mitlenatch Island in 1993, with 10 nests present (Chatwin et al. 2002). This then grew to the highest nest count for the island in 2000, with 70 nests present (Chatwin et al. 2002; Carter et al. 2018). The most recent count of nests occurred in 2014 with 25 DCCO nests present (Carter et al. 2018).
Both DCCO and PECO nest on Mitlenatch Island, and similar to Gabriola, DCCO nest at the top of the cliffs while PECO nest below among the caves and crevasses. However, unlike Gabriola, the DCCO nest along a rounded open cliff top (Figure 3).

At Mitlenatch Island, the GoPro camera set up was the same as Gabriola Island's, however, the camera and related equipment was installed on a pole above the nesting colony (Table 2). The field of view is the same that was used for the 2021 nesting season, focusing on ~10 nests as some nests are abandoned and created throughout the season which represents 40% of the total DCCO nests at Mitlenatch Island (Figure 3 & 4) (Wilkin 2022). The camera was installed on April 2nd, 2022, before the cormorants arrived, and retrieved September 18th, 2022, after all cormorants had vacated the colony for the season. The Mitlenatch Island data from 2021 was also used in this study. During the 2021 data collection, the GoPro camera was installed on April 26th, 2021, and the last photo was taken on August 14th, 2021 (Table 3). However, the

GoPro camera malfunctioned after June 4th, resulting in 16 more useable days' worth of photos and a total of 35 days of photos.

Figure 3. Field of view from the GoPro camera, Mitlenatch Island, British Columbia, taken July 12, 2022.

Figure 4. The Mitlenatch Island GoPro camera installed above the nesting colony, taken September 18, 2022, British Columbia.

2.1.3. Photo monitoring at the Ironworkers Memorial Bridge

The IWMB is a large six lane, 1.29 km long bridge that connects East Vancouver to North Vancouver. The bridge is made up of a network of steel beams below the road upon which the cormorants nest. Both DCCO and PECO nest within the bridge's structure, however there are significantly more DCCO than PECO. In 2020, the bridge held 61 PECO nests and 296 DCCO during peak nesting season (Ong 2021). PECO primarily nest on Spans 3 and 4 of the bridge and DCCO nest on Spans 1 and 2. PECO prefer to nest within corners created by the meeting of girders and gusset plates, while DCCO tend to nest along the cross-frames (Ong 2021). The IWMB is likely the most important nesting site for DCCO within the province of British Columbia as it holds the largest nesting colony for the species of special concern. Although the bridge is located in a very industrialized setting, it has been hypothesized that the complex structure of beams act as a deterrent for predators such as the Bald Eagle.

At the IWMB panoramic photos were taken 3 times a week within the time of 10:00 and 13:00, between the dates April 07 and September 9th. Photos were taken with a Sony a7R IV dslr camera equipped with a 200-600 x zoom lens. To take panoramas, a GigaPan Epic Pro was used to take prescribed dimensions to create multiple smaller photos (tiles) that when put together, creates a large panorama (see post processing for IWMB) (Figure 6). The IWMB was broken up into 5 spans: 1A, 1B, 2, 3, and 4 (Figure 5). Each span had its own individual panorama taken of it (Table 3). Spans 1A, 2, 3, and 4 were taken on the North Vancouver side of the bridge from an eastern point of view located on a rocky shore. Span 1B was taken from a concrete bridge in Bates Park, Vancouver. Spans 1A and 1B were taken fully zoomed in at 600x, while Spans 2, 3, and 4 used a zoom of 375x.

Figure 5. The GigaPan EpicPro with the Sony camera mounted on top in front of the IWMB, North Vancouver, British Columbia

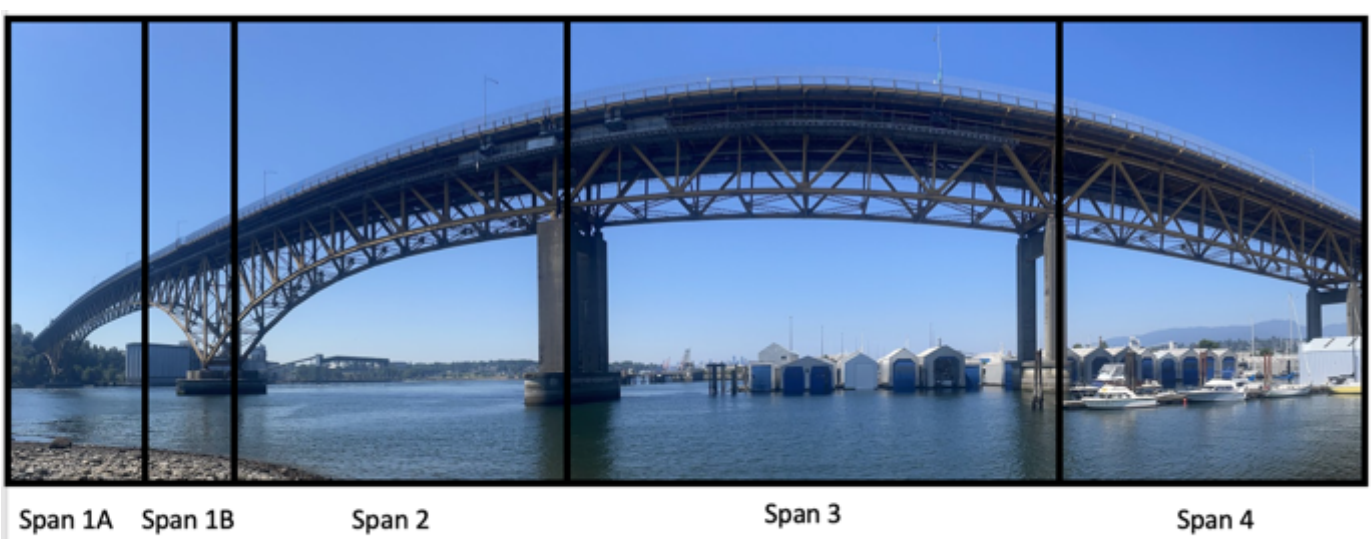

Figure 6. A panoramic photo of the entire IWMB, British Columbia, from the site of Span 1A, 2, 3, and 4 photo capturing events. It should be noted that the photo is skewed in size due the angle of observation.

Table 4. Example panoramas for Spans 1A, 1B, and 2 at the IWMB in Vancouver, British Columbia, taken on August 5th, 2022.

Span #	Panorama
Span 1A	
Span 1B	
Span 2	

2.1.4. Ironworkers Memorial Bridge: post processing

Photos that were taken with the camera placed on a GigaPan produced tiles that make up a panorama. A computer software called PTGui was then used to stitch the tiles together to create the panorama. In order to reduce file size, tiles that did not contain any bridge were removed from each panorama, for example, tiles of sky and surrounding buildings (Table 3). Photos were saved as Tiff files and were resized in PTGui to 4GB for computers to have the RAM to easily load the photo for processing.

2.2. Predation

Predation and presence of predators was monitored at Gabriola and Mitlenatch Island. There was no apparent predation observed at the IWMB colony during photo collection during 2020, 2021, and 2022, and therefore, it was not an analysed factor at that location. At Mitlenatch Island, presence of gulls (species unknown), crows, and Bald Eagles were noted for each day. At Gabriola, it was noted each time a Bald Eagle was seen within the field of view of the GoPro camera as well as gulls (species unknown), and crows.

2.3. Nest Success

2.3.1. Nest success at Mitlenatch Island

Rather than analysing nest success, an average measure of nest attendance was produced for the 2022 breeding season at Mitlenatch Island. The average weekly number of nests, number of incubating adults, and number of total adults present in the colony was documented between May 06 and September 02. These numbers show the proportion of nests that contained incubating adults out of the total number of nests present to understand nest attendance and possible effects of predator presence.

2.3.2. Nest success at the Ironworkers Memorial Bridge

Nest success was determined for the IWMB for the years 2020, 2021, and 2022 by recording the state of a subset of nests on of the bridge from each panorama taken over the course of the breeding period. Nest success was measured by determining the proportion of active nests that produced at least one successful young compared to those who did not. For the years 2020 and 2021, the state of each nest on Span 1B and Span 2 from each panorama session was used to determine nest success. In 2020, 309 nests were followed throughout the nesting season and in 2021, 342 nests were assessed.

2.4. Chick care at Gabriola Island

The average length of chick care was determined for the years 2020 and 2022 at Gabriola Island. Only nests with that experienced fledging within the timeframe studied were used in this analysis by finding the mean number of days chicks were present. The 2021 data was omitted from this calculation due to the low quality of the data collected.

2.5. Multi-event model

2.5.1. Data organization for the model

In this study, a hidden Markov capture-recapture framework was applied to photographic GoPro data across multiple DCCO breeding seasons to 'capture' nest dynamics over time, where each photograph taken was considered a new capture event. To analyze the photo data from 2020, 2021, and 2022, each nest within the field of view was followed, rather than individual cormorants. The data captured at each nest described discrete life history classes or "states". In order to condense the data from the 55 photos taken each day, daily average states were recorded for every nest within the field of vision beginning on the first day of camera deployment and ending on the day the camera was retrieved. Observed states that were recorded include the presence of an incubating adult in a nest denoted by '1', the visible presence of at least one chick denoted by '2', and the presence of a non-incubating adult or an empty nest prior to fledging denoted as '3'. Assumptions that were made include that if an adult stayed in an incubating position within a nest for 90% of the time, it was assumed to be continually incubating an egg or chick (Gaston et al. 1994; Lorentzen et al. 2012). If the adult was seen in a non-incubating position in the nest for over 10% of the time, including standing upright or away from the nest, or it was clear the nest was empty, it was assumed the adult was not incubating eggs and the clutch failed.

To input this data into the multi-event model, daily nest observations were further compiled into average weekly nest observations to simplify the model outputs (Appendix A). These weekly observations are the sampling occasions that the model used to produce probabilities on the parameters of DCCO breeding. To simplify the model, the number of sampling occasions was reduced to focus on the time of chick rearing. Therefore, the first sampling occasion chosen for each year was the week before the first chick was visible and the final sampling occasion was determined by the first instance of fledging. It was assumed that all chicks that were alive at this point survived to fledge following assumptions made by others such as Lorentzen et al. (2012) who modeled Brunnich's Guillemot (*Uria lomvia*) in Svalbard.

Due to technological errors of the Gabriola Island GoPro, data from the 2021 season was intermittent and did not offer the same amount of detail as the other years. Data from this year is highly fragmented and missing session dates were inferred from the closest available data point (Appendix A). Although the data from 2021 was not complete, it is still thought to offer insight on the amount of variability in nest success between each year. As well, GoPro technical errors resulted in the loss of 11 days of photos across the nesting season in 2020 however, after condensing daily photo data into weeks, this likely did not affect sampling occasion outcomes.

2.5.2. Model creation

Time-structured capture-recapture models are widely used in animal demographic studies to assess population dynamics. To calibrate these models, a weekly time-series of images captured in the camera's fixed field of view were determined at the nest level to estimate demographic breeding parameters of the DCCO nesting colony. The breeding season of the DCCO was monitored from April to September for the years 2020, 2021, and 2022. Instead of offering a single value for nest success based on one visit, the model is able to describe the dynamics of different life history states with the uncertainty of an observation process throughout the time of rearing (Pradel 2005; Gimenez et al. 2012). This model decouples underlying state dynamics such as survival of the egg and chick state and the transition between these states from the observation model (Figure 7).

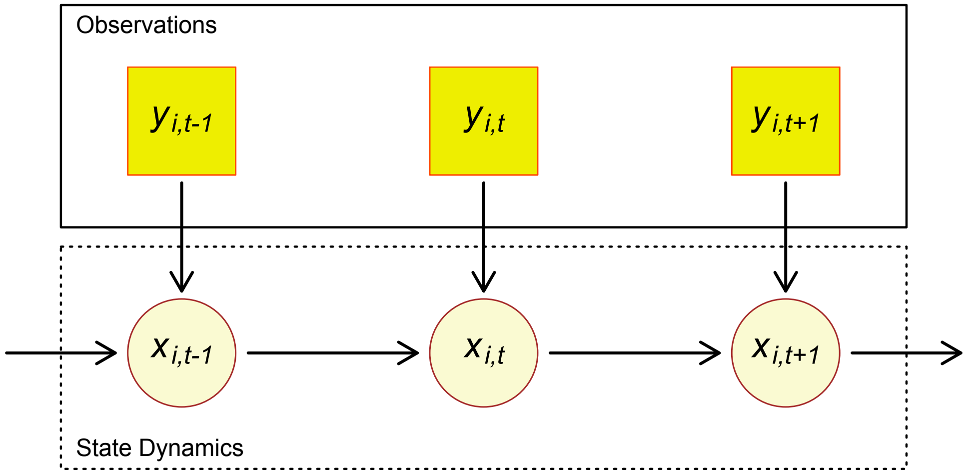

Figure 7. Schematic representation of the hidden process mark-recapture modelled for nest *i* between three sampling occasions *t-1, t, and t+1.* The first layer is a series of hidden states (circles) that describe the 'true' state of nest *i* at times *t-1, t, and t+1*. The dynamics of the state are driven by the survival probabilities, phiE and phiC, for egg and chick states, and the transition probability from egg to chick, psiEC. Because the state, x, is not observed directly, rather we observe, y, there is a probabilistic relationship between the observation and the state.

Three states were considered in the model which consist of Egg, Chick, or Dead (E, C, D), based on the observation events Adult incubating in nest, Chick, or Non-incubating adult/visible chick death([A, C, D). A model was fit with state specific survival for each time step where we assumed at the first sampling occasion that a nest had a probability of 1 of being in the egg state if an incubating adult was present. Then the nest moves forward to the next time occasion, and either stays in the egg state, transitions into the chick state, or incubation is no longer occurring due to the observation of a non-incubating adult or chick death. This repeats until the first instance of fledging. From these observations, the model is able to determine the probability of surviving the time interval as an egg, phiE, or as a chick, phiC, and the probability of transitioning to chick from an egg, or the hatching probability, psiEC. Two matrices make up the basis of the model and guide the probabilities of the occurrence of transitions through the observed states. These matrices also follow the assumptions that a chick cannot become an egg, and an egg and chick cannot return from death. The transition matrix describes the state process is shown below where the state at the previous time interval, *t-1*, is represented by the rows, and the current time interval, *t*, is represented by the columns.

Transition Matrix:

x (t)

Egg	**Chick**	**Death**	
phiE*(1-psiEC)	phiE*psiEC	1-phiE	**Egg**
0	phiC	1-phiC	**Chick**
0	0	1	**Death**

x (t - 1)

The observation process is conditional on the underlying state dynamics and is described by the detection probabilities of observing the states E, C, D (Pradel 2005; Lorentzen et al. 2012; Gimenez & Turek 2022). In our images we never saw the eggs as the adults incubating were the only visible cue eggs, therefore, the probability of observing an egg was the same as observing an adult incubating, pE=1. Likewise, if a nest was empty before the young could have fledged, we assumed the nest failed, and we set the probability of observing death, *pD*=1. Adults incubate both eggs and chicks, and therefore there is uncertainty what the underlying state is of beneath it. This uncertainty of nest state is summarized by a row (stochastic) matrix where the rows each sum to 1 (Lorentzen et al. 2012; Louvrier et al. 2018). The event process that we describe in this study is that the uncertainty is conditional on observing an adult when the underlying state is the chick, *pC,* or an egg, *1-pC*.

Observation Matrix:

y (t)

Adult	**Chick**	**Death**	
1	0	0	**Egg**
1-Pc	Pc	0	**Chick**
0	0	1	**Death**

y (t)

The DCCO hidden Markov model was solved as a Bayesian state space model using the NIMBLE (Numerical Inference for Hierarchical Models Using Bayesian and Likelihood Estimation) package in R (Gimenez et al. 2012). The Bayesian state space framework provides a great deal of flexibility in modeling time-dependent demographic parameters (Gimenez et al. 2022). As a Bayesian framework was used, the model begins with setting priors for all the parameters of interest pC and phiC for each time interval, and the overall phiE and psiEC for each yar. For every occasion (t) and each parameter, we set the priors equal to the standard uniform distribution to be between 0 and 1. As well, the probability of being alive during the first occasion was set to 1. The transition and observation matrices are applied based on the state observations, y_t, from each following week's GoPro image data (Appendix E).

In order to select the best fitting HMM model, WAIC scores were compared between each model version. Model versions include the addition of parameters such as the probability of hatching and egg survival. However, it was found that the least parameterized model was the best fit and offered the lowest confidence intervals. This least parameterized model includes having one output for phiE and psiEC for each year.

2.5.3. Breeding success at Gabriola Island

In this study, a metric similar to nest success was calculated using a hidden Markov multi-event model. Using the equations from Lorentzen et al. (2012), I calculated breeding success using estimates of parameters from the multistate model, including the probabilities of chick survival, egg survival, and hatching. Three equations were used across time to incorporate the time-dependant aspect of the model and subsequent weekly breeding success rates. The first equation produces the probability of an egg to hatch within the initial occasion of the first week (t=1) and for the chick to survive until the final occasion K, in this case the first instance of fledging. This is represented by $h(1)$ where:

$$h(1) = \text{phiE} \times \text{psiEC} \times \text{phiC}^{K-2}$$

The next equation includes the probability of an egg hatching between occasions t=2 and t=3, followed by the continued survival of a chick until the last occasion K.

$$h(2) = \text{phiE}^{2} \times (1 - \text{psiEC}) \times (\text{psiEC} \times 2) \times \text{phiC}^{K-3}$$

The third equation is a generic formulation that can be applied to a nest in which the egg hatched at some occasion between t>3 and *K-1,* and for the chick to survive until the last occasion *K.*

$h(t)$= phiE $^{t-1}$ x (1-psiEC) x (1-psiEC x 2) $^{t-3}$ x (psiEC x 2) x phiC $^{K-t}$

To get the population's value for breeding success, I calculated the sum of each nest $h_i(t)$ as follows, and the average value can be taken.

Breeding success = $\sum_{t=2}^{K-1} h(t)$

Chapter 3. Results

3.1. Mitlenatch Island

Similar to Wilkin's (2021) results, Mitlenatch Island experienced full nest failure with zero nest success for the 2022 nesting season. It was assumed that no eggs made it to the chick state as young were never seen through the daily images captured. There was one instance of a DCCO egg in a nest on July 22nd, 2022, however, it was taken by a crow (Figure 8).

Figure 8. A photo captured by the GoPro camera installed at Mitlenatch Island, British Columbia on July 22nd, 2022, at 6:02 am. This photo shows a crow with the only egg seen produced at Mitlenatch Island for the 2022 nesting season. This predation event occurred after the entire colony had flushed.

3.1.1. Predation

With predation being hypothesized to be the greatest limiting factor on the DCCO breeding season within the Strait of Georgie, predator presence was closely assessed at Mitlenatch Island. The entire nesting colony within the camera's field of view was flushed a total of 55 times where 22 of those times included the presence of a Bald Eagle (Figure 8). Gulls were seen within the nesting area 86 days and crows 38 days out of 117 days over the nesting season. It should be noted that photos were taken 5 times a day, covering a total of 55 minutes per day, and therefore, numerous flushing events and predatory interactions were assumed to have occurred outside of the camera's operational times.

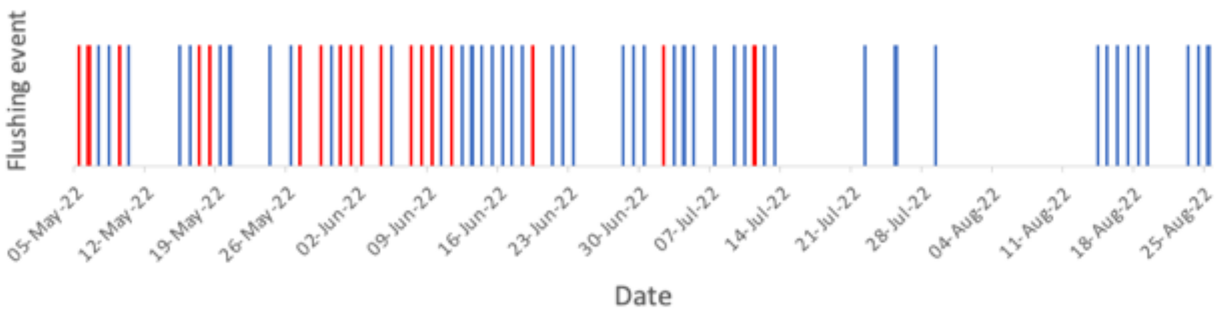

Figure 9. The entire DCCO colony at Mitlenatch Island, British Columbia, was flushed a total of 55 times (blue) between May 05, 2022, and August 27, 2022, with a total of 22 Bald Eagle sightings during flushing events (red).

3.1.2. Adult nest attendance

An assessment of adult and nest presence was completed for the Mitlenatch Island 2022 nesting season. The daily number of individuals present, nests present, and total incubating adults were counted once a week at Mitlenatch from the GoPro data. This began on May 6th when the first nests began to be incubated (Figure 9). Each photo selected to be assessed was from 2 pm, unless the nests had been completely flushed at that time. This time was chosen due to the fact many cormorants stay within the nesting site at night and then leave in the morning, therefore the middle of the day offers a more robust count of the individuals who are incubating. It was found that the mean proportion of incubators in nests was 58% throughout the period of active incubation between May 27th and August 19th, with two dates found (August 19th and July 15th) where every nest contained an incubating individual.

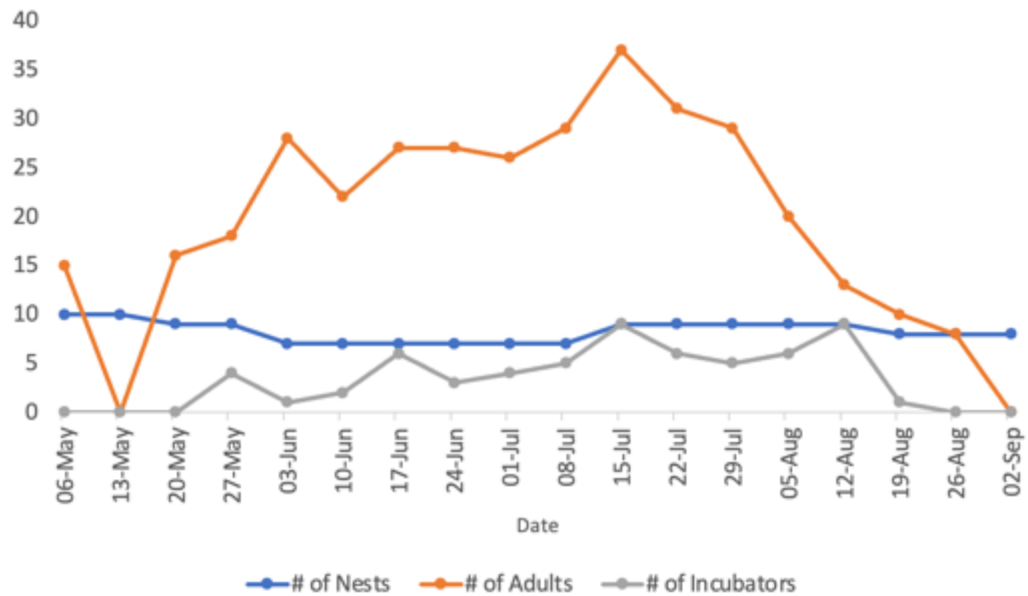

Figure 10. Number of DCCO nests, adults, and incubators assessed once a week throughout the nesting season at Mitlenatch Island, British Columbia. The nesting season began on May 06, 2022, when individuals arrived, and ended on September 02, 2022, when all individuals left.

3.2. Gabriola Island

3.2.1. Entire Gabriola Island colony count

A full colony count occurred for Gabriola Island on July 5th, 2022, where 205 DCCO nests and 90 PECO nests were counted. At this time, nest attendance would be high for incubating parents although, chicks may not have been visible from an angle below where photos were being taken.

3.2.2. Nest Phenology and length of chick care

Nest phenology is an important factor as it can show how susceptible the DCCO are to changes in their ecosystem dynamics including predator mediated delay effects. The first chick that was visible from the photography data in 2020 at Gabriola Island was seen on June 22nd, the first fledgling that left the nest occurred on July 30th and it was assumed that all chicks fledged by the week of August 22nd (Figure 11). The Gabriola Island photography data for the 2021 season experienced technical difficulties and did not record the entire season. However, some details were observed through the photos captured. This includes that the first chick seen occurred within the week of June 06th and by the week of August 15th all chicks had fledged (Figure 11). In 2022, the first chick was seen on July 8th, the first chick fledged on August 8th, and all chicks had fledged by the week of September 5th (Figure 11). Chicks were seen on average for 34 days before fledging in 2020 and 37.8 days in 2022.

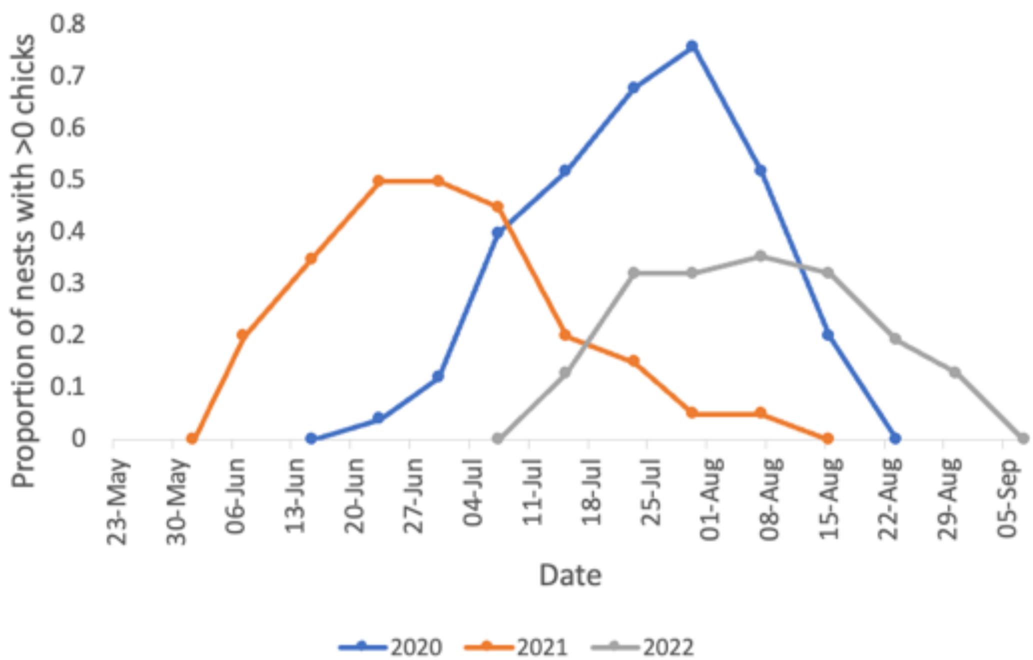

Figure 11. The proportion of chick presence within the GoPro's field of vision during weekly sampling occasions across the years 2020, 2021, and 2022 at Gabriola Island, British Columbia.

3.2.3. Predation

In the year 2022 at the Gabriola Island DCCO colony there were 21 instances of flushing seen through the photos taken. Of these 21 flushing events, 7 included all nests present, while the remaining 14 occurred for nests numbered 12 to 29 with the exception of nests 27 and 28. It was these nests that eventually were abandoned. Although nests were abandoned during the day, the adults did often return to the cliff at nighttime to roost, however, nest building was not kept up for these nests and most completely diminished. During these flushings, four sightings of Bald Eagles were also detected (Figure 12).

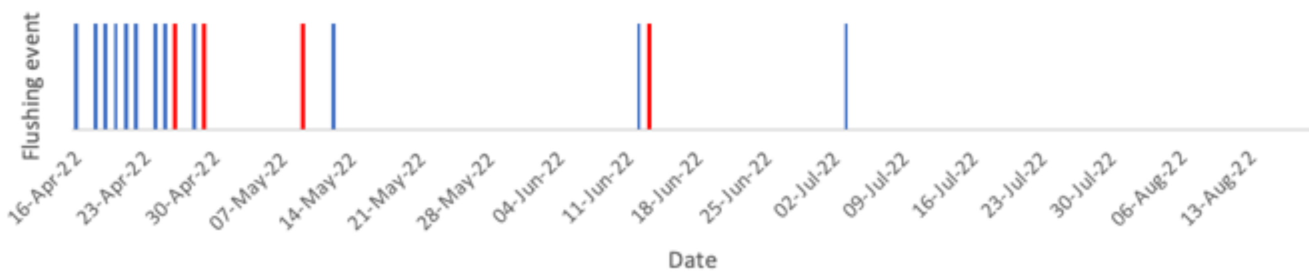

Figure 12. Recorded flushing captured by the GoPro camera at Gabriola Island, British Columbia, for the 2022 nesting season. There were 21 instances of flushing (blue and red) along with 4 sightings of bald eagles in conjunction with flushing events (red).

In the 2022 nesting season, fewer predators were seen at Gabriola than Mitlenatch. Gulls were seen flying near the nests, but rarely landed on them. Crows were seen less than 10 times and only after flushing events where they could be spotted within the nesting area. Bald Eagles were mainly seen within the periphery of the field of view, however, one juvenile Bald Eagle landed on the cliff after a flushing event on May 9th, 2022, and was seen taking eggs from a nest which later successfully re-laid its clutch (Figure 13). One photo also showed an adult Bald Eagle flying with a captured adult cormorant on April 26th, 2022, early in the breeding season (Figure 14).

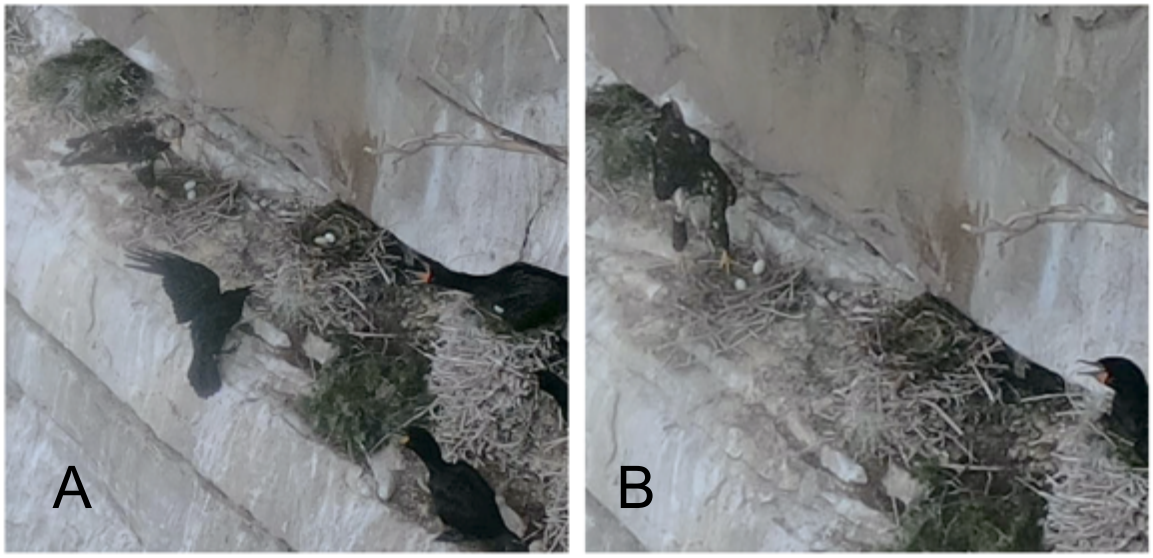

Figure 13. Photos captured by the GoPro camera at Gabriola Island, British Columbia, that show two acts of predation upon the DCCO colony on May 9th, 2022. Photo A was taken at 9:32 am and shows a juvenile Bald Eagle present in the nest, second from the left (nest 5), and a crow present at the nest third from the left (nest 4). Photo B was taken at 9:33 am and shows that the crow likely predated upon the eggs in nest 4, and the Juvenile Bald Eagle reaching for the eggs in nest 5.

Figure 14. A photo captured by the GoPro camera installed at Gabriola Island, British Columbia on April 26th, 2022, at 13:01. This photo shows a Bald Eagle predating on an adult cormorant. It is unknown if the prey is a DCCO or PECO.

3.2.4. Probability of chick observation

The probability of observing a chick (pC) is an important parameter of the observation matrix as it offers the likeliness of the viewer to see a chick while monitoring the nesting site. Chick observation probability, pC, is the only parameter in the observation matrix, and therefore, pC represents the probability of directly observing the chick, or the true state. The model results for pC show that there are variable start times of the first observation of a chick between each year (Figure 15). The earliest detection of a chick between the three years occurred in 2021 within the week of June 8th followed by June 23rd in 2020, and July 1st in 2022, The results of pC for the years 2020 and 2021 are similar in that they follow the same pattern of increase over time, beginning at 74% and increasing until 96% the final week before fledging occurs. It can be noted that for the year 2020 between the weeks of June 23rd and July 1st, pC plateaus at a value of 88%. For the year 2021, pC also plateaued within the weeks of June 8th and June 15th, remaining at 88%. In 2022, pC begins at 17% during the week of July 1st, followed by a slight reduction to 15% the following week, and then begins to increase to the maximum of 78% during the week of July 23rd. The year 2022, contains the lowest probability of chick observation and had the highest occurrence of nest failure.

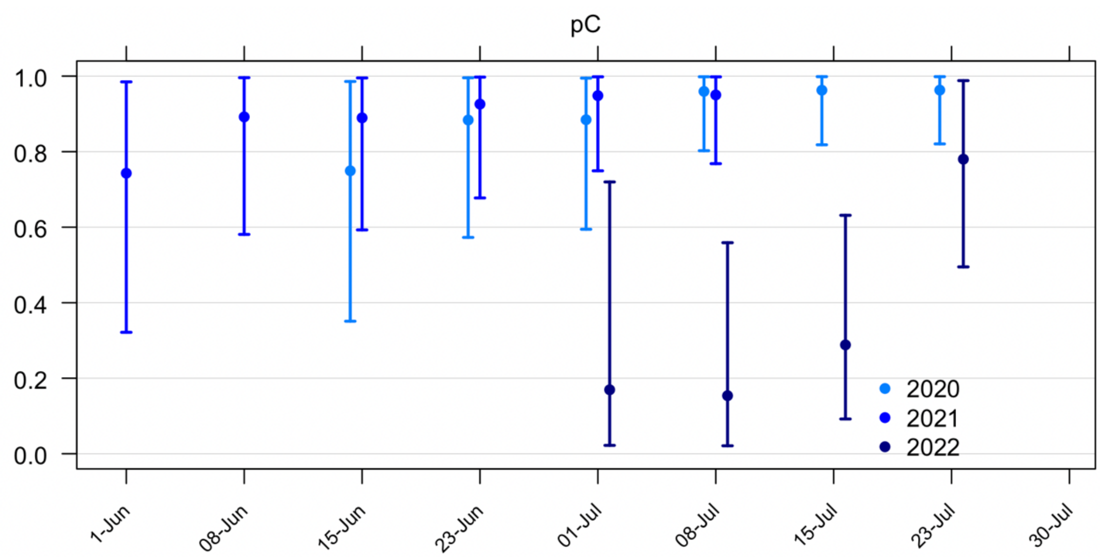

Figure 15. The probability of observing a chick from the output of the multi-event model for the three years of data collection at the Gabriola Island DCCO colony in British Columbia. The year 2020 is represented in light blue, 2021 as mid-blue, and 2022 as dark blue.

3.2.5. Probability of chick survival, egg survival, and hatching

The probability of chick survival (phiC) represents the ability of a chick to hatch and remain alive during each weekly occasion as seen in the transition matrix (Section 2.4.2). Measures of chick survival between the three years follow the same variability in phenology as observed in pC where the first visible chick in 2020 occurs within the week of June 23rd, in 2021 within the week of June 08th, and in 2022 within the week of July 8th. In 2020, phiC begins at 87% during June 23rd, the first week of chick presence, and continues to increase until a maximum of 96% during the week of July 30th. For the year 2021, phiC begins at 89% during the week of June 8th and then decreases to 82% during the weeks of June 15th and 23rd, before increasing again until reaching the maximum value of 95% in the week of July 1st. This decrease likely occurred due to three chick deaths in the colony. Finally, for the year 2022, phiC was estimated to be 75% during the first week of chick presence of July 8th. This phiC was lower than both 2020 and 2021 for the week of initial week of chick presence. In 2022, phiC continued to increase until reaching the maximum value of 95% during the week of July 23rd.

The weekly probability of egg survival (phiE) represents an egg's ability to survive within one week and remain alive for the following week. Weekly egg survival was highest for the year 2020 at 97%, followed by 2021 with 92% and 2022 with 67% (Figure 16). The probability of hatching (psiEC) is the likelihood an egg will become a chick within a particular week This value was the highest for the year 2022 at 45% with a confidence interval of 17-96%, however the transition to chick is conditional on surviving the egg state which is the lowest in 2022. The hatching probabilities are 26% in 2021, and 25% in 2020 (Figure 16).

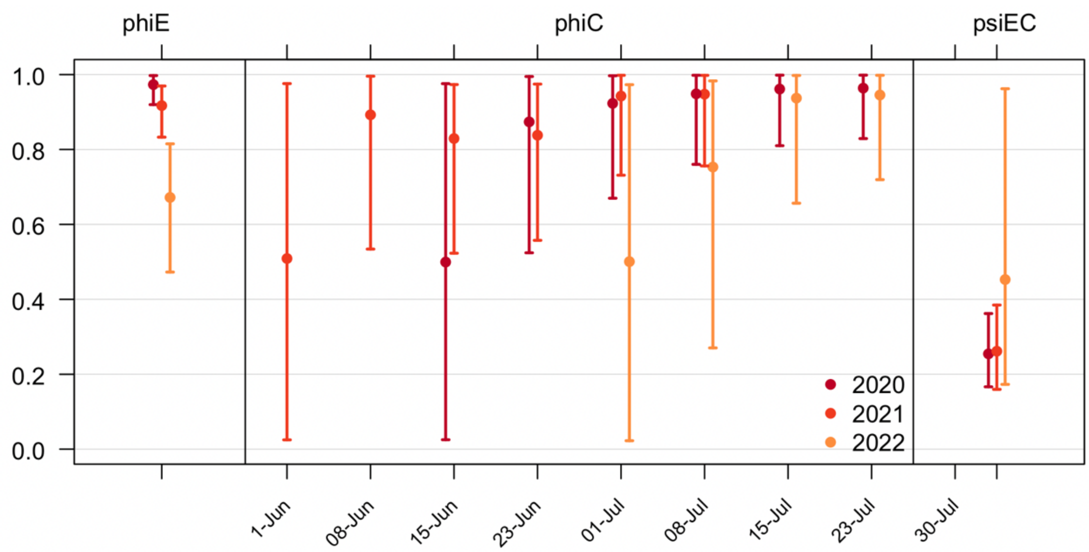

Figure 16. The probability of chick survival from the output of the multi-event model for the three years of data collection at the Gabriola Island DCCO colony in British Columbia. The year 2020 is represented as dark red, 2021 as red, and 2022 as orange.

3.2.6. Breeding success

Breeding success at Gabriola Island was defined by the probability of a DCCO egg to survive long enough to transition into a chick and then survive to fledge. In the year 2020, breeding success was 46%, in 2021, this value was 34%, and in 2022 breeding success was calculated to be 20%. The most successful year was 2020, however, nest failure still occurred through the death of eggs in nests 12, 14, 16, 18, and 23, and chick death in nest 14. In 2021, the colony experienced egg death in nests T1, 8, 13, and 17, while probable chick deaths occurred in nests 1A, 2A, and 11. The year 2022 had the lowest breeding success where egg death occurred in 19 nests and one chick death occurred in nest 27. For this year, nest failure occurred early in the breeding season starting around June 15, while the first chick wasn't observed until July 7th. Almost all the nests found on the left side to the middle of the field of vision failed, leaving the only successful nests to be T1, 1, 2, 3, 4, 5, 6, 7, and 28.

3.3. Iron Workers Memorial Bridge

The highest nest count for the IWMB occurred on July 10th, 2022, with 346 nests counted. This counted was conducted from adding the nests on Spans 1A, 1B, and 2 together. This count is not comparable to previous years counts where nests counted on Spans 1B and 2 where in 2020, 296 nests were counted on July 8th and in 2021, 231 nests were counted on July 9th (Ong 2020; Wilkin 2021).

3.3.1. Nest Success

The IWMB was found have nest success values of 49% in 2020, 69% in 2021, 63% in 2022. These nest success values were calculated through the proportion of nests that produced at least one successful fledgling from the panorama photos collected. Additionally, the multi-event model was not run on the IWMB data as the nesting season is significantly longer and more complex than the nesting colonies. For example, in the 2020 and 2021 nesting season this includes early breeders beginning in late May-June, followed by a secondary wave of later breeders beginning in late July (Appendix A).

3.3.2. Predation

As the photo collection process differed between the IWMB and the two cliff nesting sites, predation pressure cannot be compared between the natural and man-made sites. However, it can be noted that there were no visible flushing events on the IWMB and no acts of predation directly upon the colony while panorama photos were taken over 45 minutes, three times a week. One instance of predation by a Bald Eagle on an adult PECO was documented from the data collection site on July 10, 2022, however, it was not seen if the cormorant was taken from the bridge, water, or sky (Figure 17).

Figure 17. A picture showing the predation of a PECO by a Bald Eagle from the IWMB site, North Vancouver, British Columbia, June 10th, 2022.

Chapter 4. Discussion

4.1. Mitlenatch Island

The photos collected from the GoPro in 2022 confirmed that despite observing an egg, the nests at Mitlenatch Island were predated upon too many times to successfully fledge young. My camera images captured predation by crows and the presence of gulls which are known predators of seabird eggs (Carle et al. 2017). Predation of eggs was facilitated for secondary consumers from nest flushing by Bald Eagles. Most of the predator presence and flushing events occurred in the first half of the nesting season when eggs were present, suggesting eggs are being targeted by predators. These flushing and predator presence results are similar to Wilkin's (2022) where it was reported that of the 35 days of the GoPro captured photos, 34 days had at least one instance of the entire DCCO colony flushing leaving the eggs exposed. Of the 35 days, 26 included at least one Bald Eagle sighting (Wilkin 2022). This amount of flushing may have also affected breeding effort in adults as nest attendance through the assessed images which suggested the mean proportion of incubators in nests was 58% throughout the period of active incubation.

When installing the GoPro at Mitlenatch Island on April 19th, 2022, a Bald Eagle nest was observed on the island, however, it is not known if this is the only source of Bald Eagle presence at Mitlenatch. In fact, Great Blue Herons (*Ardea herodias fannini*) in the Pacific Northwest have been seen to nest within the vicinity of Bald Eagles to receive protection from predation by other Bald Eagles outside their territory (Jones et al. 2013). This shows an intricate relationship between Bald Eagles and their prey, and a thorough study would need to be completed to understand the predator interactions with the DCCO colony at Mitlenatch Island. Such studies could include more research on the behaviour of Bald Eagles in the area and in person monitoring to see the mechanism of flushing events for the whole colony.

4.2. Gabriola Island

Although the Gabriola Island DCCO colony experienced moderate to low breeding success with values of 46%, 34%, and 20% throughout the years studied, it is still an important natural nesting site for the DCCO within the Strait of Georgia by contributing to species productivity with 205 nests counted in 2022. This colony has tripled in size since 2014 when 64 DCCO nests counted (Carter et al. 2018). Overall, more years of data collection are needed to understand if the Gabriola Seacliff colony is a population sink, or if it is continually growing as a source of new generation recruits. Further research could also include the installation of more cameras to incorporate more nests into the study.

4.2.1. Predation

Predator presence is currently the strongest hypothesis for the cause of the low breeding success in the year 2022 at Gabriola Island compared to 2020 and 2021. The amount of predation pressure was substantially different between the three years analyzed with only 2022 experiencing predator presence and extensive nest failures at Gabriola. Disruption to the colony was seen through the number of flushing events that occurred in the to-be-abandoned nests at the beginning of the nesting season, and the year 2022 was the first year that recorded predation of DCCO young. In the year 2020, there were no apparent predator sightings through the photos collected, and zero flushings events (Ong 2021). This is the same for the photos that were able to be captured during the 2021 nesting season. However, this remains a theory as the Gabriola Island camera failed to capture the colony at an angle which would allow for information on predators that flew by.

Further photogrammetric data collection at the Gabriola Island DCCO colony will be able to offer a greater understanding on the strength of the relationship between predation presence and nest success, and if the colony will continue to experience predation pressure. Further research involving the installation of more cameras to include more nests in the study particularly in locations with a field of view that covers different nests to see which predators pass by, how often, and how their interactions with the colony affect breeding success.

4.2.2. Chick care and nest phenology

Although chicks were seen on average 34 days before fledging in 2020 and 37.8 days in 2022, the length of chick care is likely longer as chicks are hidden beneath a parent when they are very young and would not be captured by the camera. Even with an assumed extended period of chick care of 6-10 days, this length of chick care fits in with Moul & Gebauer's (2002) estimated length which said to be between 25 to 42 days.

There was moderate nest synchronicity within each year studied for the Gabriola Island DCCO colony and a large amount of variability seen between the nesting seasons each year. Gaston & Hipfner (2006) define a relatively synchronous colony as one that at least 50% of its eggs within one week of each other. For the DCCO at Gabriola, it is uncertain when their eggs are laid, however, fledging, under this definition, is relatively synchronous with at least 50% of the chicks present fledging within the same week. Additionally, Henny et al. described DCCO nesting as synchronous. However, within the Gabriola Island colony in 2022, there was an outlier nest (CL2A) which fledged one week before the rest of the colony I monitored (Appendix A).

The beginning of the nesting season in 2022 started 27 days after the 2021 season and 14 days after the 2020 season. It is suspected that the increase in predator presence and resulting flushing of the entire colony on multiple occasions at the beginning of nesting forced the colony to abandon nests and relay clutches, thus, delaying the nesting season in 2022. These results are similar to Sullivan (1998) who found that in 1993, Five Finger DCCO colony's nesting season was delayed three months due to multiple Bald Eagle flushing events. Delays in the breeding season can lead to decreases in nest success as bird species have adapted to lay eggs at a time that offers highest rate of prey availability, colonial protection, and non-inclement weather (Hällfors et al. 2020; Shipley et al. 2020). However, during this time of increasingly unstable environmental conditions including extreme weather, changes in planktonic patterns, and ocean warming, seabirds are likely to experience species specific effects (Sydeman et al. 2012). It is unknown how these climactic and oceanographic changes are linked with DCCO and their breeding success, however, environmental changes combined with predatory pressures could lead to further unstable and un-productive nesting occasions.

4.2.3. The probability of observing a chick, chick survival, egg survival, and hatching

These results for pC are important to the contribution to the monitoring and understanding of the DCCO within the Strait of Georgia as there is a lack of up-to-date information on the breeding biology of the species. A general increase in pC overtime shows that the optimal time to monitor a nesting colony for chick parameters, such as the number of offspring produced, is best to occur later in the nesting season. This is due to the higher visibility of young.

In order to restore wildlife populations, survival needs to be increased and/or reproductive output (the number of nestlings per nest) needs to be increased. Before restorative actions can be taken, it is important to understand current colony productivity. To understand DCCO chick survival at Gabriola Island, the multi-event capture-recapture model produced weekly estimates of model parameters. The weekly results for the probability of chick survival show a general trend of increasing over time (Figure 12). However, the year 2021 experienced a slight decline in chick survival during the week of June 15th along with the occurrence of chick death. As well, for the year 2022, values for chick survival were lower during the week of July 8th, or the first instance of a visible chick. This could be due to a lower egg survival or young nestling survival. These results show that DCCO chicks are most vulnerable to predation pressure within the earliest weeks after hatching. These low chick survival estimates also show how limitations leading to chick death can reduce the probability of colony wide chick survival.

The estimates of egg survival were highest in 2020 which aligns with the lowest instance of egg death/nest failure. This is followed by the year 2021, where there was one more occurrence of egg death than 2020. As well, for the year 2022, the model predicts the lowest probability of egg death as over half the nests failed. For the probability of an egg to hatch (psiEC), 2020 and 2021 had similar estimates of around 25%. In 2022, the hatching rates were less precise with estimates of 45% with 95% confidence intervals between 18% and 98%. Hatching probabilities results for 2022 are higher than 2020 and 2021 indicating that nests failed early such that any nests that wasn't predated at the egg stage, had a higher probability of surviving past the hatching transition. This aligns with the observation that there was higher predation and a large number of nest failures. Further studies on a wider number of nests would be helpful to understand these results further.

Overall, in most cases, the multi-event model was able to generate ecologically appropriate outputs for each year of data collected at Gabriola Island. This research is important as it reduces the need for human presence at monitoring sites through the implementation of remote cameras. It also shows that even without human presence, conclusions can be made about breeding parameters that are not visible through the use of multi-event modelling. As climate change persists, monitoring parameters such as chick survival and nest phenology over time will offer insights into the fecundity and restoration options for the DCCO.

4.2.4. Colony site topography and predator access

Through the data collected on predator interactions at the three sites, it is possible that the topography of each site and the structure of the IWMB affects the ability of predators to access DCCO nesting colonies. The colony at Mitlenatch Island is upon the top of a rounded cliff, where the highest number of Bald Eagles, crows, and gulls were seen. The shape of this site may allow easy access of predators to the DCCO nesting ground, such that, Bald Eagles could easily land and take off from the colony, and the nests are directly exposed from all vantage points. While at Gabriola Island, Bald Eagles, crows, and gulls were seen far less than Mitlenatch Island. It could be possible that the steepness of the Gabriola cliff contributed to more difficult access of predators. Furthermore, there were no flushing or predation events seen upon the IWMB for the duration of photo collection over a period of 45 minutes, three times a week. It is possible that the intricate structure of the bridge inhibits access of Bald Eagles, however, further studies would be needed to pursue this hypothesis.

4.3. Ironworkers Memorial Bridge

4.3.1. Nest Success and further limits on DCCO productivity

The overall average nest success for the IWMB for the three years studied is 60%, which is higher than nest success at both of the natural nesting sites. This level of nest success at the bridge, combined with the fact that is holds the largest DCCO colony within the Strait of Georgia shows that the IWMB is the most productive nesting site in the region. However, 60% is lower than nest success rates historically documented at natural nesting sites within the Salish Sea which were ~ 80% (Table 1). As Ong (2021), Wilkin (2022), and I observed no nest predation, this suggests that the IWMB offers protection from Bald Eagle predation unlike the natural rookeries at Gabriola and Mitlenatch Islands. The current state of nest success at the bridge may show that a limiting pressure exists for the DCCO nesting in this location, which is not related to predation pressure, however, more studies are needed to research this hypothesis. Richardson (2008) suggested that limits on DCCO productivity could be anthropogenically driven and include changes in prey abundance caused by mass fishing and/or changes in ocean temperature resulting in altered planktonic communities and therefore, altered energy transfer within the food chain. Additionally, the Strait of Georgia holds Canada's largest shipping port which can lead to multiple environmental hazards due to high vessel traffic including toxic pollution and noise pollution to the marine environment. There is currently a pattern of overall seabird population decline within the Strait of Georgia as seen in a study completed by Crewe et al. (2012) where it was found that between the years 1999 and 2012, 22 out of 57 seabird studied species were declining in the area. This could show that a source of non-specific species degradation is occurring within the region, and perhaps through monitoring the DCCO, we can get closer to uncovering the limiting factor(s).

4.4. Suggested restoration

This research shows there are likely at least two main potential pressures that the DCCO currently face within the Strait of Georgia. The first is predation pressure which is facilitated by a growing Bald Eagle population in British Columbia (Goulet et al. 2021). This pressure seems to be highest when chicks are most vulnerable, leading to lower probabilities of survival in the early stages of chick growth and overall low breeding success. The second is the creation of an ecological trap at the IWMB with the threat of exclusion for the bridge nesting colony. Other pressures may exist, and further studies are needed to uncover the relationship the DCCO have with current oceanographic factors within the Strait of Georgia.

Although predation pressure is likely the culprit of poor DCCO nest success at natural sites within the Strait of Georgia, a cause-and-effect experiment would be needed to identify the full impact of predation by Bald Eagles. This would include removing predation pressure from a nesting colony at a natural site. However, it is highly unlikely that predator restrictions would be placed upon a well-known species such as the Bald Eagle for the often-disparaged cormorant. Other studies on this topic could include studying the impacts Bald Eagles are having on other bird species nesting success across the Strait of Georgia. As well, an up to date, and continued, count of Bald Eagle populations should be undergone in order to understand the effects the current, and future, population size will have on the ecosystem they occupy.

At the IWMB discussions have occurred within the Ministry of Transportation and Infrastructure on the potential exclusion of the DCCO. However, the DCCO is listed as a species of special concern within British Columbia and is considered a species at risk. The removal of the DCCO from their largest nesting ground in the province will likely lead to further reductions in population without a plan in place to relocate the colony. Furthermore, population declines could lead the species to becoming listed as threatened within the province. In San Francisco, DCCO had been nesting upon the San Francisco-Oakland Bay Bridge and the Richmond-San Rafael Bridge, however when construction and maintenance occurred on the bridges, DCCO presence on the bridges was reduced by 71% and the Bay Area population declined by 39% (Rauzon et al. 2019). This shows that even with nests remaining on the bridge, there was still a substantial decrease in DCCO population in the Bay Area. Therefore, fully excluding DCCO from the IWMB could result in substantial reductions for the at-risk species. Actions taken to remove the DCCO from nesting on the IWMB due to concern over the impact their acidic guano has on its structural integrity would be unfounded due to the lack of evidence on the subject. In order to understand if the DCCO have any impact on the steel beams of the bridge, a study should be completed to show the effects of guano on steel.

If exclusion occurs on the IWMB, the question remains as to where the nesting DCCO will go. It is assumed that cormorants began nesting on the bridges within the City of Vancouver due to the degradation of their natural nesting sites. If the bridge colony is excluded, cormorants may be pushed to nest in areas that are less favourable to human residents of the city and potentially create more significant issues. Without a plan for restoring degraded nesting habitat, there will likely be negative results for the DCCO. One options to combat this is to create “Cormorant Condos”. Cormorant condos include a metal scaffolding that can be installed along the IWMB to replace nesting sites after bridge exclusion. This has successfully been implemented at the San Francisco, Oakland Bay Bridge. The condos are made up of a continuous 2.5-foot-wide steel platform upon which the DCCO nest (Rauzon et al. 2019). The DCCO within San

Francisco only began to nest up the condos when their bridge nesting sites became fully excluded. In order to coax the DCCO to the condos, decoy DCCOs, call-play backs, and artificial nests could be used following methods described in Rauzon et al. (2019). Cormorant condos could be created for the IWMB which would offer a permanent solution for this human-wildlife conflict.

In British Columbia, there are some provincially listed species that lack federal listing through SARA. One such species is the DCCO. Currently there is a no legislation that offers protection for these provincially listed species. British Columbia is currently working on creating such legislation that will uphold laws in order to protect provincially listed species and make it mandatory to produce a recovery action plan (Ministry of Environment and Climate Change Strategy 2018). Additionally, cormorants do not receive protection under the Migratory Bird Convention Act and their nests are not protected by British Columbias Wildlife Act while inactive (Migratory Bird Convention Act 1994; Wildlife Act 1996).

4.5. Study considerations and further work

This work is in the beginning stages of a potential long-term study which leads to advantages and disadvantages in regard to data collection and analysis. Advantages include that baseline monitoring methods have already been created, leaving more time to uncover new ideas within the data such as breeding success. However, more years of data will result in a more robust understanding of the DCCO relationship with the Strait of Georgia. Considerations or limitations within this study include that a subset of the nest population was analysed at Gabriola where 17% of the total nests within the colony were monitored. Future studies may benefit by installing more cameras on Gabriola to monitor more nests in a different location within the cliff colony. Additionally, the project would benefit through installing more cameras at other colonies such as Mandarte Island, and or, completing at least one entire annual survey for DCCO colonies within the Strait of Georgia.

Limitations that occurred for the multi-event model include that the probability of egg survival and hatching were not indexed for each week and only one output that described the entire nesting season was produced. In reality, it is possible egg survival would change throughout the nesting season and even more likely that the probability of hatching would decrease after all chicks had hatched. Changes to the model are not expected to change my estimates of breeding success, only to provide greater flexibility in understanding survival in the different life stages. More data would be required to include these additional parameters.

At the IWMB, panoramas for Span 1A only began on July 6th, 2022, therefore, a nest counts for the entire bridge before this date will have a lower sum and counts occurring after this date will be higher. Although dates after July 6th, 2022 will have a higher nest count number, the project would benefit by continually adding Span 1A into the total nest counts to get a more robust count for the total colony population. Additionally, the IWMB was not modelled using the multi-event model as the bridge's breeding season is more complex with a longer nesting season that has multiple intervals of chick presence and fledging due to an overall higher level of asynchronous breeding. In order to compare the probability of chick observation and chick survival at the bridge to the natural sites, a more complete model that does not make the assumption of synchronicity in egg laying and incubation will have to be designed.

Future studies could include other factors of population limitation including changes in prey abundance. In order to research this, foraging locations for the DCCO within the Strait of Georgia could be located by fitting individuals with biologging devices which would offer information on ocean temperature, depth of dives, and locations of foraging. Such work has been successfully completed by Peck-Richardson et al. (2018) in Oregon and Washington for the DCCO in that region.

4.6. Conclusion

This research aimed to better understand limitations in the breeding season for the DCCO within the Strait of Georgia at multiple locations that represented different colony topographies. Additionally, this study gives an idea of the variable to poor nest success and productivity within natural nesting sites to highlight the significance of the IWMB for the breeding DCCO population in the Strait of Georgia. It was found that breeding success has been low within natural sites as seen through the repeated failure at Mitlenatch Island and low breeding success calculated for Gabriola Island in 2022. Additionally, egg and chick death is highest during the earliest stage of incubation and therefore, the colony is more prone to impacts through predation early in the season. A major contributor to low breeding success is the presence of Bald Eagles and the predation they facilitated for opportunistic predators such as crows and gulls at DCCO colonies. Due to the current state of breeding for the DCCO at their natural nesting sites, it is likely that the Strait of Georgia population may experience a decline in DCCO if the bridge is to be excluded and the natural rookeries continue with the observed rates of predation. However, further studies are needed to understand other possible limitations such as prey availability and oceanographic factors.

Although Bald Eagle pressure is likely to have impacts on the breeding season of DCCO at their natural nesting sites, and more specifically, the early breeding season as seen in the model outputs, it is unlikely restrictions will be put in place on Bald Eagle predation. Therefore, restoration suggestions are focused on the management of the IWMB by the province. Cormorants may be selecting to nest more regularly on bridges in the City of Vancouver as they have been pushed out of their natural nesting habitat due to degradation through development and/or increases in disturbance. Another hypothesis is that the bridges offer protection from predation. If the IWMB is to become excluded, questions arise on where they will be displaced to, and where will they find nesting platforms. Are natural nesting sites below carrying capacity or will DCCO attempt to create another nesting site within the urbanized area. This will have population level effects for the DCCO as the species will be reliant on the natural nesting sites to uphold the population, while leaving ~350 breeding pairs without a nesting site. Due to variability in the DCCO natural nesting sites, there is the possibility for greater losses to the population if adequate nesting site(s) cannot be found for the bridge colony.

Although, DCCO are faced with limitations to their nesting habitat such as predation, degradation, and human-wildlife conflict, the species has shown resilience. This can be seen in the ability to adapt to novel nesting sites at urban bridges within Vancouver. This also occurred while the DCCO population at the East Sands Island was being controlled and reduced beginning in 2015 (Turecek et al. 2019). About 1,700 breeding pairs from the island eventually moved to the Astoria-Megler Bridge by 2018 (Turecek et al. 2019). These events show the species ability to quickly change nesting locations after impacts have reduced the ability to nest.

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Wilkin R (2022) Developing new methods for monitoring Double-crested Cormorant nesting colonies in the Strait of Georgia. Master's Thesis, Simon Fraser University, Burnaby, BC https://www.sfu.ca/~rjoy/Rose%20ARP%20FINAL%20final.pdf (accessed 7 November 2022)

Wires L, Cuthbert F (2006) Historic Populations of the Double-crested Cormorant (*Phalacrocorax auritus*): Implications for Conservation and Management in the 21st Century. *Waterbirds* 29:9–37

Appendix A. Daily nest states from Gabriola Island GoPro data and the Ironworkers Memorial Bridge

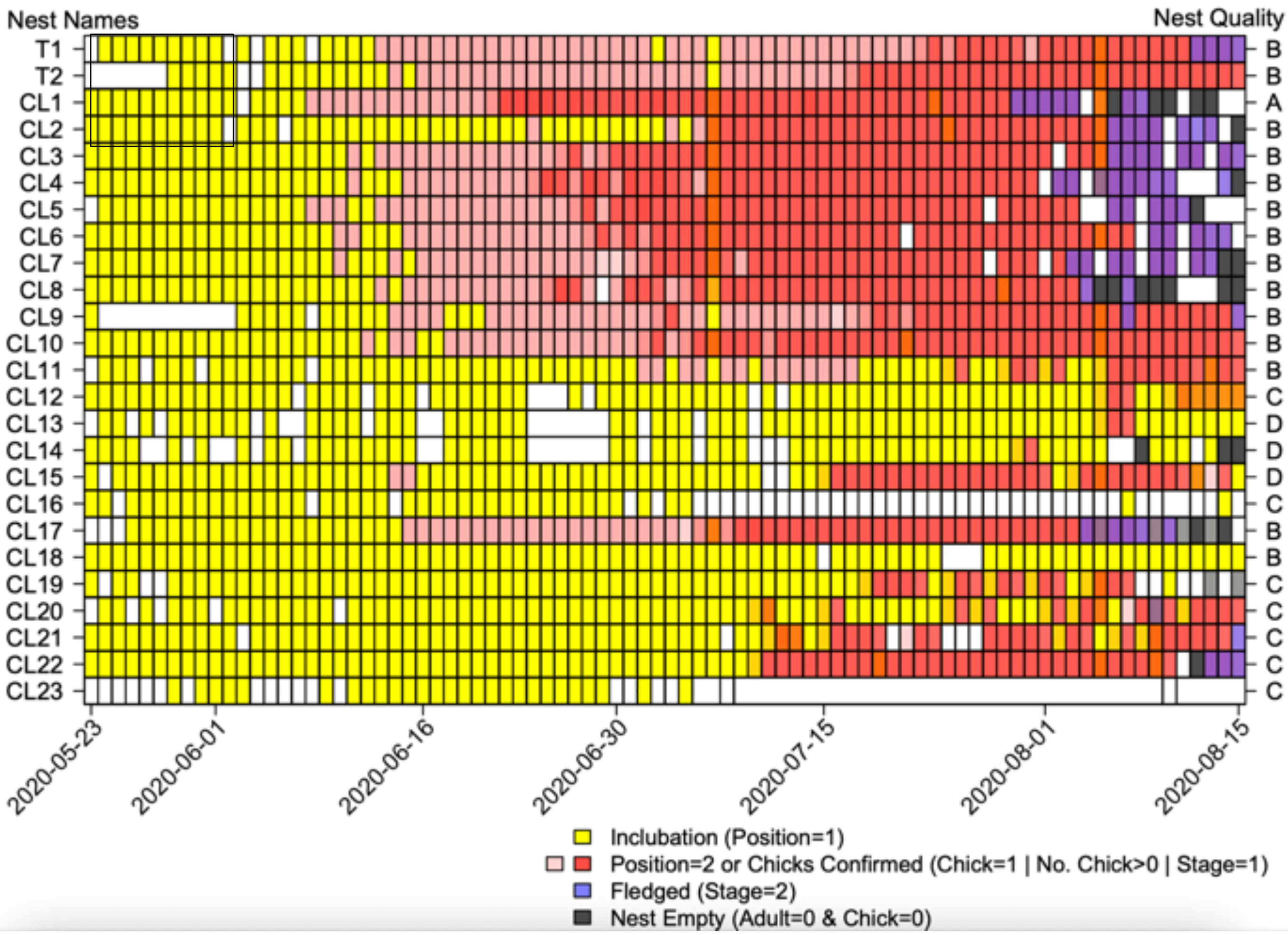

Figure A-1. Data collected from the GoPro photos for each day of the 2020 DCCO nesting season at Gabriola Island, British Columbia. An adult was assumed to be incubating an egg/chick which is denoted by yellow. Red shows positive sightings for a chick in a nest, purple is the occurrence of fledging, and white is an empty nest.

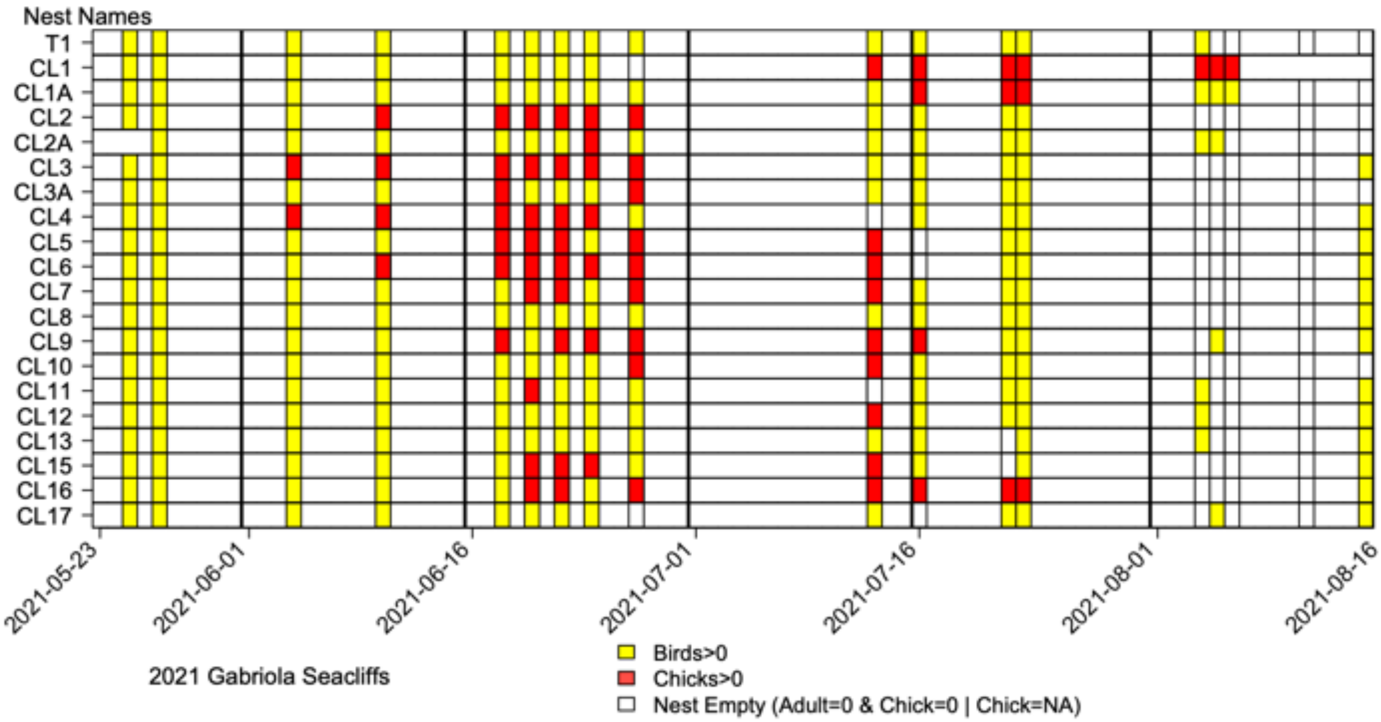

Figure A-2. Data collected from the GoPro photos taken in 2021 at Gabriola Island, British Columbia. Out of 84 days of GoPro camera monitoring, the camera collected data on 18 days. Due to camera malfunctions, these dates were all that contributed to our 2021 hidden Markov model. Yellow represents an adult in the nest, red representing a chick in the nest, white squares represent an empty nest, and white space represents no data collected.

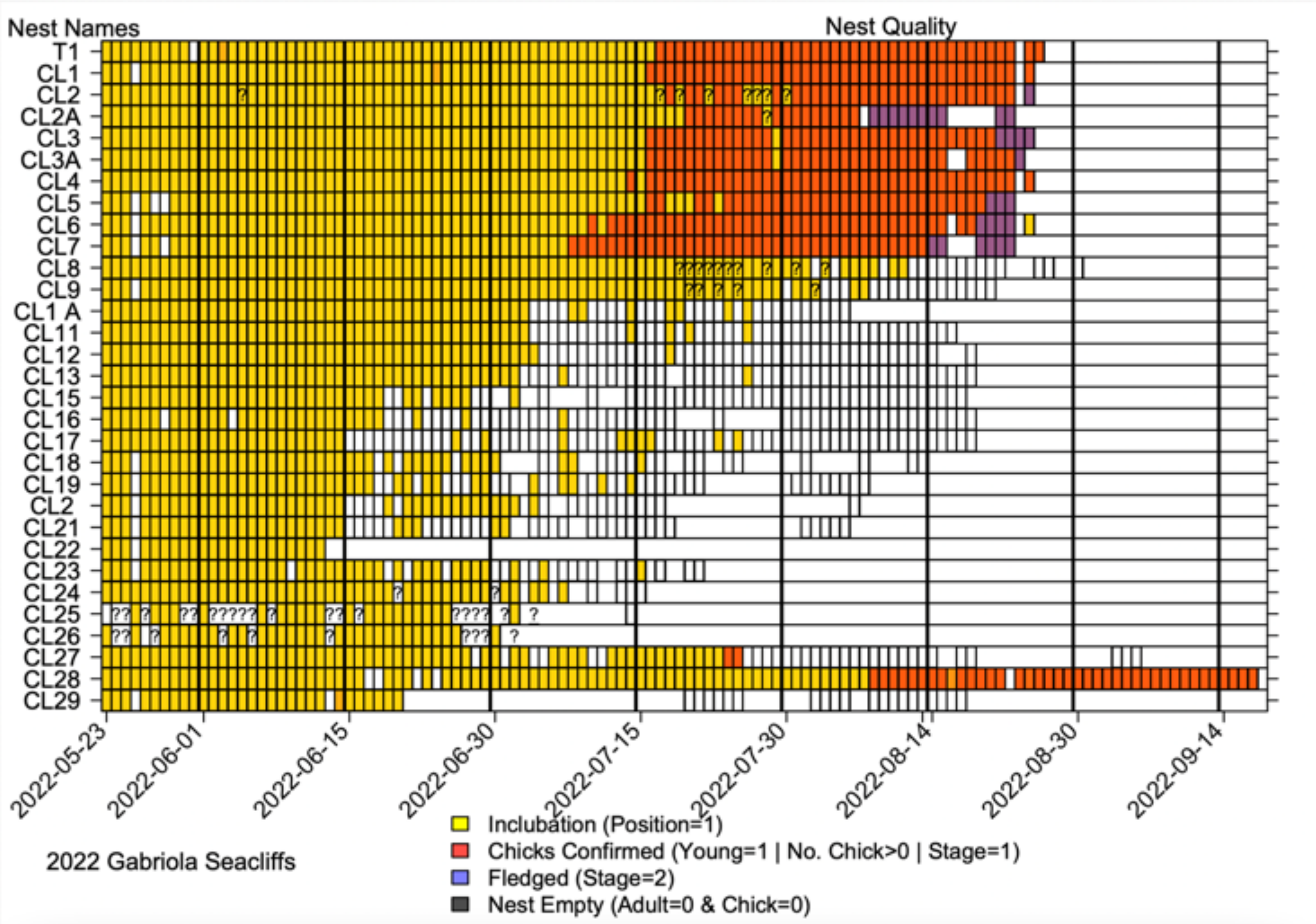

Figure A-3. Data collected from the GoPro photos for each day of the 2022 DCCO nesting season at Gabriola Island, British Columbia. An adult was assumed to be incubating an egg/chick which is denoted by yellow. Red shows positive sightings for a chick in a nest, purple is the occurrence of fledging, and white is an empty nest. There was difficulty in determining the state of nests with a question mark (?).

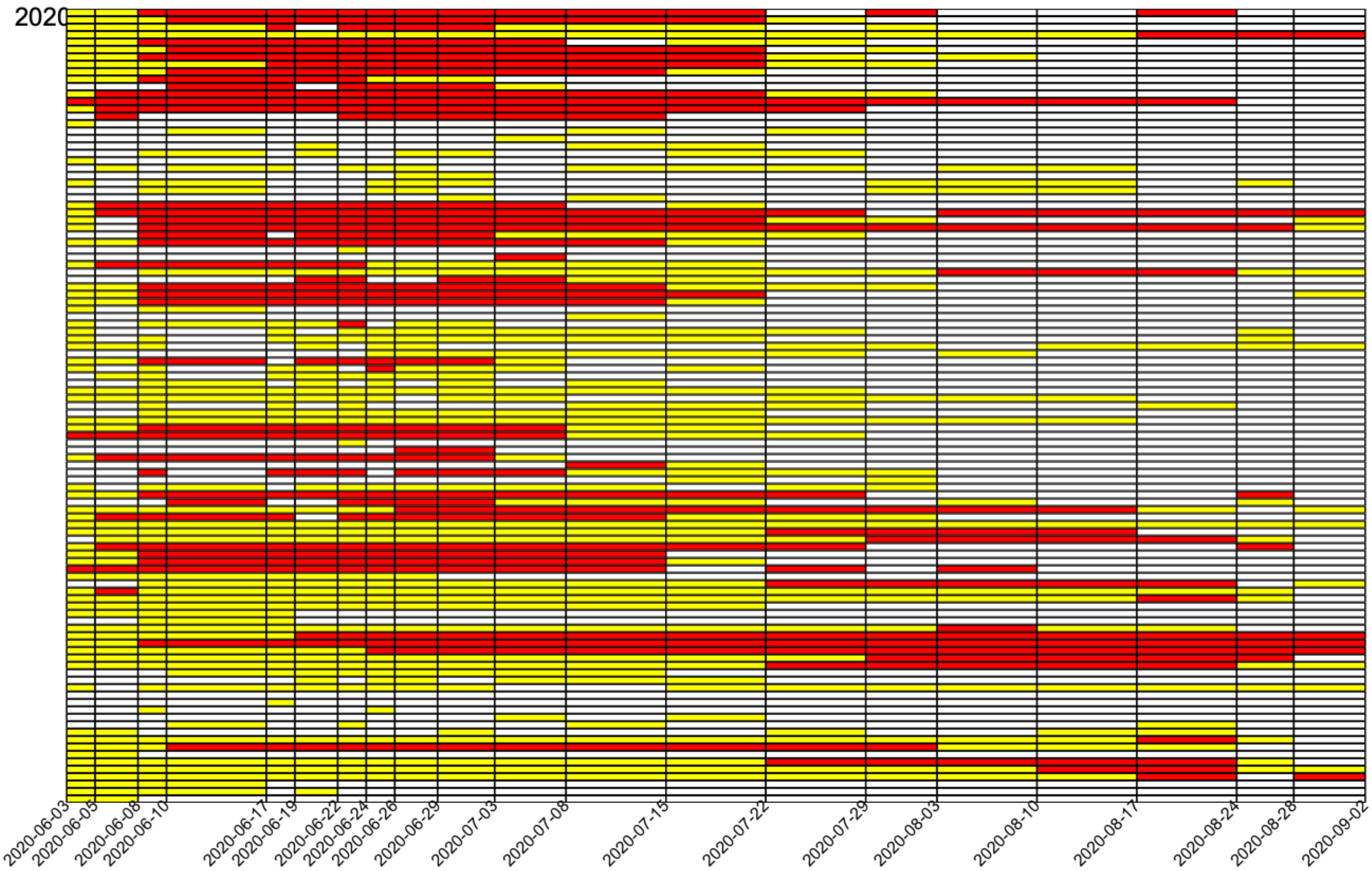

Figure A-4. Daily nest states for the IWMB, British Columbia, where panorama photos were taken up to 3 times a week in the year 2020. An adult was assumed to be incubating an egg/chick which is denoted by yellow, red shows positive sightings for a chick in a nest, and white represents an empty nest. Nest data for this year was taken from Span 1B and 2, where 309 nests were followed through the progression of the breeding season.

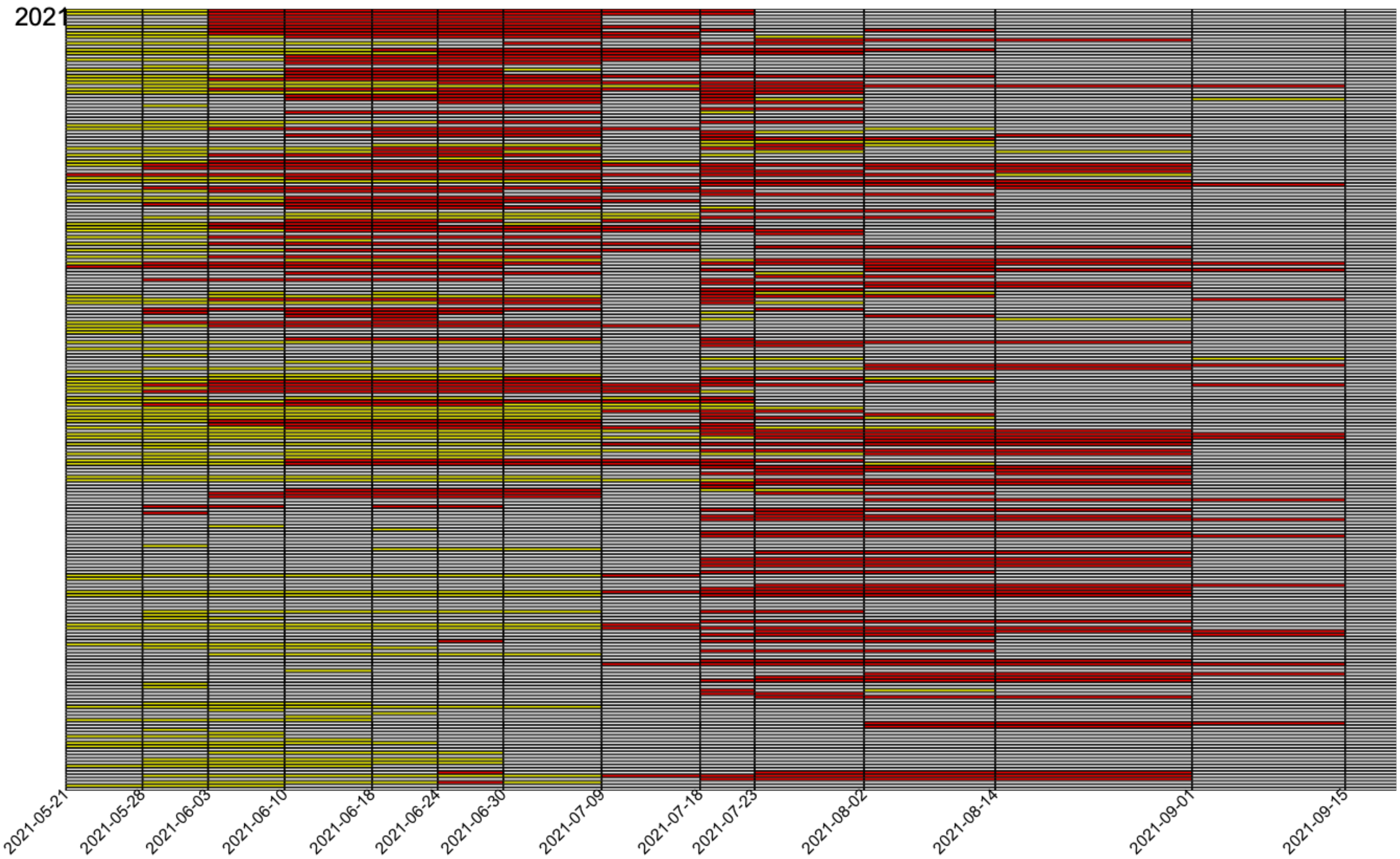

Figure A-5. Daily nest states for the IWMB, British Columbia, where panorama photos were taken up to 3 times a week in the year 2021. An adult was assumed to be incubating an egg/chick which is denoted by yellow, red shows positive sightings for a chick in a nest, and white represents an empty nest. Nest data for this year was taken from Span 1B and 2, where 345 nests were followed through the progression of the breeding season.

Appendix B. GoPro images

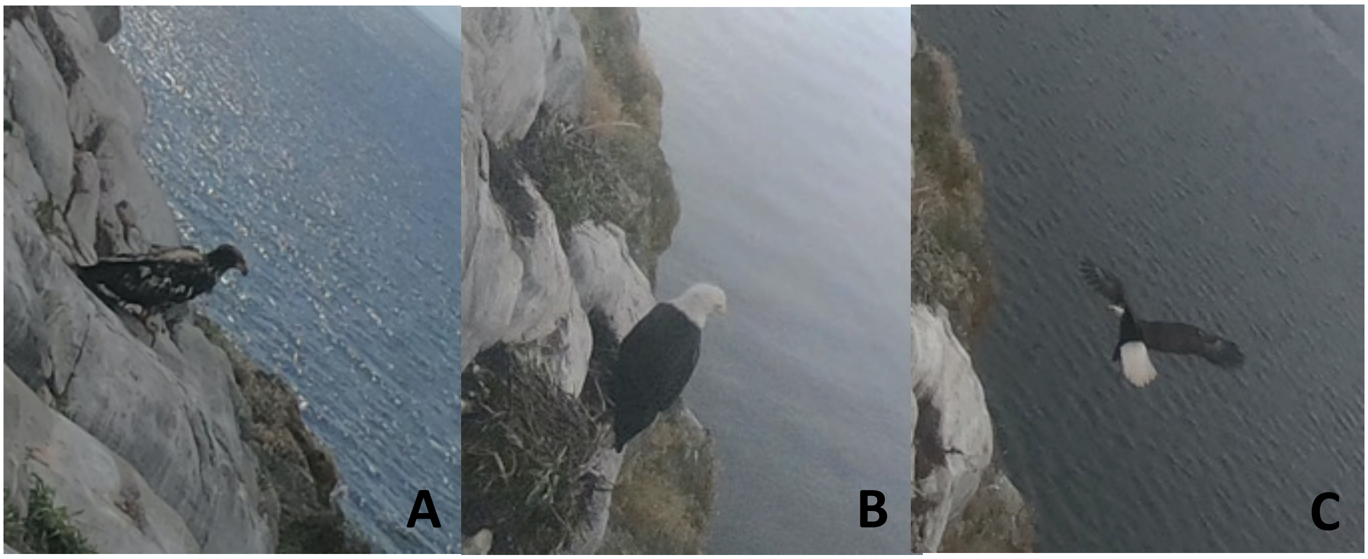

Figure B-1. A collection of photos which show some of the Bald Eagle presence at Mitlenatch Island, British Columbia during the 2022 nesting season. Photo A was taken on June 02,2022, at 9:31 am, photo B was taken on June 07, 2022, at 8:01 am, and photo C was taken on June 08, 2022, at 9:32 am. In each photo present the entire DCCO colony flushed.

Figure B-1. A photo taken from the GoPro camera at Mitlenatch Island, British Columbia, on June 10, 2022, 4:30 pm. This photo shows the entire DCCO colony flushing their nests.

Appendix C. Labelled Gabriola Island diagram

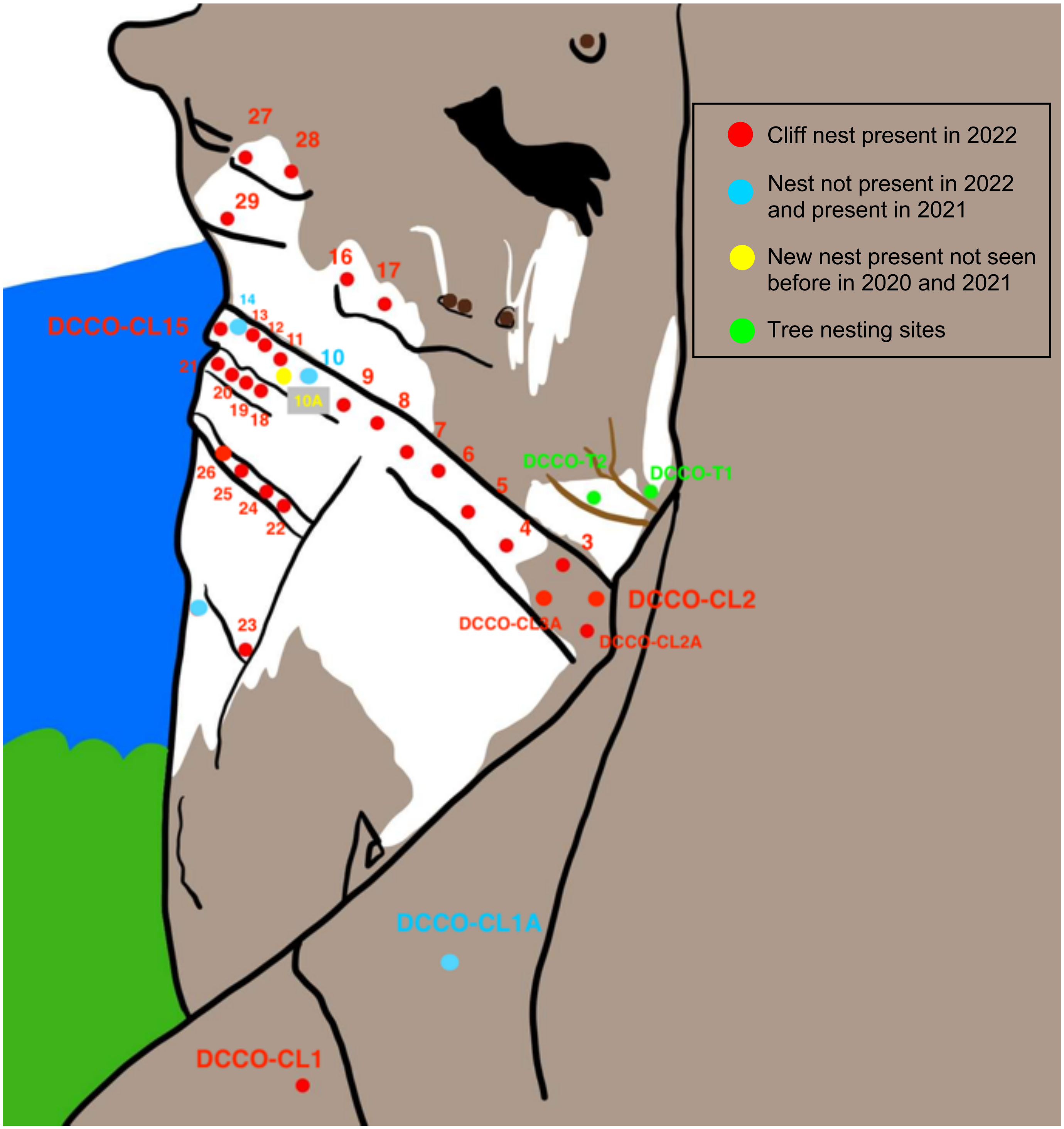

Figure C-1. A labelled diagram of the Gabriola Island, British Columbia nesting sites based on the previous two years of data collection in 2020 and 2021. Each cliff nesting site is labelled at DCCO-CL# and each tree nesting site is labelled as DCCO-T#.

Appendix D. Raw data for model

2020

	Session 4	Session 5	Session 6	Session 7	Session 8	Session 9	Session 10
DCCO-T1	1	1	1	1	1	2	2
DCCO-T2	1	1	1	1	2	2	2
DCCO-CL1	1	2	2	2	2	2	2
DCCO-CL2	1	1	1	2	2	2	2
DCCO-CL3	1	2	2	2	2	2	2
DCCO-CL4	1	2	2	2	2	2	2
DCCO-CL5	1	2	2	2	2	2	2
DCCO-CL6	1	1	2	2	2	2	2
DCCO-CL7	1	1	2	2	2	2	2
DCCO-CL8	1	2	2	2	2	2	2
DCCO-CL9	1	1	2	2	2	2	2
DCCO-CL10	1	1	2	2	2	2	2
DCCO-CL11	1	1	1	1	2	2	2
DCCO-CL12	1	1	1	1	1	1	1
DCCO-CL13	1	1	1	1	1	1	1
DCCO-CL14	1	1	1	1	1	1	2
DCCO-CL15	1	1	1	1	2	2	2
DCCO-CL16	1	1	1	3	3	3	3
DCCO-CL17	1	1	1	2	2	2	2
DCCO-CL18	1	1	1	1	1	1	1
DCCO-CL19	1	1	1	1	1	1	1
DCCO-CL20	1	1	1	1	2	2	2
DCCO-CL21	1	1	1	1	2	2	2
DCCO-CL22	1	1	1	1	2	2	2
DCCO-CL23	1	1	3	3	3	3	3

2021

Nests	Session 2	Session 3	Session 4	Session 5	Session 6	Session 7	Session 8
T1	1	1	1	1	1	1	3
CL1	1	1	1	1	1	2	2
CL1A	1	1	1	1	1	3	3
CL2	1	2	2	2	2	2	2
CL2A	1	1	1	2	3	3	3
CL3	1	2	2	2	2	2	2
CL3A	1	1	2	2	2	2	2
CL4	1	2	2	2	2	2	2
CL5	1	1	2	2	2	2	2
CL6	1	2	2	2	2	2	2
CL7	1	1	1	1	2	2	2
CL8	1	1	1	1	1	1	3
CL9	1	1	2	2	2	2	2
CL10	1	1	1	1	2	2	2
CL11	1	1	2	3	3	3	3
CL12	1	1	1	1	1	2	2
CL13	1	1	1	1	1	1	3
CL15	1	1	1	2	2	2	2
CL16	1	1	1	1	2	2	2
CL17	1	1	1	1	3	3	3

2022

	Session6	Session7	Session8	Session9	Session10
DCCO-T1	1	1	1	1	2
DCCO-CL1	1	1	1	1	2
DCCO-CL2	1	1	1	1	2
DCCO-CL2A	1	1	1	1	2
DCCO-CL3	1	1	1	1	2
DCCO-CL3A	1	1	1	1	2
DCCO-CL4	1	1	1	2	2
DCCO-CL5	1	1	1	1	2
DCCO-CL6	1	1	1	2	2
DCCO-CL7	1	2	2	2	2
DCCO-CL8	1	1	1	1	1
DCCO-CL9	1	1	1	1	1
DCCO-CL10A	1	1	3	3	3
DCCO-CL11	1	1	3	3	3
DCCO-CL12	1	1	3	3	3
DCCO-CL13	1	1	3	3	3
DCCO-CL15	3	3	3	3	3
DCCO-CL16	3	3	3	3	3
DCCO-CL17	3	3	3	3	3
DCCO-CL18	3	3	3	3	3
DCCO-CL19	3	3	3	3	3
DCCO-CL20	3	3	3	3	3
DCCO-CL21	3	3	3	3	3
DCCO-CL22	3	3	3	3	3
DCCO-CL23	1	3	3	3	3
DCCO-CL24	1	1	3	3	3
DCCO-CL25	1	3	3	3	3
DCCO-CL26	1	3	3	3	3
DCCO-CL27	1	1	1	1	1
DCCO-CL28	1	1	1	1	1
DCCO-CL29	3	3	3	3	3

Appendix E. Multi-event model

```
library(tidyverse)
library(nimble)
library(MCMCvis)

data=read.csv("/Users/rachelstapleton/Documents/Cormorant/csv used/Weekly2020
1.4.csv")
{data[i,j]=2}}}
head(data)

yy = data
yy = (yy[,which(substr(dimnames(yy)[[2]],1,4)=='Sess')])
y = apply(yy, 2, as.numeric)
dim(y)
head(y)
tail(y)


hmm.cormorants4 <- nimbleCode({
 # priors

 # priors
 phiE ~ dunif(0, 1)  # prior survival egg time 1
 psiEC ~ dunif(0, 1) # prior transition egg to chick



 delta[1] <- 1 # Pr(alive t = 1) = 1
 delta[2] <- 0 # Pr(dead t = 1) = 0
 delta[3] <- 0 # Pr(dead t = 1) = 0

 for (t in 1:(K-1)){
  phiC[t] ~ dunif(0, 1) # prior survival
  gamma[1,1,t] <- phiE * (1 - psiEC)   # Pr(H t -> H t+1)
  gamma[1,2,t] <- phiE * psiEC      # Pr(H t -> I t+1)
  gamma[1,3,t] <- 1 - phiE        # Pr(alive t -> dead t+1)
  gamma[2,1,t] <- 0                                    # Pr(I t -> H t+1)
  gamma[2,2,t] <- phiC[t]                              # Pr(I t -> I t+1)
  gamma[2,3,t] <- 1 - phiC[t]        # Pr(alive t -> dead t+1)
  gamma[3,1,t] <- 0           # Pr(dead t -> alive t+1)
  gamma[3,2,t] <- 0           # Pr(dead t -> alive t+1)
  gamma[3,3,t] <- 1           # Pr(dead t -> dead t+1)
  pC[t] ~ dunif(0, 1) # prior detection
  omega[1,1,t] <- 1                  # Pr(E t -> non-detected t)
```

```
  omega[1,2,t] <- 0                  # Pr(E t -> detected H t)
  omega[1,3,t] <- 0                                    # Pr(E t -> detected U t)
  omega[2,1,t] <- 1 - pC[t]      # Pr(C t -> non-detected t)
  omega[2,2,t] <- pC[t]        # Pr(C t -> detected H t)
  omega[2,3,t] <- 0                 # Pr(C t -> detected I t)
  omega[3,1,t] <- 0       # Pr(F t -> non-detected t)
  omega[3,2,t] <- 0       # Pr(F t -> detected H t)
  omega[3,3,t] <- 1       # Pr(F t -> detected I t)
 }
 # likelihood
 for (i in 1:N){
  z[i,first[i]] ~ dcat(delta[1:3])
  for (j in (first[i]+1):K){
   z[i,j] ~ dcat(gamma[z[i,j-1], 1:3, j-1])
   y[i,j] ~ dcat(omega[z[i,j], 1:3, j-1])
  }
 }
})

#'
#' Get the date of first capture.
## ---------------------------------------------------------------------------
first <- apply(y, 1, function(x) min(which(x !=0)))
my.constants <- list(N = nrow(y), K = ncol(y), first = first)
my.data <- list(y = y + 0)
# ---------------------------------------------------------------------------
zinit <- y
for (i in 1:nrow(y)) {
 for (j in 1:ncol(y)) {
  if (zinit[i,j]==3) zinit[i,j]=sample(c(1,2), 1) # time units
  if (j < first[i]) {zinit[i,j] <- 0}
 }
}
zinit <- as.matrix(zinit)
# zint <- y

initial.values <- function() list(phiC = runif((ncol(data)-1), 0, 1),
              phiE = runif(1, 0, 1),
              pC = runif((ncol(data)-1), 0, 1),
              psiEC = runif(1, 0, 1),
              z = zinit)
# ---------------------------------------------------------------------------
parameters.to.save <- c("phiE",
          "phiC",
          "pC",
          "psiEC")
```

```
# "z"
# "beta",
# "pC_bad", "pC_good")
# "z") # id you want WAIC (see below)
#           "psiCF")
n.iter <- 75000
n.burnin <- 25000
n.chains <- 2

out.4 <- nimbleMCMC(code = hmm.cormorants4,
        constants = my.constants,
        data = my.data,
        inits = initial.values,
        monitors = parameters.to.save,
        niter = n.iter,
        nburnin = n.burnin,
        nchains = n.chains,
        WAIC = TRUE) # this only works if z converges

# WAIC: The computed WAIC, on the deviance scale. Smaller values are better when
comparing WAIC for two models.
# lppd: The log predictive density component of WAIC.
# pWAIC: The pWAIC estimate of the effective number of parameters, computed using
the pWAIC2 method of Gelman et al. (2014).
out.4$WAIC$WAIC; out.4$WAIC$lppd; out.4$WAIC$pWAIC


# index
index = substr(dimnames(out.4$samples$chain1)[[2]],1,1)!='z'
apply(out.4$samples$chain1[,index],2,quantile,c(.5,.025,.975), na.rm=T)
apply(out.4$samples$chain2[,index],2,quantile,c(.5,.025,.975), na.rm=T)

dev.off()
quartz(height=4, width=8)
par(mfrow=c(1,1), oma=c(4,4,4,1), mar=c(0,0,0,0))
plot(1:sum(index), rep(.5,sum(index)), type='n', axes=F, ylim=c(0,1), ylab='Parameter
Estimate and 95% Conf Interval', xlab='', cex=.8)
abline(h=seq(.0,1,.2),lwd=.5, col='grey80')
points (1:sum(index), apply(out.4$samples$chain2[,c(1:sum(index))],2,quantile,c(.5),
na.rm=T), pch=16, col=rainbow(1), cex=1.2)
for (i in 1:sum(index)) {lines(c(i,i),
          apply(out.4$samples$chain2[,c(1:sum(index))],2,quantile,c(.025,.975),
na.rm=T)[,i],
          col=rainbow(1),
          lwd=3)
}
```

```
box()
axis(2, las=2)
axis(3, at=1:sum(index), label=F)
# axis(1, at=1:sum(index),
label=dimnames(apply(out.4$samples$chain2[,1:sum(index)],2,quantile,c(.025,.975),
na.rm=T))[[2]], cex.axis=.8)
text(1:sum(index), rep(1.12, sum(index)),
  label=dimnames(apply(out.4$samples$chain2[,1:sum(index)],2,quantile,c(.025,.975),
na.rm=T))[[2]],
  cex=.8, srt=45,xpd=NA, adj=0)
axis(1, at=1:sum(index), label=F)
text(1:sum(index), rep(-0.14, sum(index)),
  label=dimnames(apply(out.4$samples$chain2[,1:sum(index)],2,quantile,c(.025,.975),
na.rm=T))[[2]],
  cex=.8, srt=45,xpd=NA, adj=1)

text(7, 1.3, adj=1,xpd=NA, paste0("out.3 with dim(data) = 25 x ",ncol(data)))
```

Appendix F. Confidence intervals for model outputs

2020

		50	2.5	97.5
pc		50	2.5	97.5
	15-Jun	0.7492927	0.3510195	0.9858088
	23-Jun	0.8837416	0.57289	0.9956498
	01-Jul	0.8845159	0.5944006	0.9947551
	08-Jul	0.9594913	0.802515	0.9983107
	15-Jul	0.9627008	0.8181317	0.9986664
	23-Jul	0.96297	0.8205346	0.9986078
phic				
	15-Jun	0.49945914	0.02518655	0.97572105
	23-Jun	0.8737059	0.5242185	0.9947642
	01-Jul	0.9231183	0.6699414	0.9968627
	08-Jul	0.948494	0.760294	0.998164
	15-Jul	0.9613602	0.8100988	0.9984617
	23-Jul	0.963846	0.8291278	0.9984989
phiE		0.9731911	0.9731911	0.9973497
psiEC		0.2544232	0.1664369	0.3619753

2021

pc				
	01-Jun	0.7429048	0.3216191	0.9847696
	08-Jun	0.8920183	0.5808892	0.995849
	15-Jun	0.8894961	0.5927327	0.9951863
	23-Jun	0.9258937	0.6773977	0.997346
	01-Jul	0.9483068	0.7492144	0.9981911
	08-Jul	0.9501668	0.7681652	0.9980489
phic				
	01-Jun	0.50892007	0.02484632	0.97589456
	08-Jun	0.8924989	0.5340832	0.995581

	15-Jun	0.8292456	0.5231167	0.9733887
	23-Jun	0.8380507	0.5574517	0.9745739
	01-Jul	0.94266	0.7313331	0.9980665
	08-Jul	0.9476308	0.7559889	0.9979125
phiE		0.917099	0.8328697	0.9694778
psiEC		0.2614891	0.1596165	0.3847398

2022

pc				
	01-Jul	0.1695062	0.0222491	0.719771
	08-Jul	0.15380588	0.02117791	0.55894089
	15-Jul	0.28834897	0.09207309	0.63149469
	23-Jul	0.7800858	0.494871	0.9880703
phic				
	01-Jul	0.50062906	0.02246862	0.97305477
	08-Jul	0.7531941	0.2702858	0.9830914
	15-Jul	0.9371061	0.6566011	0.9976885
	23-Jul	0.9454553	0.7194823	0.9980727
phiE		0.6719368	0.4727332	0.8151136
psiEC		0.4527784	0.1729626	0.9621985