

# Brazil data

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## 1. are all males represented in all clutches of females they mate with in a season?

```
clean_data %>%  
  group_by(Season, Female) %>%  
  filter(length(unique(Nest)) > 1)
```

```
## # A tibble: 0 x 9  
## # Groups:   Season, Female [0]  
## # i 9 variables: mom_nest_combo <chr>, dad <chr>, hatchling_count <dbl>,  
## #   NestTotalHatchCount <dbl>, propdadcontribute <dbl>,  
## #   LowNestSampleSize <chr>, Season <chr>, Female <chr>, Nest <chr>
```

So far, no more than one clutch is represented per female per season in the dataset.

I will therefore assume that all males are represented in all clutches by the same female throughout the same season.

## 2. how many males do females mate with in one season?

In order to more accurately model evolution with maternal and paternal genotypes, I will build a ‘breeding pool’ of males, where each male will be represented X times, where X is the average number of females that males can mate with, rounded to the nearest integer, dependent upon the mating function. Then, for each female, I need to be able to determine how many males she will mate with to draw that many unique males from the breeding pool.

Number of males	1	2	3	4	5	6	7
Count	13	42	18	36	0	6	7
Proportion	0.11	0.34	0.15	0.30	0	0.05	0.06

Table 1. Number of males that females mated with in raw data

Min	1st Q	Median	Mean	3rd Q	Max	Variance	SD	Skew	Kurtosis
1.000	2.000	3.000	3.115	4.000	7.000	2.433	1.560	0.861	0.265

Table 2. Summary statistics of number of males females mated with

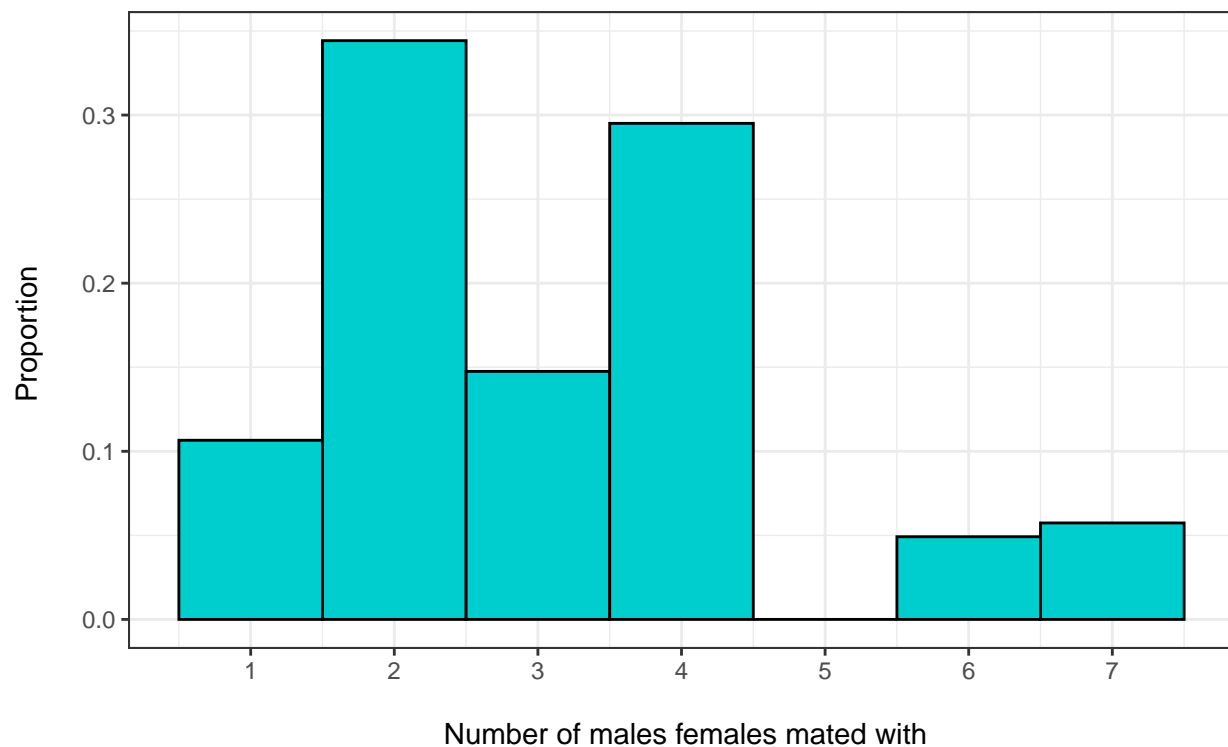


Figure 1. Density histogram of number of males females mated with per season

## why fit a model?

we can't just use the proportions of females that mated with 1 - 7 males since sample sizes are small, and no recorded female mated with 5 males.

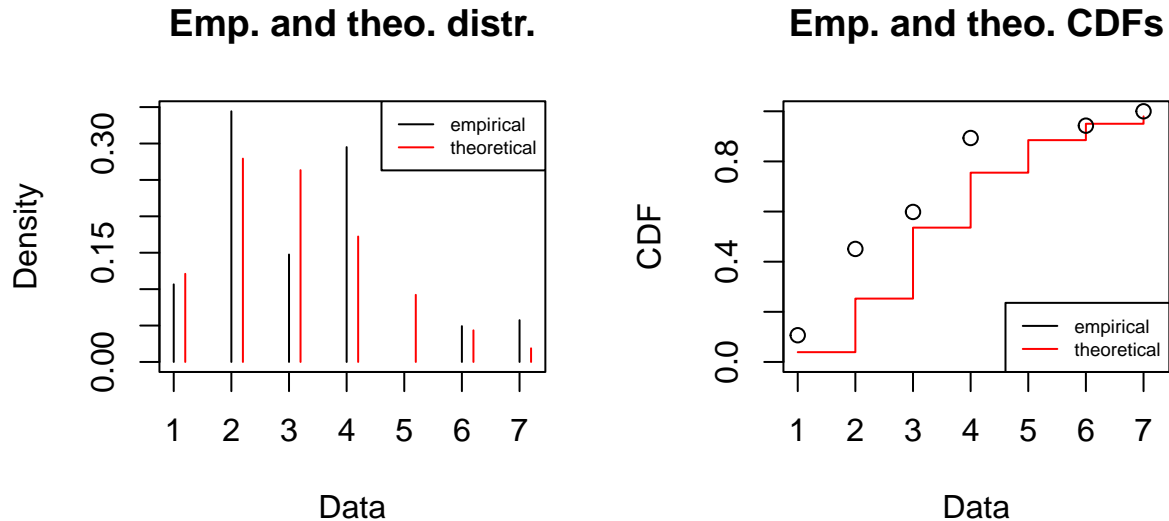
Distribution	Log likelihood	AIC	BIC
discrete gamma	-215.0036	434.0071	439.6152
poisson	-223.1883	448.3767	451.1807
negative binomial	-223.1884	450.3767	455.9848
geometric	-278.3816	558.7632	561.5673

**Table 3. Model fit outputs.**

The discrete gamma distribution had the best fit with the lowest log likelihood, AIC, and BIC values.

## model output and fit:

```
## Fitting of the distribution ' gamma ' by maximum likelihood
## Parameters :
##      estimate Std. Error
## shape 4.109537  0.5062636
## rate  1.319252  0.1728717
## Loglikelihood: -215.0036   AIC:  434.0071   BIC:  439.6152
## Correlation matrix:
##      shape      rate
## shape 1.000000  0.940128
## rate  0.940128  1.000000
```



**Figure 2. Discrete gamma model fit for the number of males females mate with in one season.**

Black lines indicate the density of males females mated with in our FdN dataset, while red lines indicate the predicted density based on the discrete gamma model fit to the data.

given this discrete model...

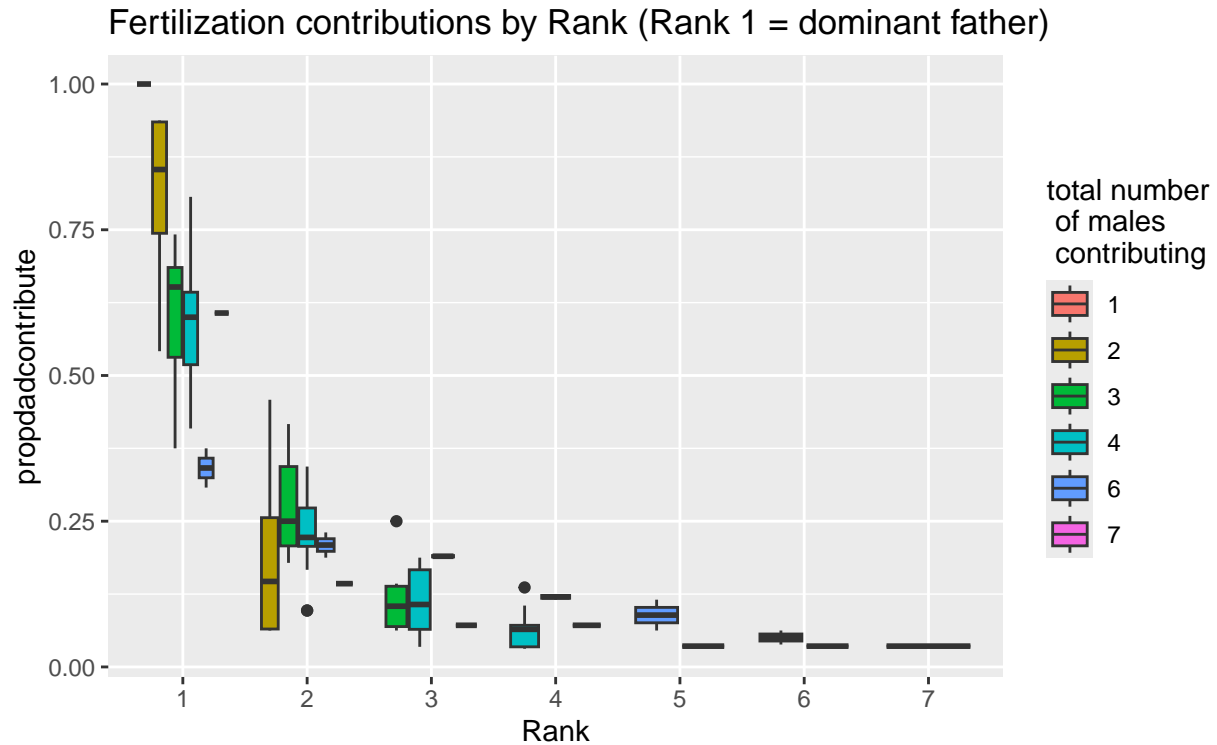
If we assume that females can mate with up to 10 males (i.e. we did not observe all contributing males in our dataset), then we can predict the proportion of females that would mate with 1 to 10 males. Unfortunately, the discrete gamma distribution has a tail that cannot be incorporated into a discrete number of potential male values, so the sum of the weights does not add up to 1, so we have to normalize the weights to add up to one in order to sample from 1:10 males in the code.

Number of males	Model weight	Normalized weight
1	0.214	0.222
2	0.283	0.295
3	0.219	0.228
4	0.130	0.135
5	0.065	0.068
6	0.030	0.031
7	0.012	0.013
8	0.005	0.205
9	0.002	0.002
10	0.001	0.001
<b>Sum</b>	0.961	1.000

**Table 4.** Weighted probabilities for females to mate with 1 to 10 males in any given breeding season.

### 3. how do males fertilize nests?

Within each clutch, do males fertilize offspring randomly, such that each male has the same probability of fertilizing any individual offspring? And do those probabilities change as the total number of contributing males changes?



**Figure 3. Fertilization contributions organized by father 'rank'**

Where rank indicates proportion of offspring fertilized by the  $r^{\text{th}}$  most dominant father, i.e. Rank 1 indicates the father that fertilized the most offspring sampled from that clutch. Per this data, it looks like the total number of contributing fathers does matter, but samples sizes are too small to extrapolate the effect, so the model was fit to grouped data where only Rank mattered.

## model fit

I chose to use a power law because mechanistically it makes sense that for the first male turtle, a certain proportion of eggs will be fertilized. For the second male, a certain proportion of what is left, and for the third male and so on it will always be a proportion of what eggs are left to fertilize, which can easily be quantified using a power rule with a negative exponent.

Power law:  $y(x) = a \cdot p^{-x}$

```
##           Estimate Std. Error   t value    Pr(>|t|)
## (Intercept) -0.3764756 0.05857507  -6.427233 1.784865e-09
## log(Rank)    -1.7101305 0.07090767 -24.117708 1.988142e-52
## [1] 0.800183
```

Where the intercept  $a = \exp(-0.376) = 0.687$  and the exponent  $x = -1.710$ :

$$\text{Proportion father contributes}(\text{Rank}) = 0.687 \cdot \text{Rank}^{-1.710}$$

*Turtles work like gravitational waves! - Jerry*

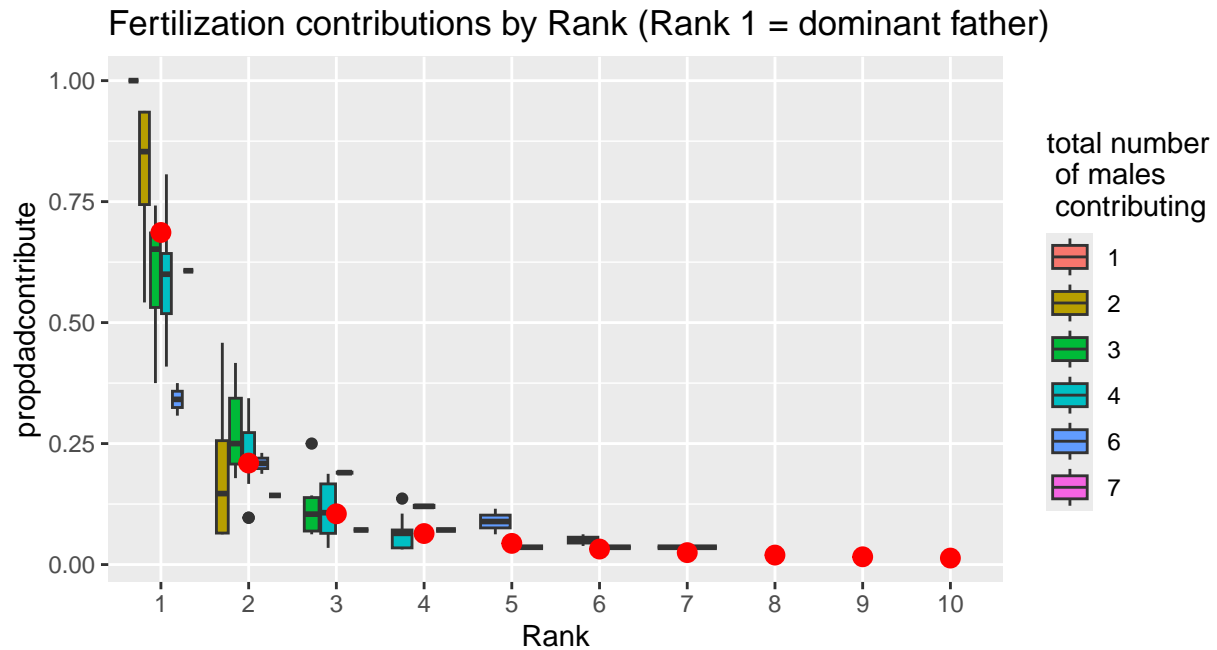


Figure 4. Power law model fit to paternal fertilization contributions organized by father 'rank'

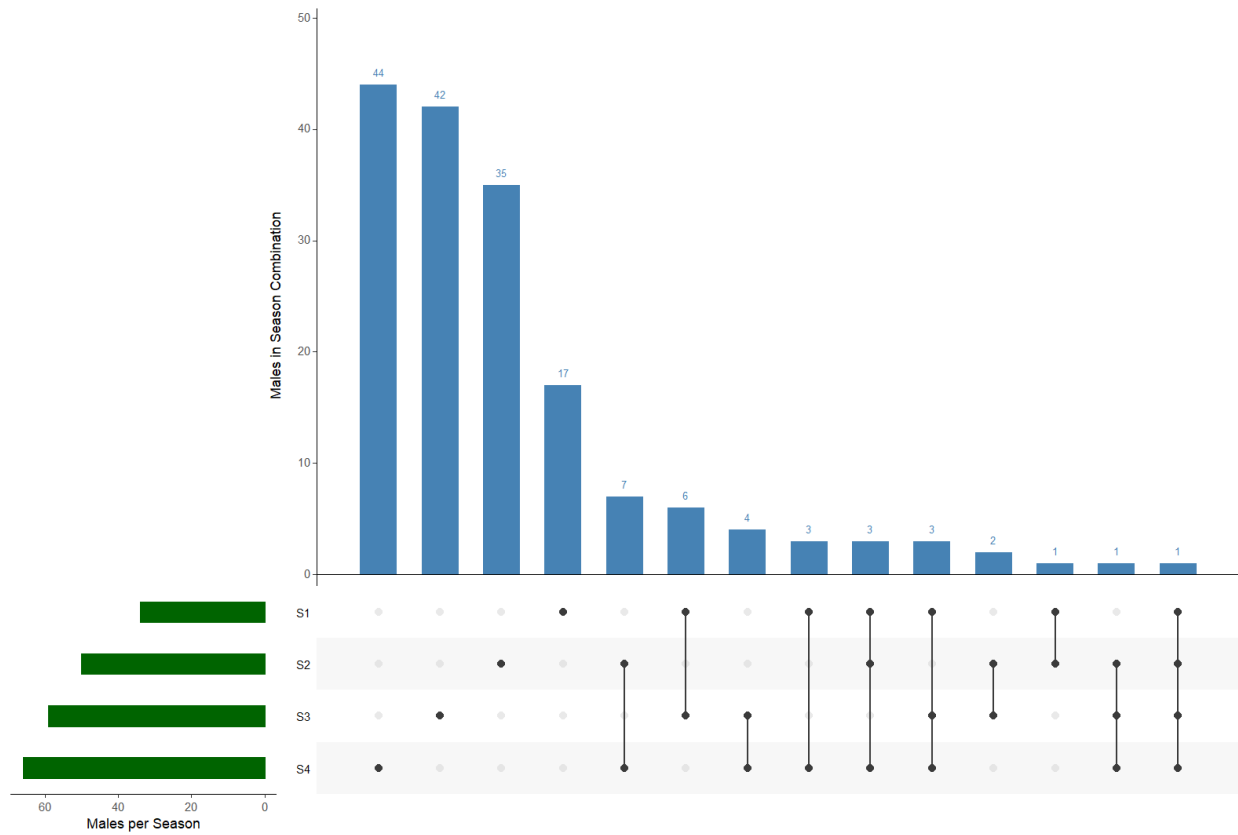
## 4. how often do males remigrate

male remigration interval used in Chapter 2: 1.47 (years)

for male green turtles at Atol das Rocas (Grossman et al., 2019)

<https://www.int-res.com/abstracts/meps/v609/p197-207/>

### FdN genetic data



**Figure 4. FdN male remigration data**

Original data, obtained from Dr. Lisa Komoroske (lkomoroske@umass.edu) on Thursday October 9, 2025. Note: "... Estefany made this upsetR graph for Mariana for an upcoming talk, helps visualize the observed remigration interval a bit for the males (again, keep in mind the difference in sampling effort in S3 and S4, these will need to be normalized to the number of samples run eventually).

## fit a binomial model

### marginalized likelihoods over number of 0 and 1 successes

Given a binomial model, or any resident male green turtle, the probability of seeing it  $k = 1, 2, 3$ , or 4 times across  $n$  years is equal to:

$$L(k) = \binom{n}{k} \cdot p^k \cdot (1-p)^{n-k}$$

We know that  $n = 4$ , since our data were collected over 4 years, giving 4 chances to observe each male. 66 males were observed in season 4, meaning they could have been observed for all previous seasons. We can assume that those males that were observed more than once were residents. For the remaining 44 males, some unknown number of them were residents and others were transient males. For RM1 resident males observed once, there were RM1 + 22 total resident males observed in our dataset.

Given probability  $p$ , the likelihoods of observing RM1 males once, 14 males twice, 7 males 3 times, and 1 male 4 times is the probability of seeing a resident male 1, 2, 3, or 4 times in any given trial of size 4 to the power of the number of times it was observed:

$$\begin{aligned} L(k=1 | p) &= \left( \binom{4}{1} \cdot p^1 \cdot (1-p)^3 \right)^{RM1} \\ L(k=2 | p) &= \left( \binom{4}{2} \cdot p^2 \cdot (1-p)^2 \right)^{14} \\ L(k=3 | p) &= \left( \binom{4}{3} \cdot p^3 \cdot (1-p)^1 \right)^7 \\ L(k=4 | p) &= \left( \binom{4}{4} \cdot p^4 \cdot (1-p)^0 \right)^1 \end{aligned}$$

And the total likelihood of seeing all of these is the product of each probability times the number of potential combinations of the order in which they were observed:

$$L(data | RM1, p) = \frac{(RM1 + 14 + 7 + 1)!}{RM1! 14! 7! 1!} \cdot \prod_{k=1}^{k=4} P(k | RM1, p)$$

The conditional likelihood is then the probability of observing RM1 males once out of all males observed (RM1 + 22) given probability  $p$ :

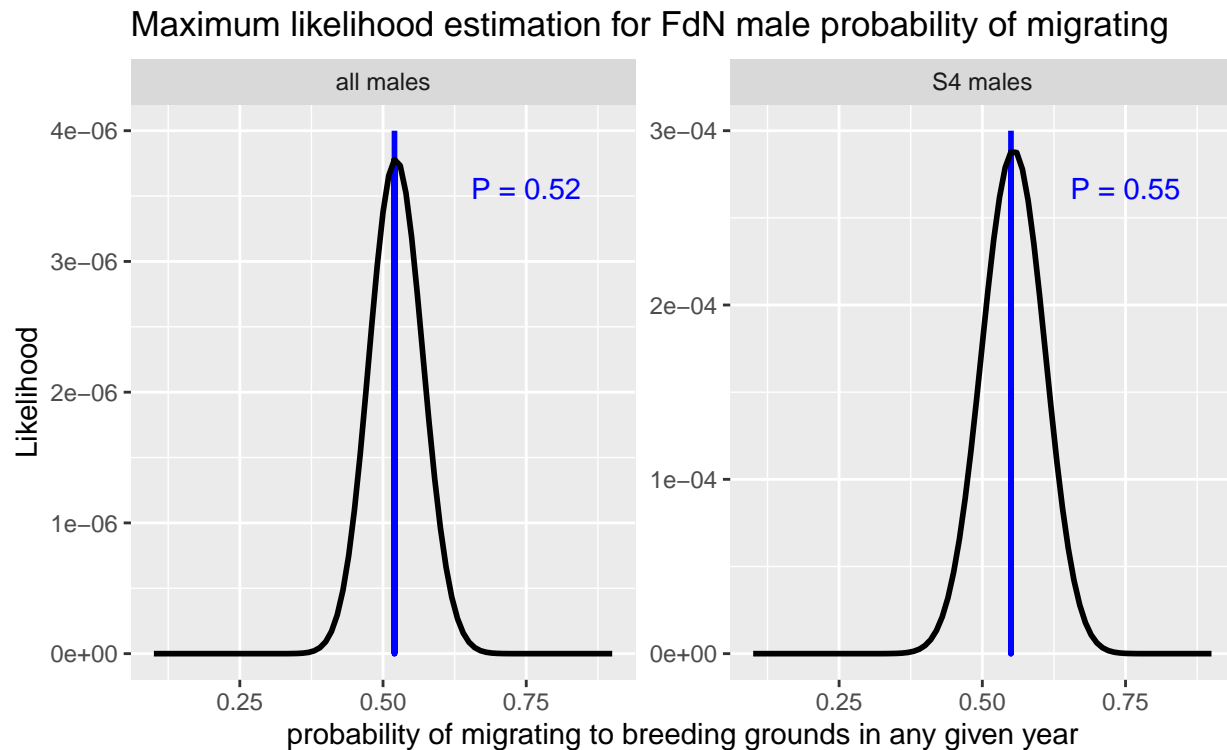
$$\begin{aligned} P(RM1) &= \binom{RM1 + 22}{RM1} \cdot (p(1-p)^3)^{RM1} \cdot (1-p(1-p)^3)^{22} \\ P(RM1 = 1) &= \binom{23}{1} \cdot (p(1-p)^3)^1 \cdot (1-p(1-p)^3)^{22} \end{aligned}$$

The marginalized likelihood for each value of RM1 is then the likelihood times the conditional likelihood, and the total likelihood for each probability  $P$  is equal to the sum of all the marginalized likelihoods across all potential values of RM1.



should we use all males or only males seen in Season 4?

If we compare the results from analysing only those resident males observed in Season 4 (as opposed to all resident males), the results do not substantially change. The maximum likelihood estimator for  $P$  drops from 0.55 to 0.52, but the overall likelihoods are much smaller.



**Figure 5.** Likelihood of different probabilities  $P$  of FdN resident males mating in any given breeding year

Analysis	Log likelihood	Probability	Remigration Interval
All males	0.00000378	0.52	1.92
Season 4 males only	0.000288	0.55	1.82

**Table 5.** Maximum likelihood estimators for probability  $P$  of any one resident FdN male migrating to breeding grounds in any breeding season.

The final maximum likelihood estimator for the binomial probability of males mating is therefore  $p = 0.55$ , with an associated average remigration interval of 1.82 years.