# Green Sea Turtle Population

## MATH 3006 Class Project

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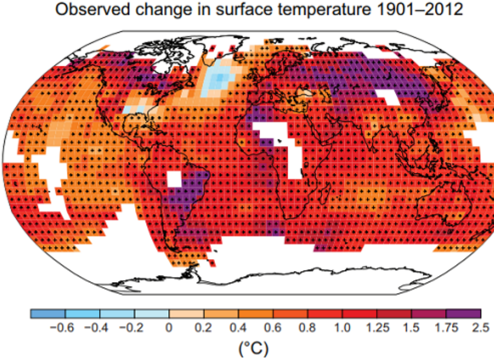
# A consequence of global warming

"Quantitative genetic analyses and behavioral data suggest that populations with temperature-dependent sex determination may be unable to evolve rapidly enough to counteract the negative fitness consequences of rapid global temperature change." (Janzen, 1994)




(Stocker,2013)

# Evidince of Janzen's claim


- The green sea turtle (Chelonia Mydas) is an endangered species (Seminoff, 2004).
- Global warming predicts a temperature increase in the coming decades (Stocker, 2013).
- Recent data shows 116 female green sea turtles to every 1 male green sea turtle (Jensen et al., 2018).

(Image credit:https://www.nbcnews.com/science/environment/population-green-sea-turtles-nearly-all-female-signalling-major-problem-n837341)

# Nesting near the equator

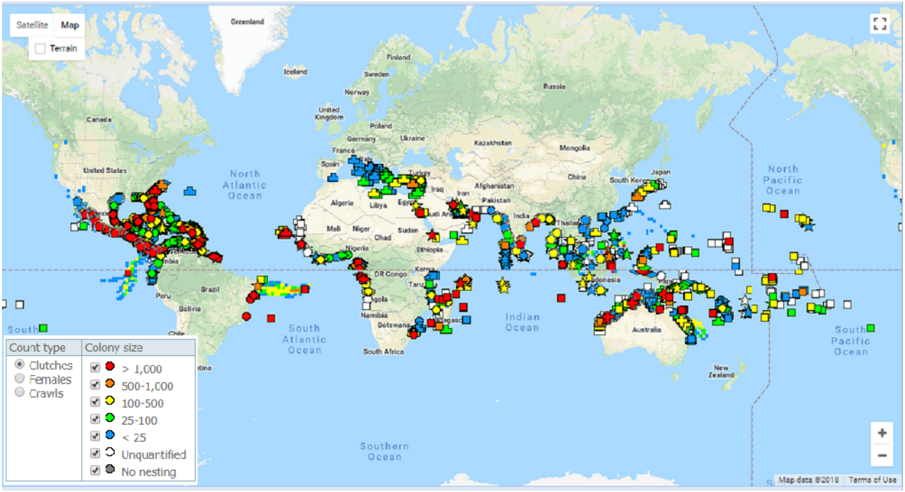
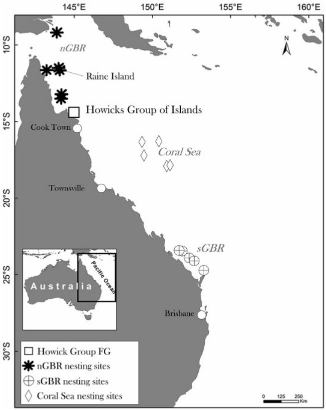



Figure: Worldwide green turtle nesting sites, aka. clutches (Halpin, 2009).

# Northern Great Barrier Reef (nGBR) subpopulation



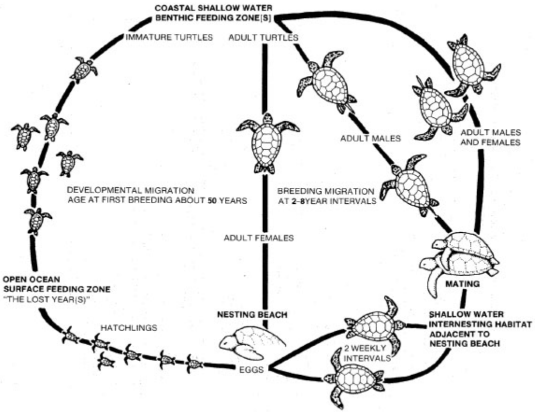




Figure: Left: Map of the region of interest (Jansen et al., 2018).
Right: Life cycle of green sea turtle (`coraldigest.com`)

# The life of a turtle

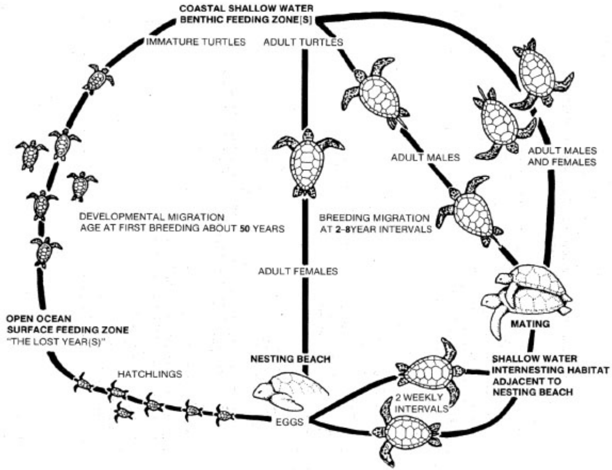



Figure: 6 stages in the life cycle (coraldigest.com)

# Our Approach

Develop a two sex population model using a modified Leslie matrix.

Determine the relationship between temperature and the proportion of the population which is female. Call this function $\chi(T)$.

Determine the relationship between air temperature ($AT$), sea surface temperature ($SST$), and nesting temperature ($T$). Call this function $T(SST, AT)$.

Apply an annual temperature increase function $T(t)$ to $T(SST, AT)$ and apply to $\chi(T)$ so we have $\chi(t)$ to use in modified Leslie matrix.

Compare to previous models.

Predict future female proportion in the region.

# Model Terminology

The following terms have important meaning:

- **Survival Rate** is the proportion of the turtles which survive each year.
- **Progression Rate** is the proportion of turtles which survive and advance to the next life stage.
- **Remaining Rate** is the proportion of turtles which survive but remain in the same life stage for another year.
- **Duration** is the length of time it takes for a turtle to grow to the next size.

# Class divisions

The stages are divided by size. Each stage has a growth rate, and thus a duration for each stage.

| Stage | Name | $\tau$ (years) | Size (cm CCL*) | % Mature |
|---|---|---|---|---|
| 1 | Egg-Hatchling | 1 | $< 5$ | 0 |
| 2 | Pelagic Juvenile | 4-5 | 5-40 | 0 |
| 3 | Benthic Juvenile | 11 | 40-62 | 0 |
| 4 | Subadult | 19 | 62-91 | 0 |
| 5 | Maturing Adult | 5 | 91-97 | $<$50 |
| 6 | Adult | 18-19 | $> 97$ | $>$50 |

Curved Carpace Length (CCL) is width of the underside of the shell.

(Chaloupka, 2004).

A turtle which has a 5cm CCL is 1 year old.
Note: 97cm indicates the size when turtles become more reproductive.

# Parameter Table

| Symbol | Meaning |
|---|---|
| $\chi$ | Proportion of hatched female |
| $1-\chi$ | Proportion of hatched male |
| $\sigma_i^m$ | Survival rate of male |
| $\sigma_i^f$ | Survival rate of female |
| $p_i^m$ | Remaining rate of male |
| $p_i^f$ | Remaining rate of female |
| $q_i^m$ | Progression rate of male |
| $q_i^f$ | Progression rate of female |
| $f_i$ | Reproductive rate |
| $\tau_i^m$ | Male duration (years) |
| $\tau_i^f$ | Female duration (years) |
| T | Temperature (Celsius) |
| t | time (year, ie. 2018) |

note: $i$ denote $i^{th}$ stage, and $i = 1, 2, 3, 4, 5, 6$.

# Assumptions

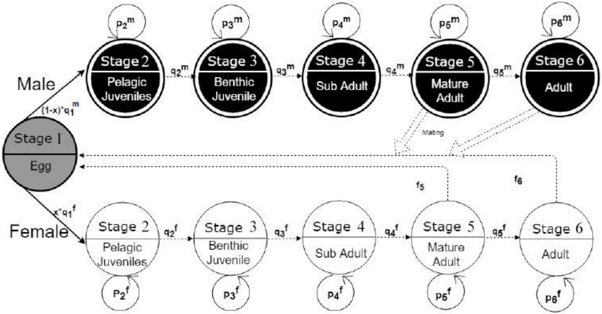
1. The model consists of six stages for both male and female turtles. These stages are based on both size and the probability of being sexually mature. (Chaloupka, 2002)
2. Migratory behavior is ignored (Crouse et al., 2008).
3. The female proportion can only be affected by temperature.
4. The proportion of female offspring ($\chi$) changes each year.
5. The parameters other than $\chi$, $T$ and $t$ remain constant from generation to generation (Crouse et al., 2008; Chaloupka & Limpus, 2005).
6. The life of turtle will end after the adult stage (stage 6).
7. The temperature ($T$) does not affect the survival rate ($\sigma$).

# Assumptions

8. The mating process is ignored.
9. The Sea Surface Temperature (SST) in the nGBR region is constant and assumed $21^{\circ}C$
10. When the size is greater than 60cm CCL, females grow faster than males (Chaloupka et al.,2004). This leads to the following assumptions about the duration of each stage:

| Stage | Name | Duration of male $\tau_i^m$ (years) | Duration of female $\tau_i^f$ (years) |
|---|---|---|---|
| 1 | Egg-Hatchling | 1 | 1 |
| 2 | Pelagic Juvenile | 4 | 4 |
| 3 | Benthic Juvenile | 11 | 11 |
| 4 | Subadult | 20 | 18 |
| 5 | Maturing Adult | 6 | 4 |
| 6 | Adult | 18 | 22 |

# Flowchart




| Symbol | Meaning |
|---|---|
| $\chi$ | Proportion female |
| $p_i$ | Remaining rate |
| $q_i$ | Progression rate |
| $f_i$ | Reproductive rate |

Figure: The population is divided by sex along the top and bottom paths. The rates of remaining, progression and reproduction are all represented by arrows. Flowchart created using `https://www.draw.io/`.

# Population vector

| Stage | Symbol | Meaning |
|---|---|---|
| 1 | $A_t$ | Eggs in year t |
| 2 | $B_t$ | Pelagic Juveniles in year t |
| 3 | $C_t$ | Benthic Juveniles in year t |
| 4 | $D_t$ | Subadults in year t |
| 5 | $E_t$ | Mature Adults in year t |
| 6 | $F_t$ | Adults in year t |

Note: t in year name, ie. 2018

# Modified Leslie matrix

If we combine two genders into one matrix we get the form:

$$\begin{bmatrix} A_{t+1} \\ B^m_{t+1} \\ C^m_{t+1} \\ D^m_{t+1} \\ E^m_{t+1} \\ F^m_{t+1} \\ B^f_{t+1} \\ C^f_{t+1} \\ D^f_{t+1} \\ E^f_{t+1} \\ F^f_{t+1} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & f^f_5 & f^f_6 \\ (1-\chi)q^m_1 & p^m_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & q^m_2 & p^m_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & q^m_3 & p^m_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & q^m_4 & p^m_5 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & q^m_5 & p^m_6 & 0 & 0 & 0 & 0 & 0 \\ \chi * q^f_1 & 0 & 0 & 0 & 0 & 0 & p^f_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & q^f_2 & p^f_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & q^f_3 & p^f_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & q^f_4 & p^f_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & q^f_5 & p^f_6 \end{bmatrix} \begin{bmatrix} A_t \\ B^m_t \\ C^m_t \\ D^m_t \\ E^m_t \\ F^m_t \\ B^f_t \\ C^f_t \\ D^f_t \\ E^f_t \\ F^f_t \end{bmatrix}$$

# Equation

We call upon earlier work on another species of turtles to derive the parameters $p_i$ and $q_i$.

$$p_i = \left(\frac{1 - \sigma_i^{\tau_i - 1}}{1 - \sigma_i^{\tau_i}}\right)\sigma_i$$

$$q_i = \frac{\sigma_i^{\tau_i}(1 - \sigma_i)}{1 - \sigma_i^{\tau_i}}$$

(Crouse et al., 2008)

| Symbol | Meaning |
|---|---|
| $\sigma_i$ | Survival rate % |
| $p_i$ | Remaining rate % |
| $q_i$ | Progression rate % |

Let's denote $\sigma_i^{\tau_i}$ for the probability for the turtles in stage $i$ surviving $\tau$ years. Then, we can have the total percentage of Remaining rate of stage $i$:

$$p_i = \left( \frac{1 + \sigma_i + \sigma_i^2 + \ldots + \sigma_i^{\tau_i - 2}}{1 + \sigma_i + \sigma_i^2 + \ldots + \sigma_i^{\tau_i - 1}} \right) \sigma_i$$

by geometric series

$$1 + \sigma + \sigma^2 + \ldots + \sigma^{\tau - 1} \Rightarrow \frac{(1 - \sigma^\tau)}{(1 - \sigma)}$$

we can rewrite $p_i$ as

$$p_i = \left( \frac{1 - \sigma_i^{\tau_i - 1}}{1 - \sigma_i^{\tau_i}} \right) \sigma_i$$

Next, we assume that the proportion of the population that grows into the next stage class and survives $q$ so we have:

$$q_i = \left( \frac{\sigma_i^{\tau_i - 1}}{1 + \sigma_i + \sigma_i^2 + \ldots + \sigma_i^{\tau_i - 1}} \right) \sigma_i$$

by geometric series, the equation can be rewritten as as

$$q_i = \frac{\sigma_i^{\tau_i}(1 - \sigma_i)}{1 - \sigma_i^{\tau_i}}$$

The proof above is from research into the loggerhead sea turtles, we use the method to get the remaining rate $p$, and the progression rate $q$ (Crouse et al., 2008).

| Male Parameter Table | | | | | |
|---|---|---|---|---|---|
| | $(\tau_i^m)$ | $(\sigma_i^m)$ | $(p_i^m)$ | $(q_i^m)$ | $(f_i^m)$ |
| Stage 1 | 1 | 0.4394 | 0 | 0.4394 | 0 |
| Stage 2 | 4 | 0.6445 | 0.5703 | 0.0741 | 0 |
| Stage 3 | 11 | 0.8804 | 0.8413 | 0.0391 | 0 |
| Stage 4 | 20 | 0.8474 | 0.8416 | 0.0058 | 0 |
| Stage 5 | 6 | 0.9482 | 0.8104 | 0.1378 | 0 |
| Stage 6 | 18 | 0.9482 | 0.9159 | / | 0 |

(Chaloupka, 2005)

| Female Parameter Table | | | | | |
|---|---|---|---|---|---|
| | $(\tau_i^f)$ | $(\sigma_i^f)$ | $(p_i^f)$ | $(q_i^f)$ | $(f_i^f)$ |
| Stage 1 | 1 | 0.4394 | 0 | 0.4394 | 0 |
| Stage 2 | 4 | 0.6445 | 0.5704 | 0.0741 | 0 |
| Stage 3 | 11 | 0.8804 | 0.8413 | 0.0391 | 0 |
| Stage 4 | 18 | 0.8474 | 0.8392 | 0.0082 | 0 |
| Stage 5 | 4 | 0.9482 | 0.7297 | 0.2185 | 36.3 |
| Stage 6 | 22 | 0.9482 | 0.9248 | / | 72.6 |

(Chaloupka, 2005)

# Modified Leslie matrix

$$\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 36.3 & 72.6 \\
(1-\chi)*0.4394 & 0.5703 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.0741 & 0.8413 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.0391 & 0.8416 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.0058 & 0.8104 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.1378 & 0.9159 & 0 & 0 & 0 & 0 & 0 \\
\chi*0.4394 & 0 & 0 & 0 & 0 & 0 & 0.5704 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.0741 & 0.8413 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0391 & 0.8392 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0082 & 0.7297 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2185 & 0.9248
\end{bmatrix}$$

Next we turn to the relationship between temperature and the female proportion of the population.

# Temperature dependent sex function

$$\chi(T) = \frac{1}{1 + e^{\beta(T - T_0)}}$$

Let $\chi$ be the proportion of female turtle hatchlings at sand temperature $T$. We expect the following behavior based on temperature dependent sex determination.

$$T \to T_{HotDeath}, \chi(T) \to 1.$$
$$T \to T_{50/50}, \chi(T) \to 0.5.$$
$$T \to T_{ColdDeath}, \chi(T) \to 0.0.$$

$\beta$ is established as $-1.3$ and $T_0 = 29.18$ Celsius (Hays, 2017). Therefore,

$$\chi(T) = \frac{1}{1 + e^{-1.3(T - 29.18)}}$$

# Sand Temperature function

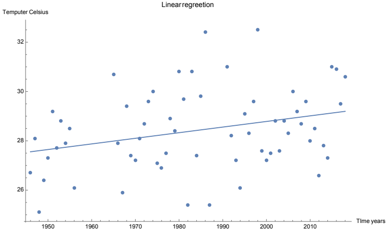
The temperature in the proportion female function is the sand temperature. The sand temperature of the nest is dependent on the air temperature (AT) and sea surface temperature (SST) (Fuentes et.al, 2009).
Moulter Cay is the near Raine Island and serves as a fair comparison The Temperature increase for the offshore nesting sites in the area.
Moulter Cay Sand temperature (Fuentes et. al., 2009) =

$$T(SST, AT) = -0.236SST + 1.022AT + 6.915$$

# Temperature Increase from global warming

We assume the sea surface temperature (SST) is constant 21°C. Air Temperature (AT) is what is subject change from global warming.
To model the increased air temperature we used data from the area and fit a linear regression model to determine the following for $t$ in year (ie, 2017).

$$AT[t] = 0.0227692x - 16.7534$$




the data is from `http://www.bom.gov.au/other/copyright.shtml`

Then we got our female proportion function

$$\chi(t) = \frac{1}{1 + 9.51172 \times 10^{24} e^{(-0.0302512t)}}$$

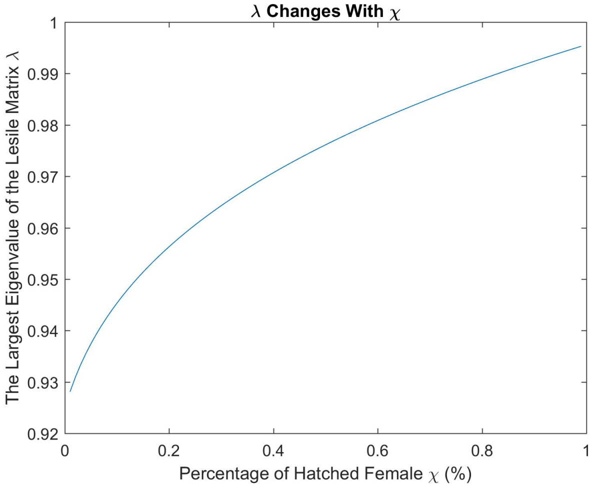
$$\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 36.3 & 72.6 \\
(1-\chi(t)) * 0.4394 & 0.5703 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.0741 & 0.8413 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.0391 & 0.8416 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.0058 & 0.8104 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.1378 & 0.9159 & 0 & 0 & 0 & 0 & 0 \\
\chi(t) * 0.4394 & 0 & 0 & 0 & 0 & 0 & 0.5704 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.0741 & 0.8413 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0391 & 0.8392 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0082 & 0.7297 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2185 & 0.9248
\end{bmatrix}$$

# Data Fitting

Temperature data with proportion female for hatching from Taiwan (Rowena, 2013).

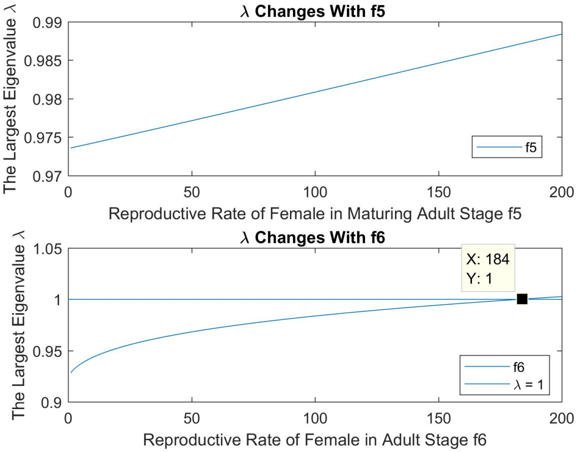
| Year | 2010 | 2011 |
|---|---|---|
| Number of eggs hatched | 142 | 102 |
| Number of females | 87 | 98 |
| Average temperature | 26.7875 | 30.275 |
| Percentage of female in data | 0.612676 | 0.960784 |
| Our prediction of female percentage | 0.781875 | 0.979835 |

# Eigenvalue

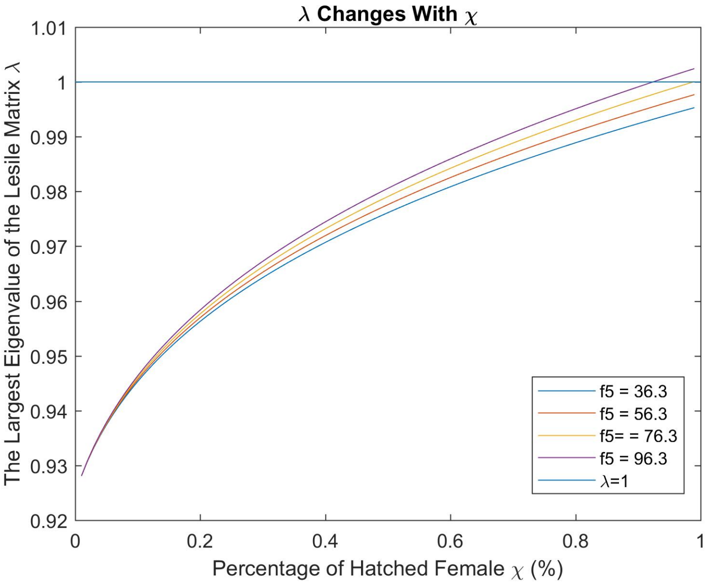


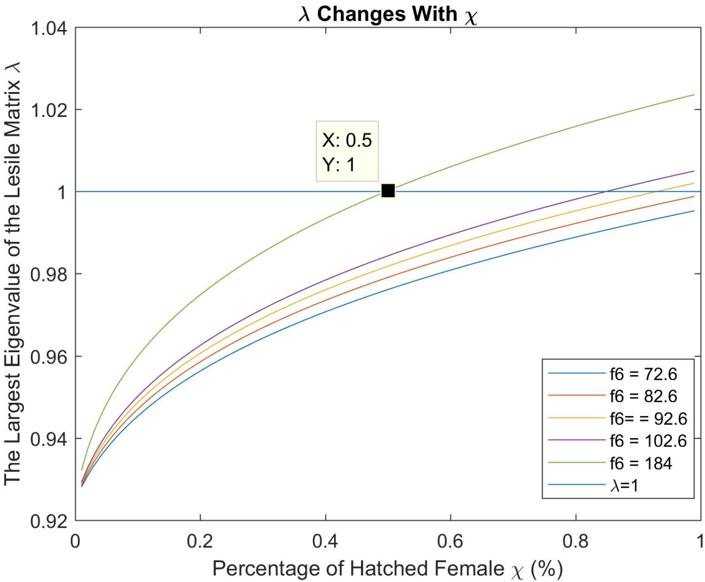

$\lambda < 1$ for all possible $\chi$

# Parameter Effects

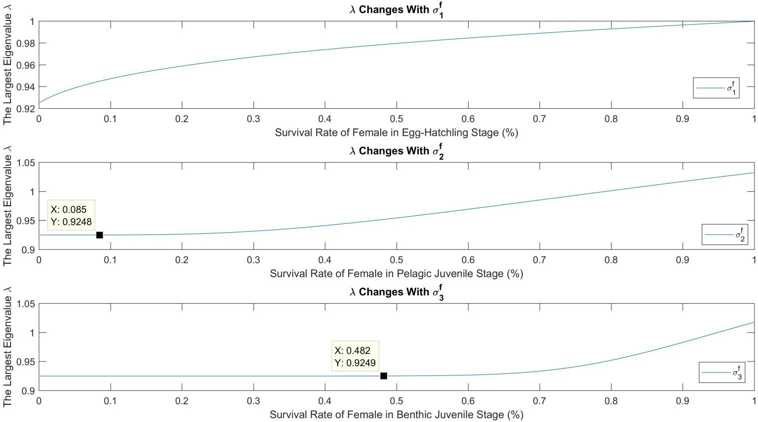



note: $\chi = 0.5$


λ Changes With χ
The Largest Eigenvalue of the Lesile Matrix λ
Percentage of Hatched Female χ (%)
1.01
1
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0
0.2
0.4
0.6
0.8
1
f5 = 36.3
f5 = 56.3
f5= = 76.3
f5 = 96.3
λ=1

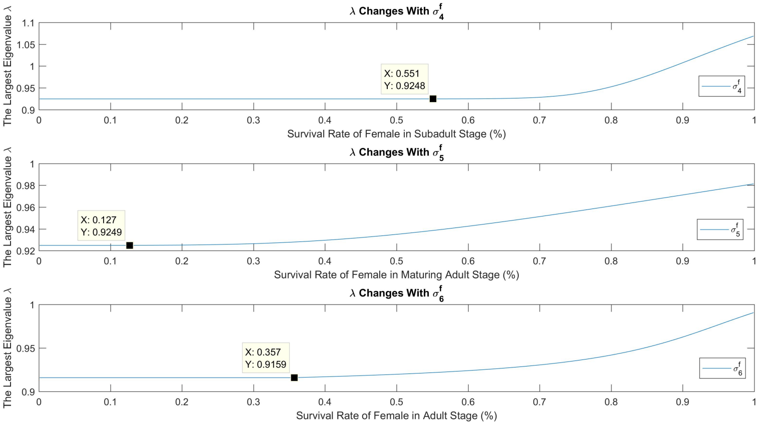

λ Changes With χ
The Largest Eigenvalue of the Lesile Matrix λ
1.04
1.02
1
0.98
0.96
0.94
0.92
0
0.2
0.4
0.6
0.8
1
Percentage of Hatched Female χ (%)
X: 0.5
Y: 1
f6 = 72.6
f6 = 82.6
f6= = 92.6
f6 = 102.6
f6 = 184
λ=1

# Parameter Effects

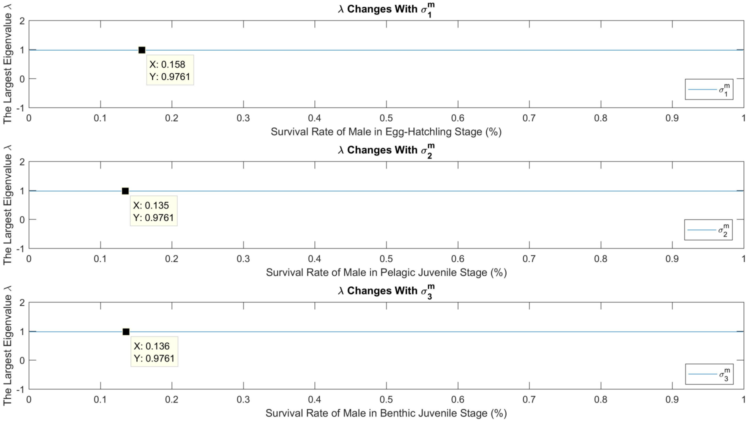



note: $\chi = 0.5$ ($\sigma_2^f = 0.6445$, $\sigma_3^f = 0.8804$)

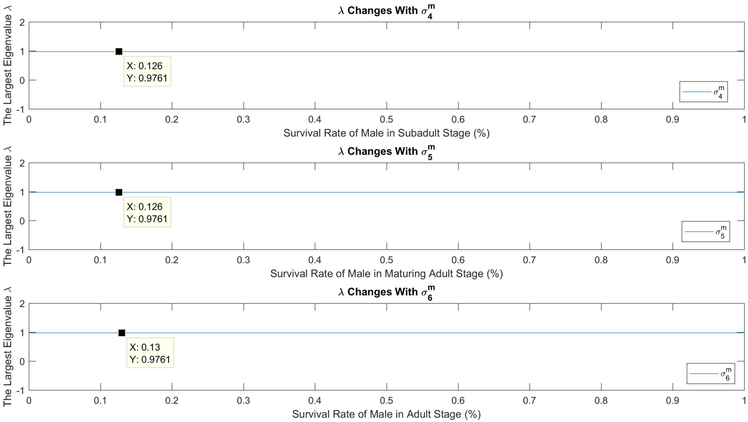
# Parameter Effects




note: $\chi = 0.5$ ($\sigma_4^f = 0.8474$, $\sigma_5^f = 0.9482$, $\sigma_6^f = 0.9482$)

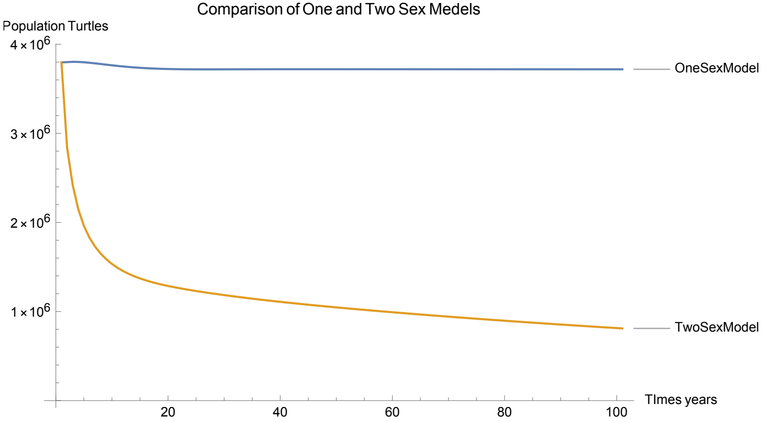

λ Changes With $\sigma_1^m$
The Largest Eigenvalue λ
X: 0.158
Y: 0.9761
$\sigma_1^m$
Survival Rate of Male in Egg-Hatchling Stage (%)
λ Changes With $\sigma_2^m$
The Largest Eigenvalue λ
X: 0.135
Y: 0.9761
$\sigma_2^m$
Survival Rate of Male in Pelagic Juvenile Stage (%)
λ Changes With $\sigma_3^m$
The Largest Eigenvalue λ
X: 0.136
Y: 0.9761
$\sigma_3^m$
Survival Rate of Male in Benthic Juvenile Stage (%)

note: $\chi = 0.5$


λ Changes With σ^m_4
The Largest Eigenvalue λ
X: 0.126
Y: 0.9761
Survival Rate of Male in Subadult Stage (%)
λ Changes With σ^m_5
The Largest Eigenvalue λ
X: 0.126
Y: 0.9761
Survival Rate of Male in Maturing Adult Stage (%)
λ Changes With σ^m_6
The Largest Eigenvalue λ
X: 0.13
Y: 0.9761
Survival Rate of Male in Adult Stage (%)

note: $\chi = 0.5$

# Two sex model vs. one sex model




note: The initial year is 2018

The reasons we used a two-sex model to determine the population of the green sea turtle.

- Determine how temperature can affect the total population.
- Most researchers use size to determine the age of the turtle, in fact the growth rates differ for males and females.
- Both males and females have multiple mating partners during a breeding season.

# Based on our model

- Our model shows the decreasing trend on green sea turtle's population.
- The increasing of temperature can affect the total population.
- Increasing the survival rate in stage 4 $\sigma_4$ is more easy to change the decreasing trend.
    - Have more laws about fishing.
    - Set some special region for the green sea turtle.
- Increasing the reproductive rate($f_5$ and $f_6$) can help to save the green sea turtle's population.
    - Develop artificial reproduction.
    - Clean up the beach.

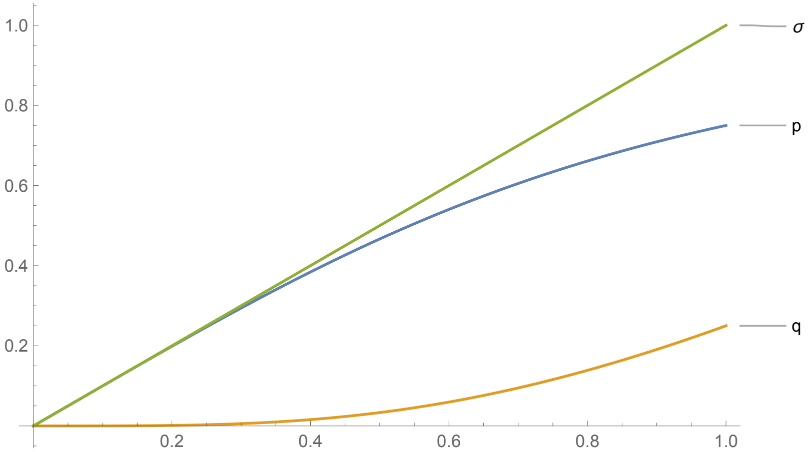
# what we did before

let $P_0$ be the initial $p_i$ value that we got in our matrix [?]

| parameter | $P_0$ | when $\lambda = 1$ | $\sigma_0$ | $\sigma$ |
|---|---|---|---|---|
| $p_2^f$ | 0.5704 | 0.813 | 0.644 5 | 1.19735 |
| $p_3^f$ | 0.8413 | 0.93 | 0.8804 | 1.0516 |
| $p_4^f$ | 0.8392 | 0.93 | 0.8474 | 0.9719 |
| $p_5^f$ | 0.7297 | 0.883 | 0.9482 | 1.5385 |
| $p_6^f$ | 0.9248 | 0.971 | 0.9482 | 1.04059 |

let $Q_0$ be the initial $q_i$ value that we got in our matrix

| parameter | $Q_0$ | $\lambda = 1 \Rightarrow q_i =$ | $\sigma_0$ | $\sigma$ |
|---|---|---|---|---|
| $q_1^f$ | 0.4394 | 0.999 | 0.4394 | 0.999 |
| $q_2^f$ | 0.0741 | 0.09 | 0.6445 | 0.6878 |
| $q_3^f$ | 0.0391 | 0.172 | 0.8804 | 1.1249 |
| $q_4^f$ | 0.0082 | 0.019 | 0.8474 | 0.9055 |
| $q_5^f$ | 0.2185 | 0.557 | 0.9482 | 1.42 |


1.0
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
1.0
σ
p
q

# Future development

| Stage | Natural Risk | Human Risk |
|---|---|---|
| 1 | Beach predators ie. Coyotes | Development loss of habitat |
| 2,3 | Ocean predators ie. Tiger Shark | Fishing bycatch Troll fishing nets |
| 4,5,6 | Ocean predators | Fishing bycatch |
| (Stocker, 2013). | | |

We have created a model which can be used to investigate the population dynamics of the green sea turtle, but we ignored some factors.
Therefore, our model do not consider some extreme condition.
The ideas for solving those problem

- Chaloupka, M. (2002). Stochastic simulation modeling of southern Great Barrier Reef green turtle population dynamics. Ecological modelling, 148(1), 79-109.
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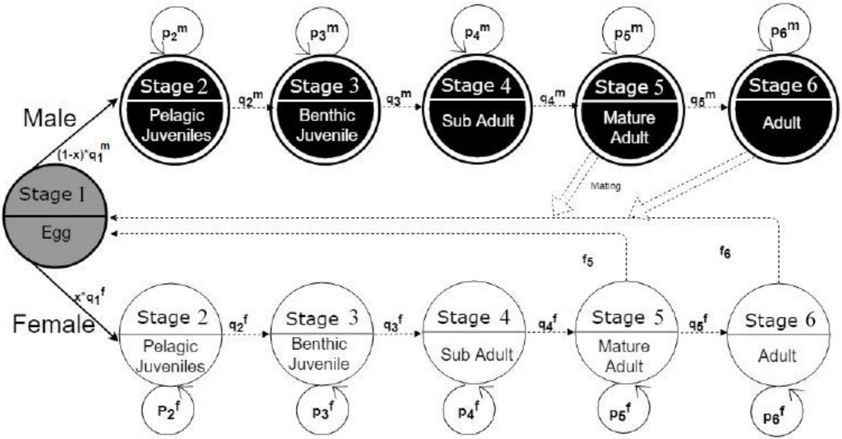
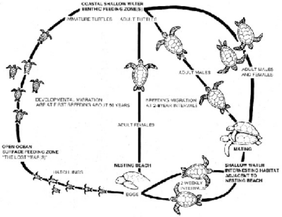
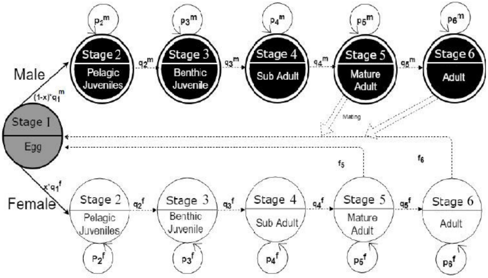

Male
Female
Stage 1
Egg
(1-x)*q1m
x*q1f
Stage 2
Pelagic Juveniles
Stage 3
Benthic Juvenile
Stage 4
Sub Adult
Stage 5
Mature Adult
Stage 6
Adult
p2m
p3m
p4m
p5m
p6m
q2m
q3m
q4m
q5m
Mating
f5
f6
q2f
q3f
q4f
q5f
P2f
p3f
p4f
p5f
p6f

| Stage | Symbol | Meaning |
|---|---|---|
| 1 | $A_t$ | Eggs in year t |
| 2 | $B_t$ | Pelagic Juveniles in year t |
| 3 | $C_t$ | Benthic Juveniles in year t |
| 4 | $D_t$ | Subadults in year t |
| 5 | $E_t$ | Mature Adults in year t |
| 6 | $F_t$ | Adults in year t |

| **Symbol** | **Meaning** |
|---|---|
| $\chi$ | Proportion of hatched female |
| $1-\chi$ | Proportion of hatched male |
| $\sigma_i^m$ | Survival rate of male |
| $\sigma_i^f$ | Survival rate of female |
| $p_i^m$ | Remaining rate of male |
| $p_i^f$ | Remaining rate of female |
| $q_i^m$ | Progression rate of male |
| $q_i^f$ | Progression rate of female |
| $f_i$ | Reproductive rate |
| $\tau_i^m$ | Male duration (years) |
| $\tau_i^f$ | Female duration (years) |
| T | Temperature (Celsius) |
| t | time (year, ie. 2018) |

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