Assessing the number of known-age chicks required for accurate age estimation of growing Atlantic Puffin (*Fratercula arctica*) and Razorbill (*Alca torda*) chicks

by

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ABSTRACT

At Machias Seal Island, chick age is used to estimate hatch dates and predict fledge dates of growing seabirds. A small percentage of chicks have a known hatch date, as the number of nest checks required to capture hatch date is limited to reduce colony disturbance. The goal of this study is to find the minimum number of known-age chicks required to accurately estimate ages of unknown-age chicks in Atlantic Puffins (*Fratercula arctica*) and Razorbills (*Alca torda*). To do this, I collected measurements of known-age chicks from the time series at MSI (1995-2021), separated these data into training and test datasets, created a series of annual linear growth models, estimated the ages of known-age chicks, and calculated the accuracy of these estimates. My results suggest that a minimum of three chicks are required to estimate chick age with 85% accuracy of puffins and four chicks for 80% accuracy in Razorbills.

DEDICATION

I would like to dedicate this to my parents for their constant support, my partner for his encouragement, and my friends who have been my second family over the past four years.

ACKNOWLEDGEMENTS

First, I would like to thank my mentor Dr. Heather Major for her guidance, patience, and support throughout the year and this project. I am extremely grateful for her taking me on as her student and this has been a wonderful experience. Second, my parents and partner, as they've supported me in my undergraduate journey across the country without hesitation. Finally, my friends, for being my home away from home over the last four years of our lives. This group has helped me become a better student, given me confidence I never thought I would have, and gifted me with memories that will last a lifetime.

STATEMENT OF RESEARCH CONTRIBUTION

Atlantic Puffin and Razorbill growth data were collected between 1995 and 2021 by researchers from the Atlantic Laboratory for Avian Research at the University of New Brunswick. I compiled all data for known-age chicks and created the models used to assess the accuracy and minimum number of known-age chicks required to estimate the age of chicks with at least 80% accuracy.

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List of Symbols, Nomenclature or Abbreviations

ACF – Autocorrelation Function

ALAR – Atlantic Laboratory for Avian Research

ATPU – Atlantic Puffin

MAPE – Mean Absolute Percent Error

MSI – Machias Seal Island

RAZO – Razorbill

Introduction

Seabirds have evolved a wide array of nesting, parenting, and fledging strategies to maximize fitness within their ecological range. These animals rely on both oceanic and terrestrial environments at varying degrees to survive, and there are a large number of factors that play a role in how offspring hatch, grow, and fledge (Durant et. al., 2003). These factors, such as food availability, sea surface temperature, or predation, play a role in the breeding success of seabird populations, and due to this there are multiple parenting strategies used by species of seabirds (Hipfner & Gaston, 1999; Ydenberg et al., 1995; Ydenberg 1989, Sealy 1973).

The seabird family Alcidae consists of 23 known extant and one extinct species (Bédard 1969; Pereira & Baker 2008). This family, which has adapted to cold climates and nests exclusively in the Northern Hemisphere, shows three main strategies of chick development (i.e., precocial, intermediate, and semi-precocial; Ydenberg et al., 1995; Ydenberg 1989; Sealy 1973). The vast majority of the 22 extant alcid species show a semiprecocial chick rearing strategy. These species (e.g., the Atlantic Puffin) remain in the nest and are provisioned by their parents until they gain independence (Ydenberg et al., 1995). Alcids categorized as intermediate (e.g., Razorbill *Alca torda*, Thick-billed Murre *Uria Lomiva*, and Common Murre *Uria aalge*), depart the nest with their male parent around halfway through the chick rearing period and are provisioned by that parent at sea (Ydenberg et al., 1995; Ydenberg 1989). Four alcid species, all members of the genus *Synthliboramphus*, are precocial and leave their nest about two days after hatching to be provisioned by their parents entirely at sea (Ydenberg et al., 1995; Ydenberg 1989).

In Atlantic Canada there are five species of nesting Alcids; Atlantic Puffin, Razorbill, Common Murre, Thick-billed Murre, and the Back Guillemot (*Cepphus grille*). During the summer months all five species nest along the coasts and islands of Atlantic Canada (Environment and Climate Change Canada, 2021). The Bay of Fundy/Gulf of Maine region is the southernmost point of the Atlantic Puffin nesting range, and also provides habitat for nesting colonies of Razorbills, Common Murres, and Black Guillemots (Butler et. al., 2020; Diamond & Devlin, 2003; Finch et. al., 1978,). Machias Seal Island (MSI), located southwest of Grand Manan, New Brunswick, has the largest nesting colony in the Bay of Fundy/Gulf of Maine of Atlantic Puffin, Razorbill and Common Murre (Gaston et. al., 2009).

While collecting data on Alcid productivity and growth, any data on known-age chicks is considered to be rather valuable. When observing or studying chicks, the term "known-age" is used to describe individuals whose day of hatch is known rather than extrapolated from measurements. These chicks are uncommon, because nests are not checked daily, and they are used to extrapolate the ages of unknown-age chicks. In order to create an accurate model of growth, these birds must first be found and measured the day they hatch, which is indicated by the state of their feathers and their mobility.

Growth rates can indicate how population health/success differs between years, and can be used to compare the difference in growth variation both over time and comparatively to different populations (Øyan & Anker-Nilssen, 1996). The goal of this study is to determine the minimum number of known-age chicks required to accurately estimate the age of puffin and Razorbill chicks from growth curves. I am conducting this study under the hypothesis that linear phases of growth in puffins and Razorbills are consistent between individuals within the same population and I can use these growth measurements to predict ages across individuals.

Methods

Study Site

Machias Seal Island (MSI), a 9.5-hectare treeless island located 20 kilometers southwest of Grand Manan in the Bay of Fundy (Figure 1), has been a federally-designated Migratory Bird Sanctuary since 1944 and is home to nine nesting seabird species: Common and Arctic Tern (*Sterna hirundo* and *S. paradisaea*), Herring and Great Black-backed Gull (*Larus argentatus* and *L. marinus*), Atlantic Puffin, Razorbill, Common Murre, Leach's Storm-petrel (*Hydrobates leucorhoa*), and Common Eider (*Somateria mollissima*) (Bond & Diamond, 2010; ALAR 2020). Since 1995, researchers from the Atlantic Laboratory for Avian Research (ALAR) visit MSI from May to mid-late August to collect data on the phenology, demography, and diet of nesting seabirds.

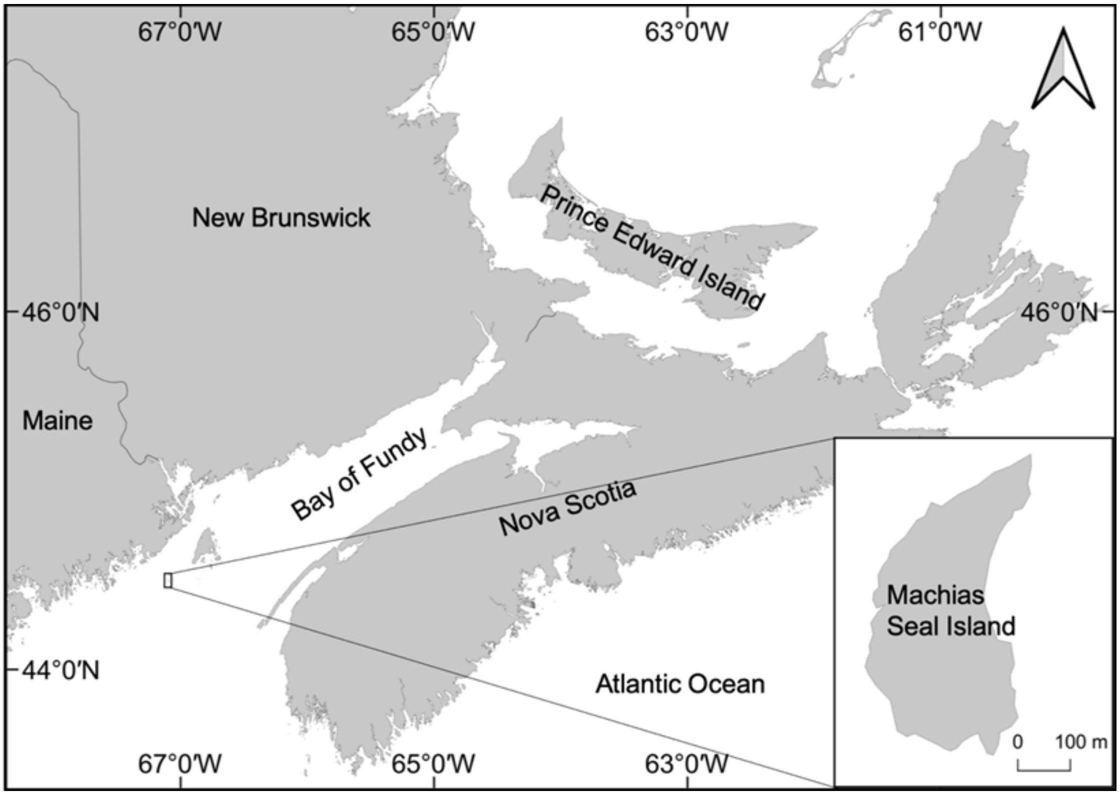

Figure 1 - Map showing location of Machias Seal Island in the southern part of the Bay of Fundy and North of the Gulf of Maine.

Burrow/Crevice Checks

In 1995 a set of nesting burrows (puffins) and crevices (Razorbills) were permanently marked, since then the total number of marked burrows/crevices has been maintained around 100 by adding new burrows/crevices for any that become unusable (e.g., collapses) or becomes unsuitable for monitoring (e.g., puffins continuing to dig deeper into their burrow, eventually making the nest contents inaccessible to researchers). To monitor reproductive success of puffins and Razorbills, researchers reach into the burrow/crevice (hereafter "nest site") so that the whole nest site can be reached to determine whether an egg and/or adult is present. If an egg is not found, the nest site is revisited and checked every 5-7 days until an egg is found or until the peak of hatching, after which it is not checked further. Nest sites containing an egg are recorded as "active" and are revisited to check for hatching after a period of 37 (puffin) or 35 (Razorbill) days, these being average incubation periods from the literature. If the egg has not hatched by this time the nest site is re-checked once every three days until a chick is found or the egg disappears. If an egg is cracked or does not hatch before early July, it is recorded as "dead".

Chick Growth

Measurements of hatched chicks begin as soon as chicks are found, unless a chick is found to have wet down or eggshell fragments are stuck to the down. In these cases, the chicks are considered to have just hatched, and so they are "known-age" and measured the next day (see below). Important measurements used in growth curves are mass (to the nearest 1g) and wing chord length (to the nearest 1.0 mm). Chick mass is measured using a spring scale and, the wing chord is measured as the length of the wing naturally resting from the "wrist" to the tip of the longest flight feather. Due to the sigmoidal growth pattern found in birds, ALAR researchers use at least two measurements taken during the linear phase of growth, when growth occurs at the fastest rate, for comparison among individuals and years. In puffins the linear phase of growth occurs during days 10 to 30 post hatch (Figures 2 and 3), and for Razorbills this phase occurs during days 5 to 15 post hatch (Figures 4 and 5).

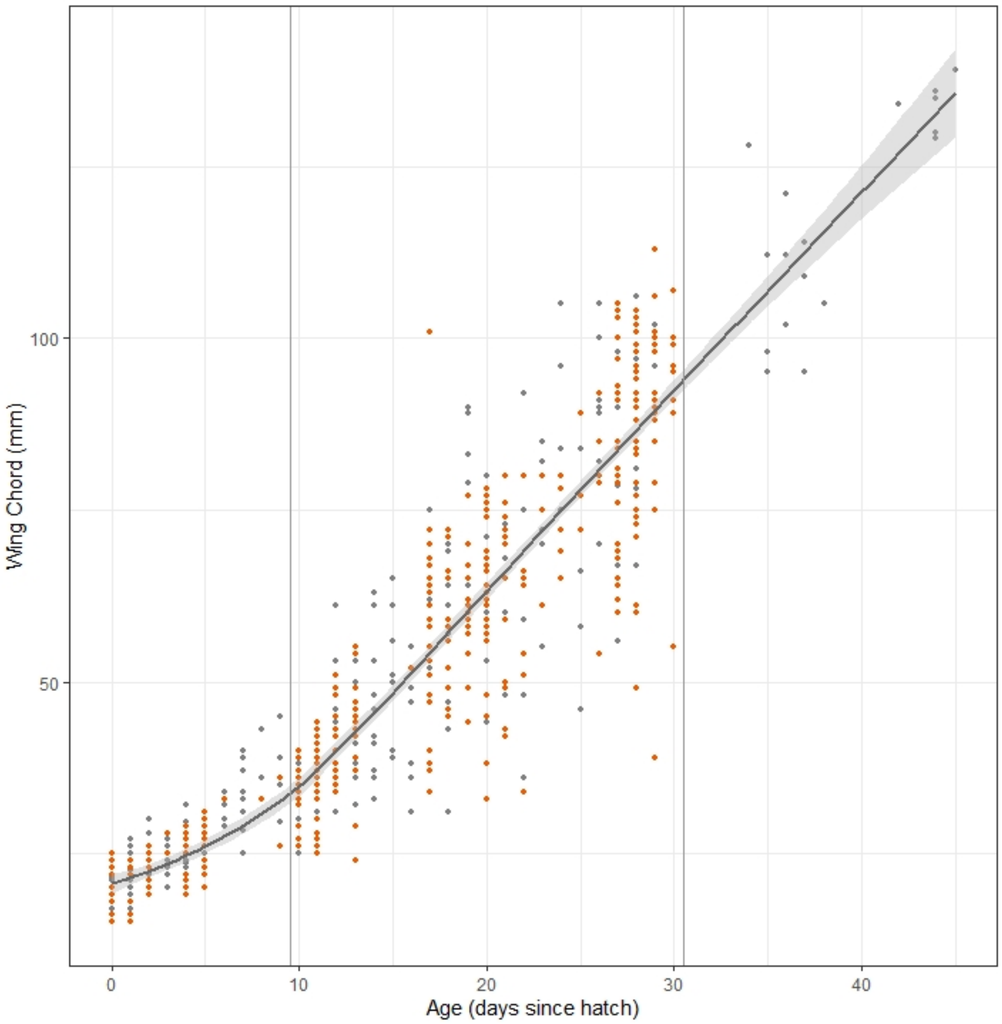

Figure 2 – Wing growth of known-age Atlantic Puffin (*Fratercula arctica*) chicks across all years (i.e., 1995-2021) at Machias Seal Island. Linear growth phase (days 10 to 30) outlined in grey lines. Years used for final models shown in orange (see Statistical Analysis for details).

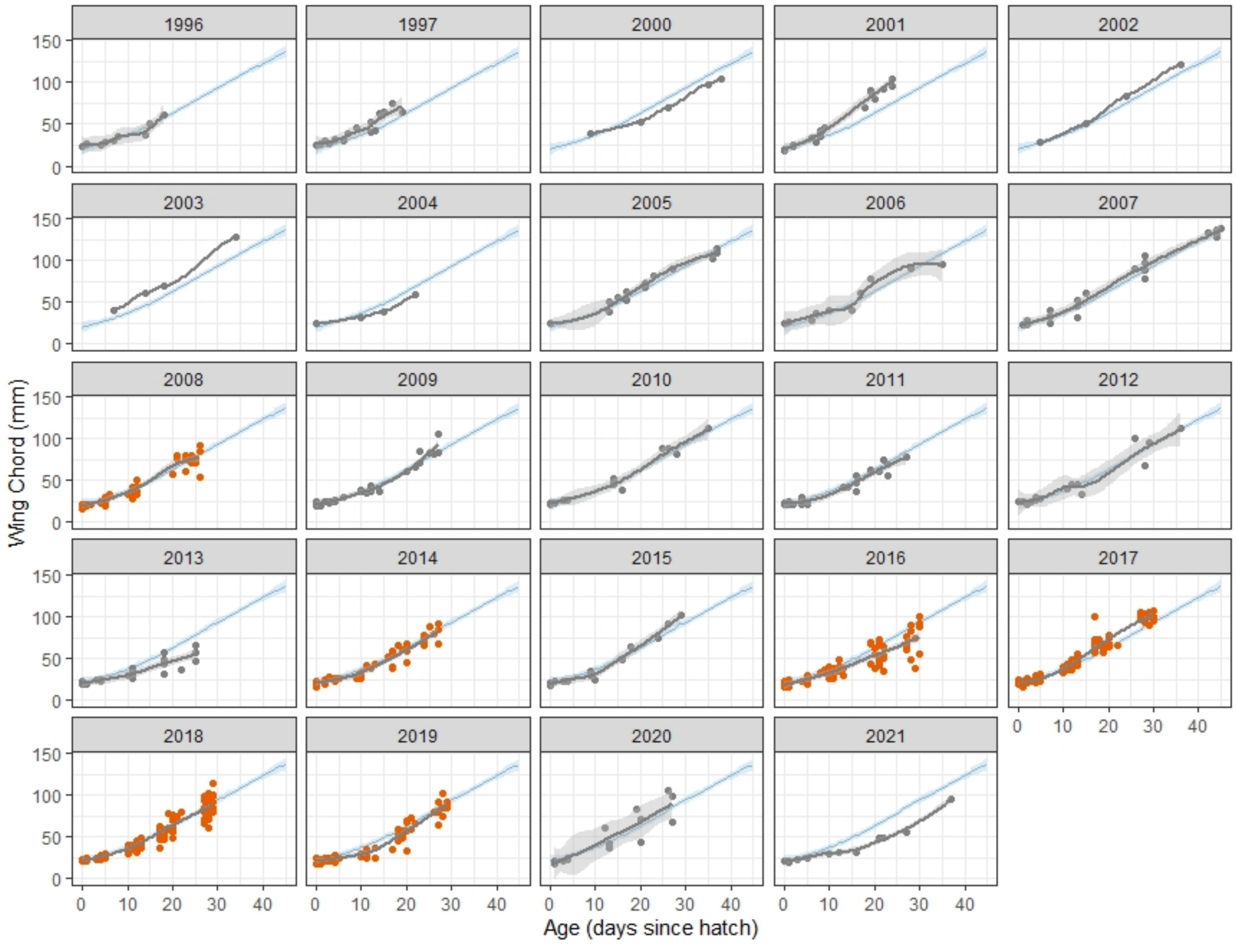

Figure 3 – Yearly wing growth curves of known-age Atlantic Puffin chicks in comparison to the overall growth curve (light blue). Years used for final models shown in orange.

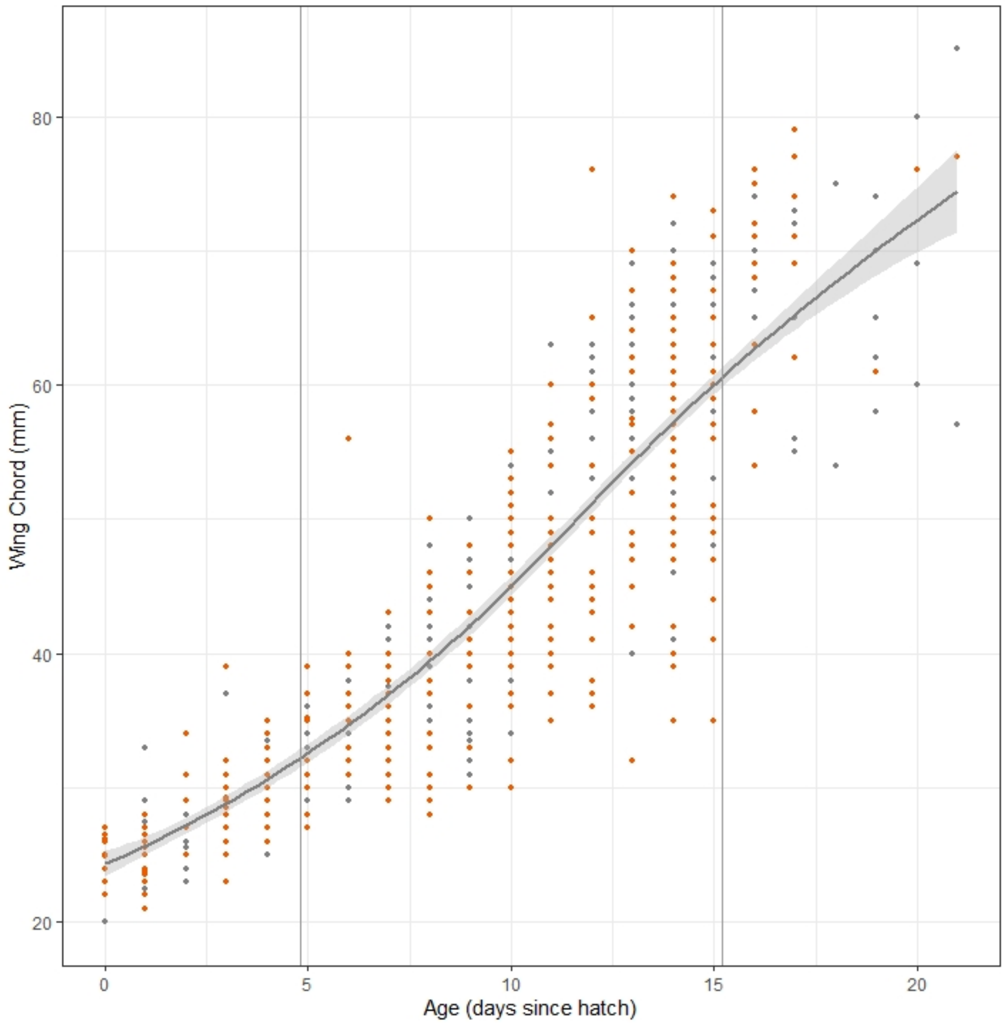

Figure 4 – Wing growth of known-age Razorbill (*Alca torda*) chicks across all years of data (i.e., 1995-2021) at Machias Seal Island. Linear growth phase (days 5 to 15) outlined in grey lines. Years used for final models and results shown in orange.

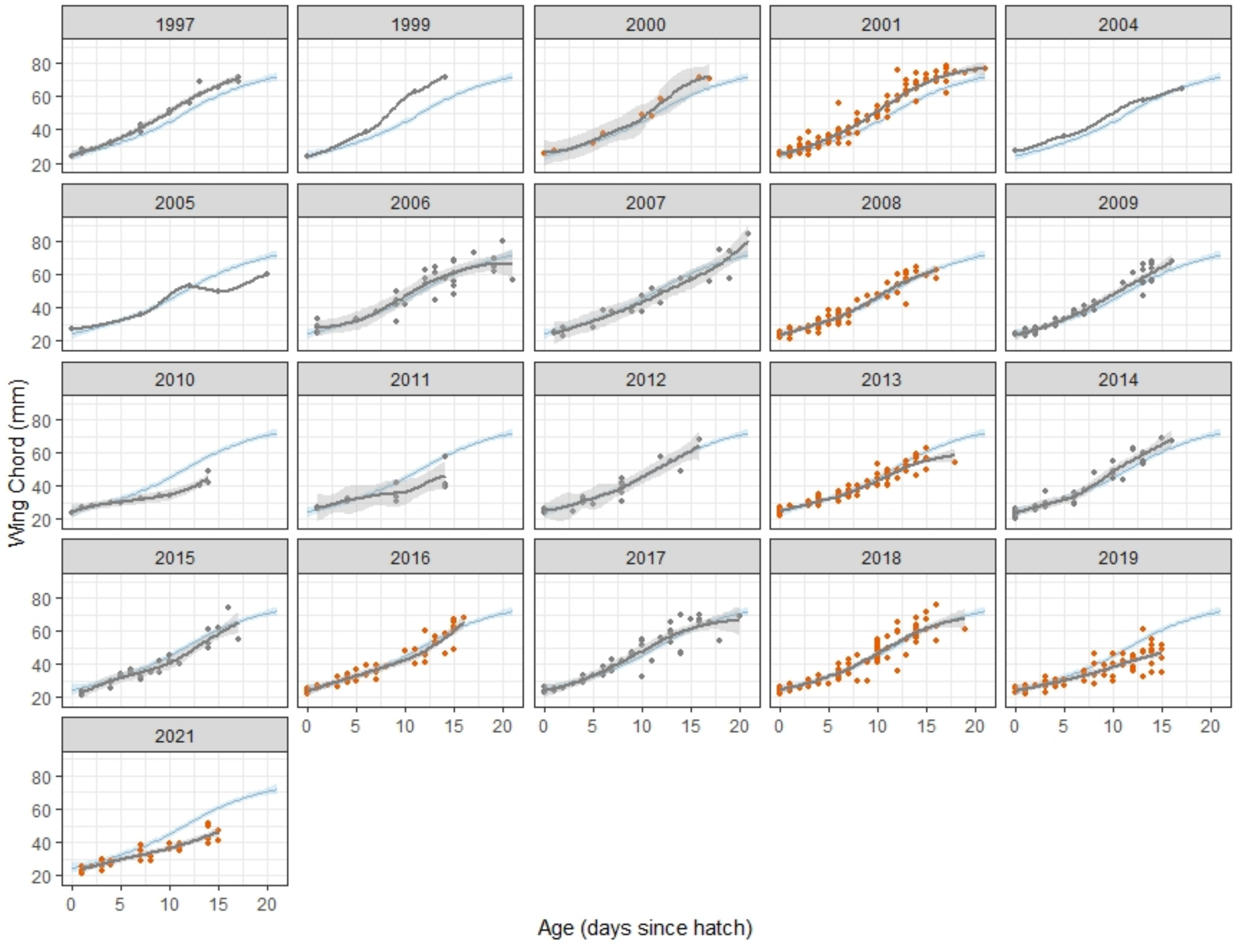

Figure 5 – Yearly wing growth of known-age Razorbill chicks in comparison to the overall growth curve (light blue). Years used in final models shown in orange.

Known-Age Chicks

All known-age chicks are measured twice within the first 5 days of. The date of hatch is recorded for every known-age chick, and this combined with the measurement data is later used to extrapolate the ages of chicks of unknown age within the same year.

Data

I collected all measurements of known-age birds from the annual chick growth datasheets for Atlantic Puffins and Razorbills, across all study years in the MSI time series (i.e., 1995-2021). I calculated the slopes (*b*) and intercepts (*a*) for the linear phase of growth for each chick using the following equations:

Equation 1:

$$b = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sum(x - \bar{x})^2}$$

Equation 2:

$$a = \bar{y} - b\bar{x}$$

where x is chick age at measurement and y is the corresponding wing chord length.

Occasionally, chicks are measured more than two times during the linear phase of growth. To account for this, I split my data into two datasets: the "Full" dataset that consisted of every measurement taken during the linear phase of growth for each individual; and the "Partial" dataset that was created by randomly removing measurements until each individual had just two measurements within the linear phase of growth. To select which measurements were removed to create the Partial dataset, every measurement was assigned a random number using the RAND function in excel. After these random values were created, any chick with more than two measurements had the measurement with the lowest randomly-generated number removed from the dataset until only two measurements remained.

Statistical Analysis

All statistics were completed in the R Studio environment (version 1.3.1093; R Core Team, 2021). To assess whether data could be pooled together and using the R package stats (R Core Team 2021), I first ran an ANOVA assessing the relationship between slope and intercept (individually) with year and second used autocorrelation function (ACF) models to evaluate whether years could be pooled together (Figure 6). These analyses showed that chick growth data could not be pooled, thus, I limited my datasets to years containing at least 10 known-age chicks with at least two measurements taken during the linear phase of growth (Table 1).

Table 1 – Summary of the species, year, and number of chicks within each full dataset used to create the linear models used for age extrapolation

Species	Year	Birds
ATPU	2008	14
	2014	10
	2016	20
	2017	29
	2018	32
	2019	17
RAZO	2000	12
	2001	30
	2008	18
	2009	11
	2013	18
	2016	15
	2018	25
	2019	18
	2021	13

To generate my final group of datasets (both the full and partial), I randomly assigned a proportion of the data for every year into two sets: "Training" or "Test" through the sample function in the R package *base* (R Core Team 2021). Here, I ran a number of different iterations of proportions of data included as training and test to determine the minimum number of known age chicks required to accurately estimate chick age from wing chord measurements. Specifically, I split the data into the following six ratios: 70% in Training:30% in Test, 60:40, 50:50, 40:60, 70:30, and 20:80. I also randomly split the data into five ratios that include just 30% of the data as test (i.e., 60:30, 50:30, 40:30, 30:30, 20:30). I used the training set to generate linear models of chick growth (i.e., wing chord change by age in days), and used these models to predict chick age in the test set. I then calculated the Mean Absolute Percent Error (MAPE) for these models:

Equation 3:

$$MAPE = \frac{\left(\sum \frac{|A - F|}{A}\right) \times 100}{n}$$

where *A* is the known age, *F* is the estimated age extrapolated from the linear model, and *n* is the number of age extrapolations calculated from the model. Each model was run 100 times such that the measurements were randomly assigned to the training and test data and a total of 100 MAPEs were collected for that ratio (n). The average of the MAPEs was then calculated and used as the percent error for that model. To create the models and predict the test group ages I used the R studio package *stats*, and I used the package *MLmetrics* to calculate the MAPEs (R Core Team 2021).

To determine the acceptable percent error of an "accurate" model, I tested a model from the year with the largest number of known-age chicks (i.e., Atlantic Puffin 2018) using a split of 80% training to 20% test. The MAPE of this model was used as the minimum accuracy a model must attain to be considered "accurate". For Razorbills, a trend of decreasing accuracy with time was observed, thus I determined the acceptable error percentage from the accuracies of the three most recent years (i.e., 2018-2021).

Once I had run models to find the accuracy of the full and partial datasets, I ran a set of models to find the minimum number of birds required for accurate age extrapolations. These models used only the Partial data to control for variation in number of measurements taken per individual. Rather than using a percentage of the full set to create the training data, I used a number of measurements representing a number of individuals to create the linear models (i.e., two points is equivalent to a single chick). The linear models created from these training sets were used to extrapolate the ages of chicks in test sets comprised of 30%, 50%, 70%, and the remaining number of points from the full data. I then determined the minimum number of known age chicks to be the lowest number of chicks that consistently surpassed the minimum accuracy level in the three most recent years.

Results

My ANOVA evaluating the relationship between slopes and intercepts and years found significant differences for both puffins (slope: F = 4.643, p-value <0.001; intercept: F = 4.646, p-value <0.001) and Razorbills (slope: F = 5.185, p-value <0.001; intercept: F = 0.867, p-value = 0.639). In addition, I did not find evidence of autocorrelation in the time series (Figure 6). Thus, I did not pool the data.

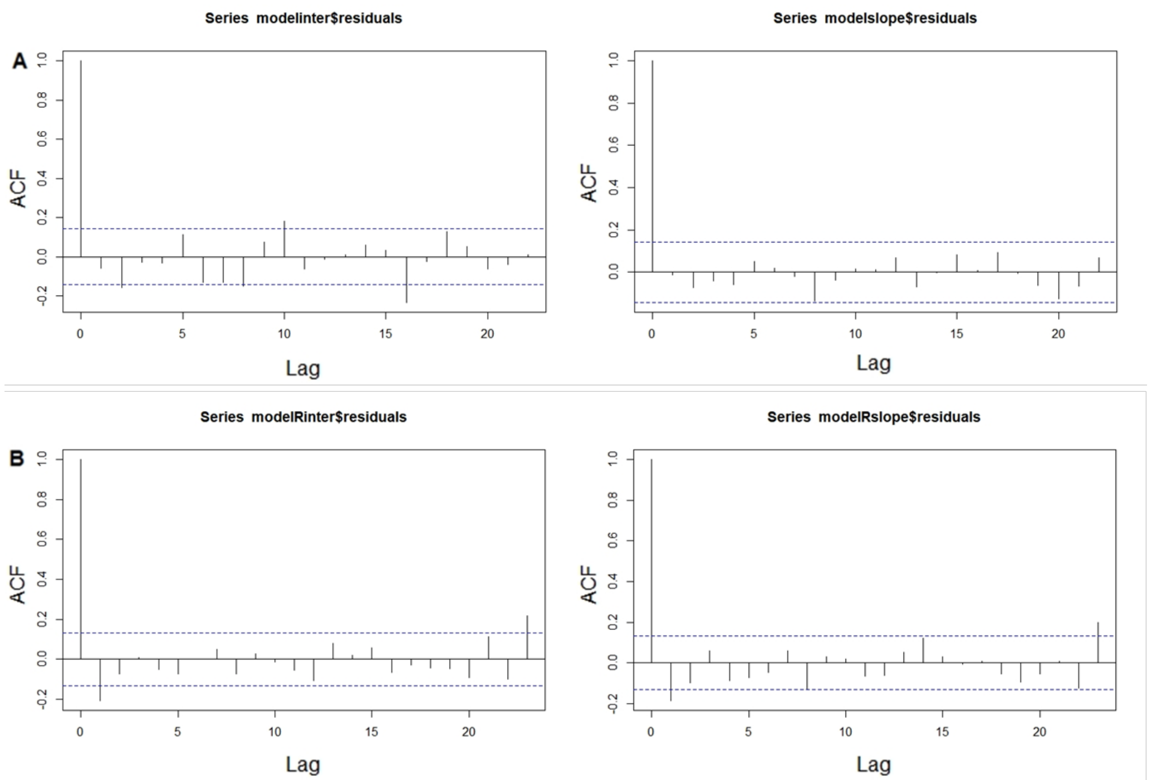

Figure 6 - ACF models testing for any time lags in the intercepts (right) and slopes (left) of measurements taken during the linear phase of growth for Atlantic Puffin (A) and Razorbill (B) chicks.

The acceptable error value was determined to be a minimum of 85% accuracy in Atlantic Puffins from comparison of the accuracy found in an 80:20 split with the largest dataset (2018), which had an average accuracy of 88.61% with a 95% confidence interval of 87.53%, 89.68%.

Due to this low error level (11.39%), 15% error was deemed to be an acceptable maximum percent error. For the Razorbill accuracy range a minimum of 80% accuracy was determined using the three most recent years in the final models.

Overall, percent accuracy from the full and partial datasets were similar (Figure 7) and showed an increase in accuracy with year for puffins (Figure 7A), and a decline in accuracy for Razorbills (Figure 7B). Accuracy was highest in 2001 (Razorbills) and 2017 (Atlantic Puffins), with average model accuracies of 90.51% and 89.73% respectively. The lowest accuracy values were found in 2016 in Atlantic Puffins and 2019 in Razorbills with average model accuracies of 76.75% and 81.43% respectively (Figure 7). ANOVA tests show that there is no significant difference between the full and partial datasets in either Puffins ($F = 0.157$, p-value = 0.701) or Razorbills ($F = 0.083$, p-value = 0.777), but there is a significant relationship between accuracy of models and year in both species (Puffin: $F = 65.66$, p-value <0.001; Razorbill: $F = 36.17$, p-value <0.001). I also ran an ANOVA on the Puffin model results while excluding the year 2016 to see if the relationship between year and accuracy of models was still significant, which gave a p-value of 0.019 ($F = 11.23$), showing that the relationship is still statistically significant.

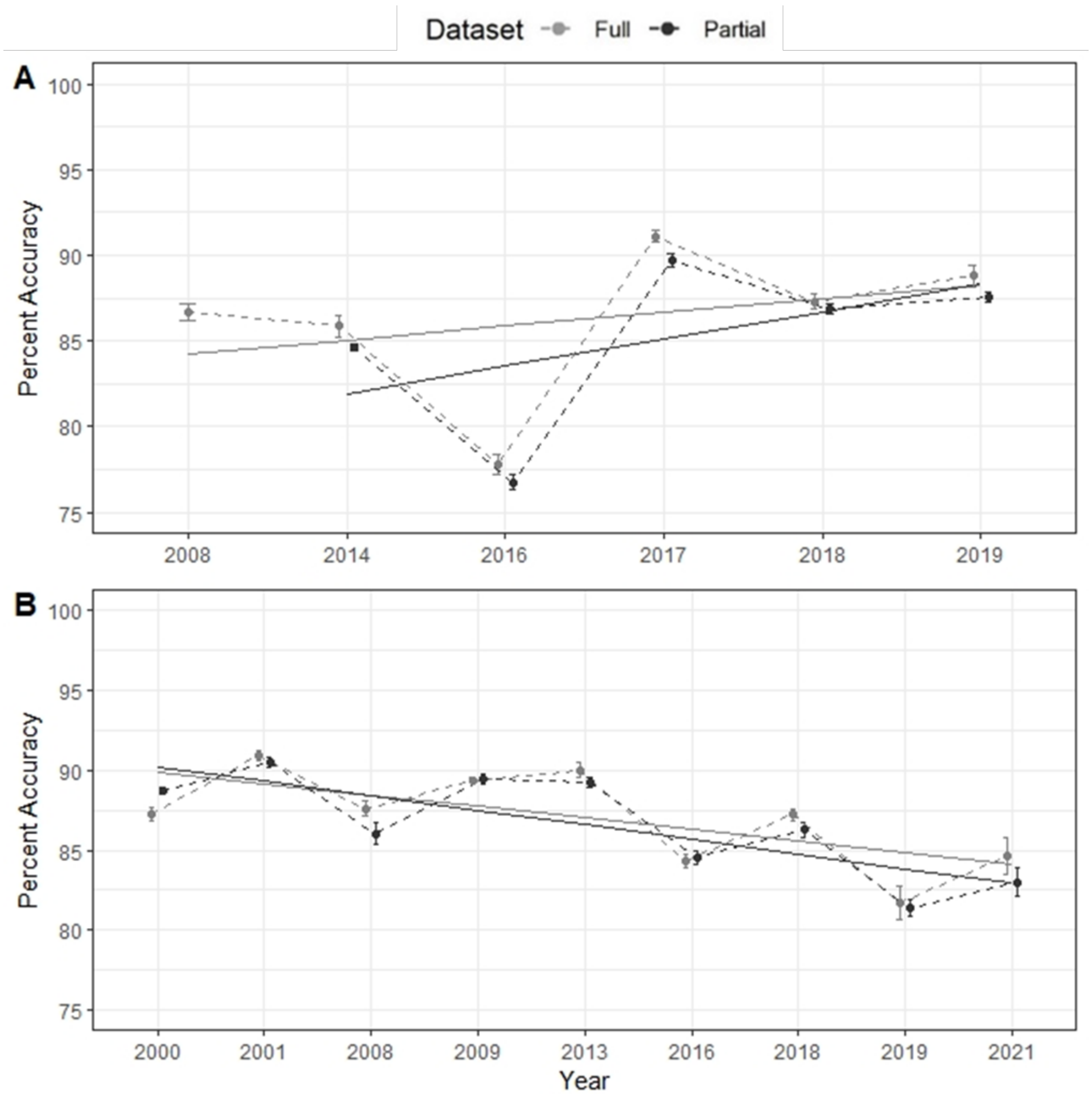

Figure 7 - Accuracy percentages found in all Atlantic Puffin (A) and Razorbill (B) models run for each year in two datasets: one containing all recorded linear growth meaurements (Full), and one containing 2 linear growth measurements per individual (Partial). Note: the Atlantic Puffin dataset for 2008 had only 2 measurements per individual so there was no splitting of data.

For Atlantic Puffins, models run multiple times made from measurements of three, four, and five chicks resulted in at least 85% accuracy in the three most recent years (Figure 8). For Razorbills, models run multiple times made from measurements of four and five chicks resulted in at least 80% accuracy in the three most recent years (Figure 8). The minimum number of known-age chicks required for age extrapolations with at least 85% accuracy in Atlantic Puffins is three, and with at least 80% accuracy in Razorbills is four (Figure 8).

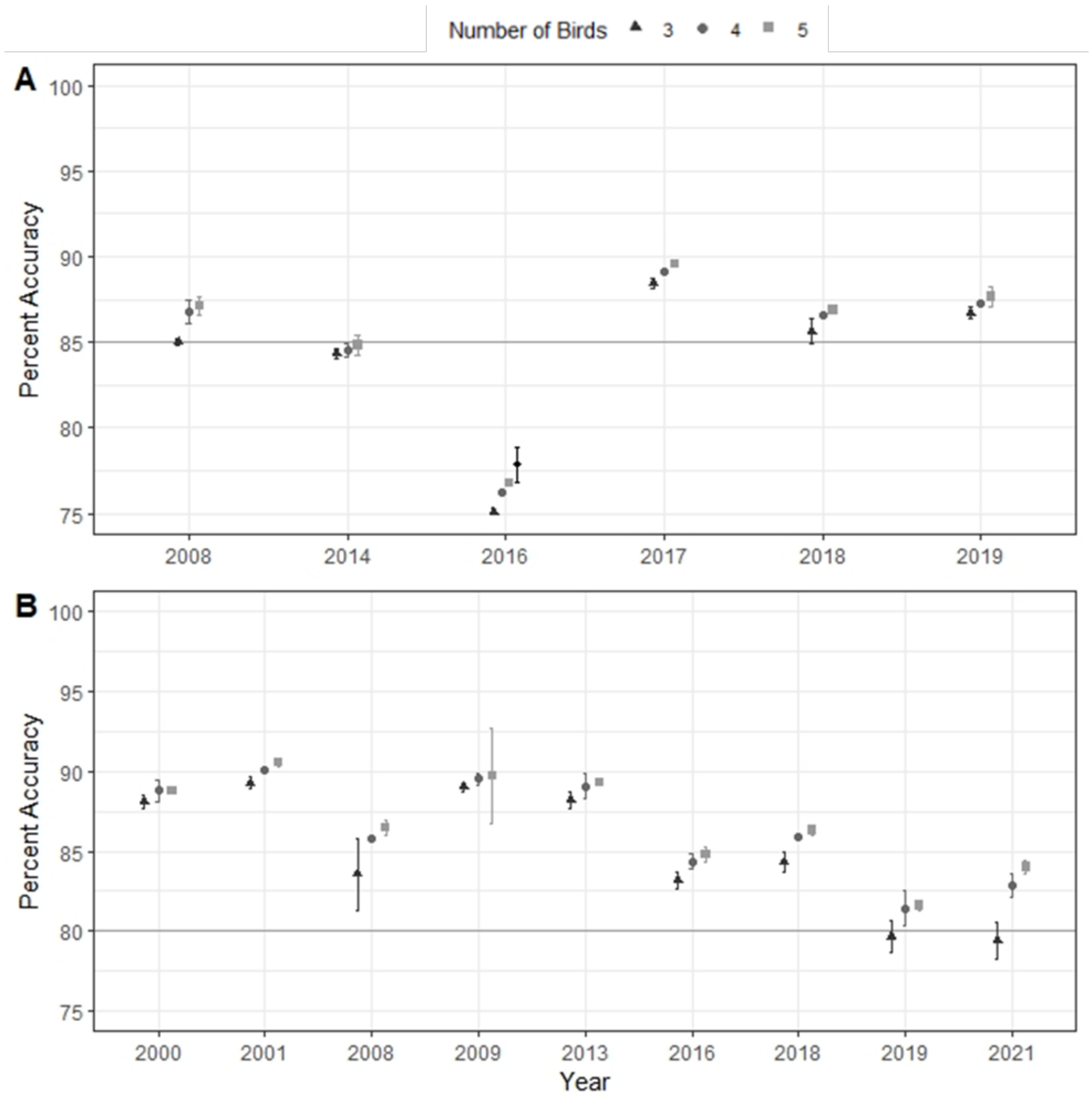

Figure 8 - Yearly percent accuracy of models run for Atlantic Puffin (A) and Razorbill (B) chick age extrapolations using 3, 4, and 5 individuals. Grey line indicates minimum accepted percent accuracy. Fourth point in Puffin 2016 models shows percent accuracy of a model using 17 of 20 individuals to extrapolate the ages of the remaining 3 individuals.

Discussion

I found that three chicks are required to extrapolate ages with 85% accuracy in Atlantic Puffin chicks and four are required to for 80% accuracy in Razorbills. These high levels of accuracy coming from a small number of individuals is encouraging, as it gives us insight into how close past age estimates are to the true chick ages.

In the models analyzed through this study, there was a higher level of accuracy found with increasing number of individuals, indicating that there is still reason to collect data on any found known-age chicks rather than having three or four known-age chicks each year. The relationship between the Full and Partial datasets showed that, although accuracy was higher by a small amount, the difference between having two measurements per individual versus more than two was insignificant. This allows researchers some leeway in how much time must be put into taking as many known-age chick measurements as possible and how that time could be otherwise allocated.

There was a significant trend/difference between years when comparing the accuracy of the datasets. Although this prevented me from pooling the data together and running larger models, these trends demonstrate how the variation of growth rates within any one year can shift the accuracy of age estimations. The largest difference in model accuracy among years occurred for puffins in 2016. The observed decrease in accuracy is interesting and corresponds with low fledge success, chick growth rates, and fledger body conditions in that year (ALAR unpublished data; Scopel et. al., 2019; Major et. al., 2021). The Gulf of Maine is rapidly warming, and marine heat waves (MHW) have become more common including notable MHWs in both 2012 and 2016 (Pershing et. al., 2018). This heat wave had similar effects to another heat wave in 2012, in which fledger body conditions and fledge success were notably low the following year (Scopel et. al., 2019; Major et al., 2021). Unfortunately, 2012 did not meet my data requirements for inclusion in the dataset (i.e., 2012 had three known-age chicks with at least two measurements during the linear phase of growth), thus a comparison of accuracy between these two years is not feasible. I also noted that a similar decrease in accuracy was not observed in Razorbills in 2016, which correlates with no decrease in Razorbill fledge success in that year (Major et al., 2021).

Even in the worst year, the data collected provided age extrapolations with more than 75% accuracy. This knowledge in combination with future synthesized data can be used to advance our knowledge on these species, our understanding on the way in which their populations are changing, and can be used as a basis for future seabird growth studies.

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Appendix

Table A-1 – Age (days) and Wing Chord (mm) measurements of known-age chicks in years used for age extrapolation models. Coloured cells are linear phase of growth measurements used in models; darker coloured cells are those used in both Full and Partial datasets, lighter coloured cells are measurements that were randomly removed to create the Partial dataset.

Species	Year	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Wing 1	Wing 2	Wing 3	Wing 4	Wing 5	Wing 6
ATPU	2008	0	4	11	20			20	25	35	58		
ATPU	2008	0	4	12	21			20	25	37	76		
ATPU	2008	0	5	12	21			21	28	51	80		
ATPU	2008	0	6	11	23			18	33	38	61		
ATPU	2008	0	5	11	23			20	30	39	80		
ATPU	2008	1	5	11	23			22	25	39	75		
ATPU	2008	0	5	12	24			21	25	34	72		
ATPU	2008	2	5	12	24			21	25	44	80		
ATPU	2008	0	4	11	25			18	23	38	72		
ATPU	2008	0	5	11	25			16	25	38	77		
ATPU	2008	0	4	10	26			22	25	33	85		
ATPU	2008	1	5	11	26			21	25	42	92		
ATPU	2008	1	5	11	26			19	20	28	54		
ATPU	2008	0		10	17			22		32	48		
ATPU	2014	0	2	9	16	24		18	21	26	52	69	
ATPU	2014	0	2	10	17	24		18	19	26	40	65	
ATPU	2014	0	2	10	17	24		16	21	32	53	72	
ATPU	2014	0	3	10	17	24		21	28	33	59	78	
ATPU	2014	0	4	11	18	25		23	27	41	65	89	
ATPU	2014	0	5	12	19	26		19	26	38	60	79	
ATPU	2014	0	4	17	20	27		20	23	38	45	68	
ATPU	2014	0	2	13	20	27		22	25	43	59	84	
ATPU	2014	0	2	13	20	27		23	25	44	68	91	
ATPU	2014	1		12	19	26		27		31	44	60	
ATPU	2016	1	5	12	19	30		17	24	49	70	100	
ATPU	2016	1	5	12	19	30		19	25	35	44	55	
ATPU	2016	1	5	8	19	30		17	25	33	67	89	
ATPU	2016	0	5	13	20			18	23	29	38		
ATPU	2016	1	5	10	20	27		20	25	36	56	62	
ATPU	2016	1	5	11	20	27		16	23	33	63	76	
ATPU	2016	0	5	10	21	27		19	22	30	49	60	
ATPU	2016	0	5	11	21			22	29	38	43		
ATPU	2016	0	5	10	21	27		15	27	32	50	68	

ATPU	2016	0	5	11	21	28		19	26	26	42	49	
ATPU	2016	1	5	10	21	28		16	29	40	71	90	
ATPU	2016	1	5	9	21	30		24	26	36	72	91	
ATPU	2016	1	5	12	21	28		21	26	40	65	83	
ATPU	2016	0	4	13	22	29		19	22	39	64	75	
ATPU	2016	1	5	11	22	29		19	20	26	34	39	
ATPU	2016	1	5	10	22	27		19	25	27	54	68	
ATPU	2016	1	5	11	22			20	22	30	51		
ATPU	2016	1	5	9	20	30		19	25		47	71	
ATPU	2016	1	5	13	22	29		20	28		38	46	
ATPU	2016	1	5	13	22			21		30	33		
ATPU	2017	0	2	10	17	27		21	24	40	70	100	
ATPU	2017	0	2	10	17	27		19	24	39	72	103	
ATPU	2017	0	3	11	17	28		23	23	39	61	96	
ATPU	2017	0	4	11	17	28		21	25	38	68	98	
ATPU	2017	1	3	10	17	27		15	23	33	64	97	
ATPU	2017	1	4	11	17	28		21	26	39	61	98	
ATPU	2017	1	4	11	17	28		22	25	41	67	104	
ATPU	2017	1	5	11	17			19	26	39	101		
ATPU	2017	1	5	11	17	28		22	25	43	64	102	
ATPU	2017	1	4	11	17	28		21	22	40	65	101	
ATPU	2017	1	4	11	17			21	26	39	58		
ATPU	2017	0	4	11	18	28		19	23	43	66	94	
ATPU	2017	0	4	11	18	28		19	23	39	65	98	
ATPU	2017	0	2	11	18	28		24	24	40	65	104	
ATPU	2017	1	4	12	18	29		21	21	48	72	106	
ATPU	2017	2	5	11	18	28		26	31	44	71	103	
ATPU	2017	0	5	12	19	29		21	23	38	65	101	
ATPU	2017	0	5	12	19	30		19	25	40	62	99	
ATPU	2017	2	5	12	19	29		23	24	37	58	90	
ATPU	2017	2	5	12	19	29		21	27	36	61	90	
ATPU	2017	0	4	13	20	27		20	29	54	78	105	
ATPU	2017	0	4	13	20	30		19	24	43	64	96	
ATPU	2017	0	4	13	20	30		22	25	55	77	100	
ATPU	2017	0	4	10	20	27		21	23	40	75	104	
ATPU	2017	1	4	13	20	30		22	24	42	66	107	
ATPU	2017	1	4	13	20	30		22	24	45	67	95	
ATPU	2017	1	5	12	22	29		19	24	37	66	90	
ATPU	2017	1		12	19			18		31	46		
ATPU	2018	0	5	10	17	27		21	29	39	63	98	
ATPU	2018	0	4	10	17	28		20	25	34	61	99	
ATPU	2018	0	5	10	17	27		20	26	34	48	80	
ATPU	2018	0	5	10	17	27		20	25	30	37	65	

ATPU	2018	0	5	10	17	28		20	29	35	51	71	
ATPU	2018	0	3	10	17	28		22	25	40	55	79	
ATPU	2018	1	5	10	17	28		23	25	34	47	77	
ATPU	2018	1	5	10	17	28		22	28	36	55	84	
ATPU	2018	1	5	10	17	28		22	26	35	55	88	
ATPU	2018	0	4	11	18	28		21	24	36	59	74	
ATPU	2018	0	3	11	18	28		20	23	34	46	61	
ATPU	2018	0	5	10	18	29		23	27	35	56	79	
ATPU	2018	1	4	11	18	28		24	25	34	52	73	
ATPU	2018	1	3	11	18	28		23	25	39	58	92	
ATPU	2018	1	4	11	18	29		22	25	38	59	92	
ATPU	2018	0	4	12	19	29		21	25	36	59	85	
ATPU	2018	0	4	12	19	29		22	26	45	77	113	
ATPU	2018	1	4	12	19	29		20	23	36	59	79	
ATPU	2018	1	4	12	19	29		22	26	40	61	98	
ATPU	2018	0	5	13	20	27		22	28	49	76	93	
ATPU	2018	0	4	13	20	27		22	25	36	56	70	
ATPU	2018	0	5	13	20	27		22	28	45	69	81	
ATPU	2018	0	4	12	20	27		21	24	31	57	69	
ATPU	2018	0	4	12	20	27		21	28	42	62	85	
ATPU	2018	0	4	10	20	28		21	24	37	74	101	
ATPU	2018	0	4	10	20	28		20	25	40	74	102	
ATPU	2018	1	4	13	20	28		20	24	37	48	60	
ATPU	2018	1	4	13	20	28		22	23	41	61	84	
ATPU	2018	0	4	12	21	28		20	26	45	74	91	
ATPU	2018	0	4	12	21	28		22	26	43	70	95	
ATPU	2018	0	4	13	22	29		21	26	46	80	100	
ATPU	2018	0	4	13	22	29		22	25	47	80	99	
ATPU	2019	0	3	10	17	28		18	23	29	34	75	
ATPU	2019	1	4	11	18	29		23	25	25	45	85	
ATPU	2019	1	4	11	18	28		18	19	34	49	85	
ATPU	2019	1	5	11	18	29		19	24	35	52	91	
ATPU	2019	2	4	11	18	28		23	27	27	58	102	
ATPU	2019	1	3	10	19	26		20	20	26	57	80	
ATPU	2019	2	4	11	19	29		25	24	28	54	90	
ATPU	2019	2	4	11	19	29		20	25	30	49	89	
ATPU	2019	1	3	10	20			18	25	30	67		
ATPU	2019	1	4	13	20	27		20	20	24	33	64	
ATPU	2019	1	5	11	20	27		23	24	34	69	92	
ATPU	2019	1	4	13	20	27		23	25	36	57	79	
ATPU	2019	1	3	11	21	27		22	25	34	72	91	
ATPU	2019	1	4	10	21	28		21	25	29	59	85	
ATPU	2019	0	4	11	22	29		25	25	30	65	88	

ATPU	2019	1		10	20	28		26		37	62	81	
ATPU	2019	1		10	20	28		25		33	56	84	
RAZO	2000	0	6	10	12	16		26	38	49	59	72	
RAZO	2000	1	5	11	17			27	32	48	71		
RAZO	2000	0		8	11	14	18	28		38	48	51	73
RAZO	2000	0		8	11	14	20	26		39	49	52	72
RAZO	2000	1		9	12	16		27		48	59	71	
RAZO	2000	1		6	13			27		39	51		
RAZO	2000	0		11	14			24		49	63		
RAZO	2000	0		6	14	18		29		38	69	73	
RAZO	2000	1		10	14	17		29		51	65	75	
RAZO	2000	1		7	14			28		40	63		
RAZO	2000	0	5	15				26	33	64			
RAZO	2000	1	5	9				26	35	40			
RAZO	2001	0	1	3	5	7	13	26	26	31	35	41	67
RAZO	2001	0	2	4	7	15	17	24.9	29	33	40	69	74
RAZO	2001	0	4	5	7	11	15	26.2	32	36	40	56	69
RAZO	2001	1	3	5	7	10	13	29	30	35.2	41	54	64
RAZO	2001	1	2	3	7	11	14	25	29	29.3	41	54	65
RAZO	2001	2	3	5	7	11	17	26	27	32	32	47	69
RAZO	2001	0	1	4	8	11	17	25	26.5	32	45	55	77
RAZO	2001	0	2	5	8	11	17	25	26	34	46	60	62
RAZO	2001	0	2	5	8			26	34	32	44		
RAZO	2001	1	2	4	8	11	17	27.5	29	33	44	54	79
RAZO	2001	1	3	5	8	11	14	28	28	37	38	52	74
RAZO	2001	1	3	5	8			27	30	35	50		
RAZO	2001	2	4	6	8	13	15	31	35	40	45	70	71
RAZO	2001	2	4	6	8	12	15	28	33	38	43	58	71
RAZO	2001	0	3	5	9	15		26.5	32	36	48	73	
RAZO	2001	1	3	6	9	12	18	23.7	29	35	46	60	75
RAZO	2001	1	2	6	10	14	19	25	29	39	49	57	74
RAZO	2001	1	3	6	10	14	16	25.5	28.5	39	52	67	75
RAZO	2001	1	3	6	10	13	16	24	25	32	47	62	72
RAZO	2001	1	4	5	10	16	20	28	32	33	51	69	76
RAZO	2001	0	3	6	12			26	39	56	76		
RAZO	2001	1	2	8	12	14		26	31	45	60	69	
RAZO	2001	1	4	7	13	17		25	31	38	61	69	
RAZO	2001	2	6	10	21			28	38	50	77		
RAZO	2001	1		8	10	18		26.5		44	53	76	
RAZO	2001	0		9	14			24		46	63		
RAZO	2001			6	15					38	78		
RAZO	2001	1	5	8				26	36	47			
RAZO	2001	1	5	8				24.5	32	44.4			

RAZO	2001	3	5	10				33	38	55			
RAZO	2008	0	4	6	9			24	30	39	42		
RAZO	2008	0	5	6	9			23	32	32	47		
RAZO	2008	0	5	6	10			22	31	35	48		
RAZO	2008	0	4	7	11			24	25	31	46		
RAZO	2008	0	4	6	12			25	32	36	60		
RAZO	2008	0	3	6	12			23	26	32	49		
RAZO	2008	1	5	6	12			25	35	33	54		
RAZO	2008	0	5	7	13			24	30	39	58		
RAZO	2008	0	5	11	13			24	39	55	57.5		
RAZO	2008	1	4	6	13			27	31	31	56		
RAZO	2008	1	5	6	13			27	35	37	60		
RAZO	2008	1	4	6	13			25	32	38	62		
RAZO	2008	1	4	6	13			21	27	30	42		
RAZO	2008	1	4	6	13			25	33	35	58		
RAZO	2008	0	5	6	14			24	32	36	62		
RAZO	2008	1	4	6	14			24	32	31	62		
RAZO	2008	1	4	8	14			25	32	45	65		
RAZO	2008	1	3	7	15			28	29	35	59		
RAZO	2009	2	4	8	12			25	31	44	61		
RAZO	2009	0	4	6	13			25	31	38	63		
RAZO	2009	0	4	6	13			24	33	39	66		
RAZO	2009	1	3	6	13	14		24	29	36	56	57	
RAZO	2009	1	2	8	13			24	27	39	55		
RAZO	2009	1	2	5	13			26	28	33	55		
RAZO	2009	1	3	7	14			27	28	36	56		
RAZO	2009	1	2	11	14			25	28	55	66		
RAZO	2009	2	3	7	14			24	29	36	64		
RAZO	2009	2	3	7	14			26	29	41	68		
RAZO	2009	1		6	13			24		38	59		
RAZO	2013	0	4	6	9	13		25	28	37	40	55	
RAZO	2013	0	4	6	9	13		25	35	31	39	49	
RAZO	2013	0	3	7	10	14		22	28	33	47	58	
RAZO	2013	0	4	6	10	13	15	24	32	33	41	52	56
RAZO	2013	0	3	7	10	14		26	30	35	45	58	
RAZO	2013	0	3	7	10	14		25	31	38	40	59	
RAZO	2013	0	4	6	10	14		25	30	35	53	54	
RAZO	2013	0	4	6	11			23	31	33	50		
RAZO	2013	0	4	8	11	15		24	31	37	45	57	
RAZO	2013	0	4	7	11	14		24	28	37	46	54	
RAZO	2013	0	4	6	11	15		26	34	34	48	63	
RAZO	2013	0	4	7	11			25	29	33	41		
RAZO	2013	0	4	7	11			27	30	40	45		

RAZO	2013	1	4	7	11	14	18	28	33	35	40	46	54
RAZO	2013	1	4	8	11			28	32	40	45		
RAZO	2013	0	4	9	12			24	30	43	50		
RAZO	2013	0	4	7	12	14		26	28	35	49	57	
RAZO	2013	0	4	8	12	15		25	29	34	45	50	
RAZO	2016	0	3	5	10	14		25	32	37	48	58	
RAZO	2016	0	4	6	11	15		22	30	33	40	67	
RAZO	2016	1	4	6	11	15		26	33	39	49	60	
RAZO	2016	0	4	7	12	15		25	34	39	60	65	
RAZO	2016	0	5	7	12	14		24	30	35	41	46	
RAZO	2016	0	4	7	12	15		23	33	31	45	49	
RAZO	2016	1	3	5	12	15		25	26	32	45	63	
RAZO	2016	2	4	7	12			27	29	35	46		
RAZO	2016	0	4	6	13	16		24	32	39	57	68	
RAZO	2016	1	4	8	13	15		27	30	38	53	61	
RAZO	2016	0	3	5	10			25	33		48		
RAZO	2016	0		6	11	14		27		35	49	56	
RAZO	2016	0		7	12	15		28		47	65	75	
RAZO	2016	0		7	12	15		26		35	49	75	
RAZO	2016	1		7	12	15		25		35.5	50	60	
RAZO	2016	1		6	13	16		27		38	56	65	
RAZO	2018	0	4	6	9	12	16	22	30	35	41	60	76
RAZO	2018	0	4	6	10			25	33	37	51		
RAZO	2018	0	3	6	10	14		25	28	32	41	56	
RAZO	2018	0	4	7	10	14		25	28	34	44	63	
RAZO	2018	0	3	6	10	14		25	30	37	48	60	
RAZO	2018	0	3	7	10	14		23	31	43	53	64	
RAZO	2018	0	3	6	10	14		23	27	33	45	56	
RAZO	2018	0	4	6	10	14		25	33	37	50	63	
RAZO	2018	0	3	6	10	14		25	27	31	43	53	
RAZO	2018	0	3	6	10	14		25	30	35	49	61	
RAZO	2018	0	3	6	10	13		26	31	33	42	45	
RAZO	2018	0	3	6	10	14		25	26	33	48	59	
RAZO	2018	0	4	6	10	14		24	30	36	50	58	
RAZO	2018	0	3	6	10	14		24	27	33	49	62	
RAZO	2018	0	3	6	10	14		25	28	40	55	68	
RAZO	2018	1	4	6	10	14		24	28	31	45	57	
RAZO	2018	1	4	7	10	14		28	33	43	53	62	
RAZO	2018	0	4	7	11			25	31	37	50		
RAZO	2018	1	4	8	11	15		26	33	45	57	67	
RAZO	2018	1	4	7	11	16		25	29	34	44	63	
RAZO	2018	0	4	7	12	15		25	33	40	65	71	
RAZO	2018	0	4	8	12	16	19	25	30	30	59	54	61

RAZO	2018	2	5	9	12			25	28	30	36		
RAZO	2018	1	4	9	13	15		25	30	41	55	61	
RAZO	2018	0		6	10	15		22		33	46	61	
RAZO	2019	1	4	8	10	14		25	28	40	46	55	
RAZO	2019	1	3	8	10	15		22	23	28	30	35	
RAZO	2019	1	3	7	10	14		24	26	30	40	48	
RAZO	2019	0	4	8	11			23	29	33	46		
RAZO	2019	1	3	7	11	14		22	30	36	39	47	
RAZO	2019	1	5	7	11	14		25	27	30	39	51	
RAZO	2019	1	3	7	11	14		23.5	29	33	40	40	
RAZO	2019	0	4	9	12	15		26	29	33	37	44	
RAZO	2019	0	4	9	12	15		25	26	36	45	44	
RAZO	2019	1	4	7	12	14		25	31	35	43	49	
RAZO	2019	1	4	9	12	15		27	27	36	36	51	
RAZO	2019	1	4	9	12	15		24	31	39	44	49	
RAZO	2019	1	4	9	12			26	28	33	38		
RAZO	2019	0	4	8	13			25	31	46	61		
RAZO	2019	1	3	7	13			25	32	35	47		
RAZO	2019	1	5	10	13			25	30	32	32		
RAZO	2019	2	5	11	13	15		27	31	42	48		
RAZO	2019	1		7	12	14		25		35	52	56	
RAZO	2021	1	3	7	10			23	29	32	37		
RAZO	2021	1	3	7	10	14		21	23	32	39	50	
RAZO	2021	1	3	7	10	14		25	30	32	36	42	
RAZO	2021	1	3	7	10			23	25	38	37		
RAZO	2021	1	4	8	11	15		25	27	31	37	41	
RAZO	2021	1	4	8	11	15		25	26	29	39	47	
RAZO	2021	1	4	7	11	14		23	29	29	35	39	
RAZO	2021	2	4	7	14			25	29	35	51		
RAZO	2021	1		8	15			24		32	40		
RAZO	2021	1		8	11			26		37	44		
RAZO	2021	4		7	11	14		30		34	41	51	
RAZO	2021	1		8	12			26		35	40		
RAZO	2021	2		9	13			24		32	37		

Table A-2 – Accuracy calculated for all models using 3, 4, or 5 birds (individuals in Training set) to extrapolate ages of other chicks (individuals in Test set). Additional model using 17 Atlantic Puffins in 2016.

Species	Year	Training Birds (n)	Testing Birds (n)	Accuracy (%)
ATPU	2008	3	4	84.89
ATPU	2008	3	7	85.19
ATPU	2008	3	9	85.01
ATPU	2008	3	11	85.08
ATPU	2008	4	4	87.46
ATPU	2008	4	7	86.6
ATPU	2008	4	9	86.47
ATPU	2008	4	10	86.6
ATPU	2008	5	4	87.02
ATPU	2008	5	7	87.39
ATPU	2008	5	9	87.02
ATPU	2014	3	3	84.59
ATPU	2014	3	3	84.19
ATPU	2014	3	5	84.16
ATPU	2014	3	7	84.32
ATPU	2014	4	3	84.16
ATPU	2014	4	3	84.64
ATPU	2014	4	5	84.53
ATPU	2014	4	6	84.76
ATPU	2014	5	3	84.48
ATPU	2014	5	5	85.32
ATPU	2014	5	5	84.89
ATPU	2014	5	5	84.65
ATPU	2016	3	6	74.83
ATPU	2016	3	10	75.16
ATPU	2016	3	14	74.98
ATPU	2016	3	17	75.2
ATPU	2016	4	6	76.41
ATPU	2016	4	10	76.24
ATPU	2016	4	14	76.21
ATPU	2016	4	16	76.24
ATPU	2016	5	6	76.67
ATPU	2016	5	10	76.7
ATPU	2016	5	14	76.81
ATPU	2016	5	15	76.88
ATPU	2016	17	3	78.7
ATPU	2016	17	3	77.39
ATPU	2016	17	3	77.35

ATPU	2016	17	3	78
ATPU	2017	3	9	88.2
ATPU	2017	3	14	88.54
ATPU	2017	3	20	88.48
ATPU	2017	3	26	88.6
ATPU	2017	4	9	89.09
ATPU	2017	4	14	89.13
ATPU	2017	4	20	89.07
ATPU	2017	4	25	89.03
ATPU	2017	5	9	89.46
ATPU	2017	5	14	89.51
ATPU	2017	5	20	89.57
ATPU	2017	5	24	89.59
ATPU	2018	3	10	85.04
ATPU	2018	3	16	85.52
ATPU	2018	3	22	86.12
ATPU	2018	3	29	85.86
ATPU	2018	4	10	86.63
ATPU	2018	4	16	86.52
ATPU	2018	4	22	86.51
ATPU	2018	4	28	86.52
ATPU	2018	5	10	86.88
ATPU	2018	5	16	86.89
ATPU	2018	5	22	86.84
ATPU	2018	5	27	86.9
ATPU	2019	3	5	87.01
ATPU	2019	3	8	86.47
ATPU	2019	3	12	86.68
ATPU	2019	3	14	86.69
ATPU	2019	4	5	87.43
ATPU	2019	4	8	87.32
ATPU	2019	4	12	87.3
ATPU	2019	4	13	87.19
ATPU	2019	5	5	87.42
ATPU	2019	5	8	87.73
ATPU	2019	5	12	87.86
RAZO	2000	3	4	88.07
RAZO	2000	3	6	88.28
RAZO	2000	3	9	87.94
RAZO	2000	4	4	88.51
RAZO	2000	4	6	88.76
RAZO	2000	4	9	89.07
RAZO	2000	5	4	88.8

RAZO	2000	5	6	88.78
RAZO	2000	5	7	88.71
RAZO	2001	3	9	89.01
RAZO	2001	3	12	89.47
RAZO	2001	3	15	89.34
RAZO	2001	3	21	89.58
RAZO	2001	3	26	88.89
RAZO	2001	4	6	90.24
RAZO	2001	4	15	90.07
RAZO	2001	4	21	90.19
RAZO	2001	4	25	90.01
RAZO	2001	5	6	90.48
RAZO	2001	5	15	90.66
RAZO	2001	5	21	90.59
RAZO	2001	5	25	90.33
RAZO	2008	3	5	84.27
RAZO	2008	3	9	85.04
RAZO	2008	3	13	83.28
RAZO	2008	3	15	81.76
RAZO	2008	4	5	85.88
RAZO	2008	4	9	85.87
RAZO	2008	4	13	85.79
RAZO	2008	4	14	85.57
RAZO	2008	5	5	86.79
RAZO	2008	5	9	86.28
RAZO	2008	5	13	86.67
RAZO	2008	5	13	86.24
RAZO	2009	3	3	88.91
RAZO	2009	3	6	89.11
RAZO	2009	3	8	88.97
RAZO	2009	4	3	89.64
RAZO	2009	4	6	89.38
RAZO	2009	4	7	89.54
RAZO	2009	5	3	89.99
RAZO	2009	5	6	89.52
RAZO	2013	3	5	88.18
RAZO	2013	3	9	88.71
RAZO	2013	3	13	88.02
RAZO	2013	3	15	87.95
RAZO	2013	4	5	88.78
RAZO	2013	4	9	89.39
RAZO	2013	4	13	89.07
RAZO	2013	5	5	89.33

RAZO	2013	5	13	89.23
RAZO	2013	5	13	89.26
RAZO	2016	3	5	82.72
RAZO	2016	3	7	83.11
RAZO	2016	3	10	83.41
RAZO	2016	3	12	83.42
RAZO	2016	4	5	84.27
RAZO	2016	4	7	84.82
RAZO	2016	4	10	84.23
RAZO	2016	4	11	84.14
RAZO	2016	5	5	84.72
RAZO	2016	5	7	84.97
RAZO	2016	5	10	84.6
RAZO	2018	3	7	84.07
RAZO	2018	3	12	84.38
RAZO	2018	3	18	84.85
RAZO	2018	3	22	83.97
RAZO	2018	4	7	86.04
RAZO	2018	4	12	85.87
RAZO	2018	4	18	85.97
RAZO	2018	4	21	85.75
RAZO	2018	5	7	86.2
RAZO	2018	5	12	86.24
RAZO	2018	5	18	86.58
RAZO	2018	5	20	86.27
RAZO	2019	3	5	78.9
RAZO	2019	3	9	79.66
RAZO	2019	3	13	79.65
RAZO	2019	3	15	80.47
RAZO	2019	4	5	82.44
RAZO	2019	4	9	81.11
RAZO	2019	4	13	81.09
RAZO	2019	4	14	81.16
RAZO	2019	5	5	81.76
RAZO	2019	5	9	81.54
RAZO	2019	5	13	81.53
RAZO	2021	3	4	79.1
RAZO	2021	3	6	78.51
RAZO	2021	3	9	79.93
RAZO	2021	3	10	80
RAZO	2021	4	4	82.6
RAZO	2021	4	6	82.77
RAZO	2021	4	9	83.18

RAZO	2021	5	4	83.88
RAZO	2021	5	6	84.19
RAZO	2021	5	8	83.98