CLIMATIC IMPACTS ON OCEAN ECOSYSTEMS:

A STUDY OF CLIMATE VARIABILITY

AND CONSERVATION OCEANOGRAPHY

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Impacts of climate change on ocean ecosystems occur globally, affecting all components of the ecosystem, from the physical environment to the biology. The Mediterranean Sea was chosen to study climate variability in the physical environment, while from the biological environment, the endangered population of Northern right whales (*Eubalaena glacialis*) was selected to study its sensitivity to different food availability scenarios. An introduction and explanation of the relevant issues relating to the Mediterranean Sea and of the salient points of ocean ecosystems and whales are presented in Chapter One. Our results indicate that the entire Mediterranean Sea has undergone an increase in temperatures with a leveling-off observed in the second half of the record (Chapter Two). This warming in the Mediterranean, which is almost double that of the global oceans, occurred at both multidecadal and interannual time scales and it is driven primarily by changes in annual net surface heat flux. We also show that survival and reproductive rates of northern right whales are dependent on food availability (Chapter Three). Under high food availability, the right whale population continues to grow into the future. However, when food availability is low, the population declines, the calving interval increases significantly, and the population will go extinct in the next three decades. However, protecting just one female out of 100 whales every year when food

concentrations are low can help the population grow and avoid extinction. We conclude in Chapter Four that it will be valuable to investigate future trends in climate variability in the Mediterranean to determine whether the recent leveling-off of temperatures represents a brief respite from a persistent warming or a new direction for the Mediterranean. Current conservation oceanography efforts should take into consideration the relationship between the whales and the variabilities of their food sources, and should attempt to maintain mortality rates as low as possible, if we are to save the right whale population from extinction. Overall, we need to understand the causes and sources of climate variability, in order to be able to make the hard decisions necessary to diminish anthropogenic impacts on global ocean ecosystems.

Ioanna Samouel, also known as Yianna Samuel-Rhoads was raised in Cyprus. After finishing high school there, she received a Fulbright scholarship that covered all four years of her undergraduate education. With the scholarship, she was able to come to the US in 1996 to attend the University of Miami, Florida. She double majored in Marine Sciences and Biology, and also minored in Chemistry. During her undergraduate years, Yianna discovered her love of teaching through 3 years of tutoring fellow students. In her senior year, Yianna interned for one semester at the Office of Protected Resources at the National Marine Fisheries Services in Silver Spring, Maryland. The internship peaked her interest in the effects of underwater sound on behavior and the well-being of marine animals. She completed her undergraduate work, under the guidance of Daniel DiResta, with Cum Laude, General Honors, and Departmental Honors in Marine Science. Yianna then moved to Ithaca in 2000 to attend Cornell University. She continued her studies pursuing an M.S. degree in the field of Zoology under the guidance of Steve Morreale, Milo Richmond, Christopher Clark, and Charles Greene. Yianna focused her research interests on the effects of underwater anthropogenic noise on sea turtles in coastal areas. When she presented her research at the 2003 International Sea Turtle Symposium, she received the Archie Carr Best Student Presentation Award for best conservation paper. During her master's studies, Yianna was awarded the Golden Apple Award for Outstanding Graduate Teaching Assistant twice, for teaching introductory oceanography laboratories, as well as for teaching the undergraduate biology laboratory course for majors. Yianna remained at Cornell University to continue her studies as a doctoral student in the department of Earth & Atmospheric Sciences under the guidance of Charles Greene, Bruce Monger, and Christopher Clark. During her Ph.D., Yianna

continued teaching undergraduate courses at Cornell as well as a summer special program in Satellite Remote Sensing in Biological Oceanography under the guidance of Bruce Monger. After completion of her Ph.D., Yianna will move back to Cyprus to work as a researcher at the Oceanography Center of the University of Cyprus.

Στην μητέρα μου Ανθούλα.

Σ'ευχαριστώ για την συμπαράσταση, την υπομονή, και την αγάπη σου.

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CHAPTER ONE

INTRODUCTION

Climate change and its repercussions trouble scientists and policy makers among all nations. Despite governmental differences concerning policy issues, there is a consensus within the scientific community on the nature, causes, and consequences of climate change and its impacts on ecosystems (Oreskes, 2004). Over the last millennium, global mean surface temperature has varied by as much as 1 ℃ (Houghton et al., 1995; Houghton et al., 2001; Levitus et al., 2000; Salinger, 2005). Since the late nineteenth century it has increased about 0.3 ℃-0.6 ℃ (Houghton et al., 1995; Salinger, 2005). The most rapid warming, however, has been occurring over the past 30-40 years, during which time global surface temperatures have increased approximately 0.2 ℃ per decade (Bindoff et al., 2007; Hansen et al., 2006; Trenberth et al., 2007), with the 1990s being the warmest decade on record (Salinger, 2005). Warming has also been recorded in the world's oceans, through measurements of heat fluxes and heat content (Karcher et al., 2003; Levitus et al., 2000), and has been estimated to correspond to a warming rate of 0.3 W/m^2 between the mid-1950s and mid-1990s (Levitus et al., 2000). Global sea level has also risen by about 20 cm during the last century, partly from melting of land ice and partly from thermal expansion of the oceans (Church and White, 2005; King, 2004). Human activity has increased the atmospheric concentration of all greenhouse gases by some 50% during the last 200 years relative to pre-industrial levels (Houghton et al., 2001).

Because of the water-enriched nature of this planet, a great deal of effort is placed on understanding climatic impacts on ocean ecosystems. Several studies have examined trends of sea surface temperatures (SSTs) at global and regional scales

during different time periods, and all show significant regional and global warming trends (Casey and Cornillon, 2001; Knutson et al., 1999; Lau and Weng, 1999; Strong et al., 2000). Unfortunately, all indications point to a continued rise in regional and global sea surface temperatures with no respite. SST varies on multidecadal and interannual time scales with significant regional differences in the specific character of the temporal variability. In ocean ecosystems, these multi-scale responses to climate forcing are well recognized phenomena, characterized by highly variable and sometimes unpredictable fluctuations in many oceanographic parameters, not just temperature (Jenouvrier et al., 2005; Skogen et al., 2007). The most practical and efficient approach to studying these responses at near real-time, is through the use of satellite remote sensing methods (Fu and Smith, 1996; Gautam et al., 1995). Satellite remote sensing methods provide researchers with global observations at high spatial and temporal resolution. The time record of observation for some sensors has exceeded two decades, and thus allows for studies of multi-decadal variability and change (Gautam et al., 1995; Young, 1999). Such studies help detect the regional impacts of climate change while revealing the interconnectedness of the global ocean.

One such interesting interconnection is that between the Mediterranean Sea and the Atlantic Ocean. The Mediterranean Sea is connected with the Atlantic Ocean through the Straits of Gibraltar. Through these Straits, there is an exchange of water masses, with the Mediterranean SSTs depending on the inflow temperatures of surface Atlantic Water (Bethoux and Gentili, 1999). Once in the Mediterranean Sea, the surface Atlantic Water is transformed into a set of cooler and saltier water masses that are characteristic for the different sub-basins within the Mediterranean Sea (Millot et al., 2006). Several studies focusing on the Mediterranean Sea have shown that SSTs, are also affected by the climate of the Atlantic Ocean, primarily by the North Atlantic Oscillation (NAO) (Hasanean, 2001; Tsimplis and Rixen, 2002; Vignudelli et al.,

1999). This is a large-scale oscillation of atmospheric pressures between the North Atlantic sub-tropical high, near the Azores, and the sub-polar low, near Iceland, which determines the strength and orientation of the poleward pressure gradient over the North Atlantic and the mid-latitude westerly winds (Hurrell, 1995; Salinger, 2005). Temperatures of the upper and intermediate waters in the Aegean Sea, temperatures of the upper waters of the Adriatic Seas, and SSTs over the eastern Mediterranean Sea were all shown to be negatively correlated with the NAO (Hasanean, 2001; Tsimplis and Rixen, 2002; Vignudelli et al., 1999). Changes occurring in the eastern and western basins are frequently out of phase as a consequence of different processes that affect the climate of the two; thus, a positive correlation exists in the western Mediterranean basin with the climate of the North Atlantic Ocean (Artale et al., 2006; Korres et al., 2000; Reddaway and Bigg, 1996).

Variability in the Mediterranean outflow water composition, affected by climate change, can have consequences for the mid-depth water characteristics in the North Atlantic (Millot et al., 2006). Further, through the exchange between the Mediterranean Sea and the Atlantic Ocean at the Straits of Gibraltar, the changes in temperature may affect the general circulation in the North Atlantic (Reid, 1979), which is a major site of dense-water formation for the global meridional overturning circulation (MOC) (Broecker, 1997; Rixen et al., 2005). Therefore, climatic impacts on the temperatures of the Mediterranean Sea can affect not only the Sea itself, but also the characteristics of water masses in the Atlantic as well as the global MOC.

From a marine perspective, one of the greatest fears associated with global warming is a potential decline in global ocean primary productivity. Such a decline might affect not only the marine food chain but also the biological pump, which is critical to the ocean's role as a sink for anthropogenically produced carbon dioxide (Gregg et al., 2003). Global ocean annual primary production has declined more than

6% since the early 1980s (Gregg et al., 2003). Additional reductions in nutrient concentrations at the surface of the oceans caused by climate change would clearly reduce productivity even further (Falkowski, 1994).

Productivity in the oceans is closely related to surface mixed layer dynamics that govern the vertical exchange of nutrient-rich, deep waters (Mann and Lazier, 1991). Mixed layer dynamics are affected by wind forcing and buoyancy forcing due to heat flux and fresh water inputs (Falkowski, 1994; Mann and Lazier, 1991). Large-scale freshening of the ocean surface due to increased glacial ice melt in a warmer global climate could increase density stratification and limit the vertical exchange between surface and deep ocean layers over longer periods of time (Durbin et al., 2003; Pershing et al., 2005). A longer period of vertical stratification is predicted to select against larger phytoplankton species and favor the smaller species (Marty and Chiaverini, 2002). This would lengthen the food chain between primary producers and larger consumer species, and thereby reduce the efficiency of energy transfer to the largest consumers (Falkowski et al., 1998). A deeper surface layer would also mean that phytoplankton would more likely be in suboptimal illumination more often, and the strengthened concentration gradient would make it more difficult for nutrients to enter the surface layer from below (Falkowski et al., 1998; Gargett and Marra, 2002). Both the increased period of stratification and the deepening of the surface layer would be expected to reduce overall productivity (Mann and Lazier, 1991).

If ocean primary productivity is reduced, then herbivorous zooplankton production would be similarly reduced for obvious reasons. Herbivorous copepods often dominate the zooplankton community biomass, and are an important food source for larger zooplankton species, many species of fish, and even baleen whales such as the North Atlantic right whale (Schmitt et al., 2006). Consequently, variation in copepod abundance due to changes in primary production can be expected to

significantly impact population growth dynamics of these higher trophic level consumers (MacGavin and Simmonds, 1996; Simmonds and Isaacl, 2007).

Some of the copepod-consuming baleen whale species are endangered or threatened (Clapham et al., 1999). Such endangered whale populations could be strongly affected by climate-associated changes in their prey resources, both in terms of lower productivity and shifts in prey species composition (MacGavin and Simmonds, 1996; Parmesan and Yohe, 2003; Root et al., 2003; Simmonds and Isaac, 2007; Thomas et al., 2004). Many whale species undergo long migrations from tropical calving grounds to high-latitude feeding grounds where prey resources are adequate to support their tremendous energetic demands (MacGavin and Simmonds, 1996). When conditions change in those feeding grounds, some whale species, such as fin whales (*Balaenoptera physalus*) and bowhead whales (*Balaena mysticetus*), have demonstrated adaptability in their feeding behavior and may be able to switch among prey species (Burns, 2002). However, other species of whales appear less flexible in their feeding behavior, and the observed rate of climate change is likely to be well outside their evolutionary capacity to adapt (MacGavin and Simmonds, 1996).

The effects of climate change on higher trophic-level consumers, such as whales, can be particularly difficult to investigate because they involve relationships that occur on large spatial and temporal scales and can include nonlinearities and significant time lags (Leaper et al., 2006; Lusseau et al., 2004). Further, many whale populations are already at extremely low population levels, as their populations are already being impacted by a range of other factors in addition to climate-associated changes in food availability (Clapham et al., 1999; MacGarvin and Simmonds, 1996). Therefore, conservation efforts to save endangered whale species, such as the North Atlantic population of Northern Right whales (*Eubalaena glacialis*), have focused on trying to understand the impacts of climate change and climate variability on the

population dynamics (Leaper et al., 2006). Ecologists are further interested in the relative contribution of growth and mortality by each major demographic group that makes up a whale population, because knowledge of these demographic contributions is required to better inform wildlife-management strategies (Caswell et al., 1999; Coulson et al., 2005).

The matrix model is an important tool for forecasting the growth of age-structured populations composed of recognizable demographic groups. There has been considerable interest in being able to forecast the consequences of climate change on age-structured populations, such as the North Atlantic right whale, using matrix models and predictive modeling as a management objective with important conservation implications for whale distribution, demography, and abundance (Baumgartner et al., 2003; Caswell, 2001; Coulson et al., 2005; Ohman et al., 2004).

This dissertation describes a satellite remote sensing study and a separate age-structured population modeling study that are related by a common goal of developing better approaches to understanding the effects of global climate change on conservation practices for ocean ecosystems. In chapter two, I present a study of climate variability in the Mediterranean Sea that is intended to be a clear demonstration of the effectiveness of using satellite remote sensing methods to monitor climate change over spatial scales appropriate for large ocean ecosystems. I analyzed sea surface temperature records of satellite remote sensing data for the period 1985-2005, and interpret them in terms of changing surface heat flux patterns as well as changing wind speeds. I further investigated both the spatial and temporal variability patterns of the above oceanographic variables. In chapter three, I present a study in conservation oceanography using an age-specific population dynamics matrix model approach. A matrix population model is used to evaluate the sensitivity of the northern right whale (*Eubalaena glacialis*) population growth to different food

availability scenarios. Food availability is expected to change as a result of climate variability. I also investigate the impacts that climate variability has on the interval between births in the right whale population. Finally, I assess the sensitivity of the female right whale population growth under varying levels of mortality rates, in an attempt to better understand the combined effects of a future change in the right whale food environment and a change in anthropogenic mortality rates on the conservation potential of this species.

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CHAPTER TWO

SEA SURFACE TEMPERATURE RISE IN THE MEDITERRANEAN SEA
DURING THE PAST TWO DECADES

Abstract – Increases in sea surface temperatures (SSTs) have been reported to occur globally over the past two decades. Here we analyze SST records from satellite data for the period 1985-2005 and interpret them in terms of changing surface heat flux patterns. We show that the entire Mediterranean Sea has undergone an increase in temperatures with a leveling-off observed in the second half of the record. This warming in the Mediterranean, which is almost double that of the global ocean, occurred at both multidecadal and interannual time scales, and it is driven primarily by changes in annual net surface heat flux, specifically by latent heat losses due to variability in regional wind speeds. It will be valuable to investigate future trends in SSTs to determine whether the recent leveling-off of temperatures represents a brief respite from a persistent warming or a new direction for the Mediterranean.

2.1. INTRODUCTION

The reality of global warming since the industrial era is manifested in part by changes in global surface temperatures (Houghton et al., 2001). Past studies have documented global sea surface temperature increases between 0.3 ℃ and 1.0 ℃ over the last millennium (Houghton et al., 1995; Houghton et al., 2001; Levitus et al., 2000; Salinger, 2005), with the most rapid warming, between 0.1 ℃ and 0.3 ℃, occurring over the past 30-40 years (Bindoff et al., 2007; Casey and Cornillon, 2001; Hansen et al., 2006; Lau and Weng, 1999; Strong et al., 2000; Trenberth et al., 2007). Regional temperature increases have also been reported in the Mediterranean Sea for each of its

two basins (Astraldi et al., 1999; Bethoux and Gentili, 1999; Brunetti et al., 2000; Demirov and Pinardi, 2002; Hasanean, 2001; Sabatés et al., 2006; Salat and Pascual, 2002; Tsimplis and Rixen, 2002). However, few studies have investigated sea surface temperature (SST) increases across the Mediterranean as a whole, and even fewer studies have investigated SST change in terms of changing surface heat flux patterns.

2.2. METHODS

2.2.1. Data Sources

Sea surface temperature (SST) data were collected by the NOAA/NASA Advanced Very High Resolution Radiometers (AVHRR) and processed by the SST Pathfinder program. For our analyses we obtained monthly averaged Level 3, version 5.0, global SST data from the nighttime pass (code numbers 1 or 4) of the satellite at a 4-km resolution and an equal-angle grid of 8192 pixels/360º from January 1985 through December 2005. Formal Pathfinder Version 5.0 (pfv50) data were obtained from January 1985 through December 2001, while Interim Pathfinder Version 5.0 (pfrt – i.e. "Pathfinder Real Time") data were obtained from January 2002 until December 2005. Monthly quality control flag files for the SST data were also obtained from January 1985 through December 2005 from the same source.

Global daily NCEP/DOE Reanalysis 2 (Kanamitsu et al., 2002) surface data of latent heat net flux, sensible heat net flux, upward solar radiation flux, downward solar radiation flux, upward longwave radiation flux, and downward longwave radiation flux from January 1, 1985 though December 31, 2005 were provided by NOAA/OAR/ESRL PSD, Boulder, Colorado on a T62 Gaussian grid (192x94). Data of each variable (latent heat, sensible heat, upward/downward solar radiation, and upward/downward longwave radiation) were obtained in 21 annual 3-D matrices per variable, with each matrix containing the global daily information.

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Daily global NCEP/NCAR Reanalysis 1 (Kalnay et al., 1996) u-direction as well as v-direction 10-meter (10m) surface wind speeds were also provided by NOAA/OAR/ESRL PSD, Boulder, Colorado on a T62 Gaussian grid (192x94), and a 2.5 ° x2.5 ° resolution. Data of each variable (u-direction and v-direction) were obtained in 21 annual 3-D matrices per variable, with each matrix containing the global daily information.

2.2.2. Processing

All data were sub-scened from the global sets to the Mediterranean Sea region, bound by these coordinates: 46 ºN to 31 ºN, and 5.5 ºW to 36 ºE.

Quality control flags were applied to the monthly SST Mediterranean data. Only pixels of highest quality, marked with a 7 quality control flag were kept.

Net heat fluxes (HTFLX) were calculated by summing the daily latent heat net flux, sensible heat net flux, and upward solar and upward longwave radiation data, and then subtracting the downward solar and downward longwave radiation data for the Mediterranean region. Sign convention used here indicates a gain of heat by the ocean as positive values.

Annual averages were calculated for 1985 through 2005 across the Mediterranean for SST, HTFLX, as well as for both the 10m surface u-direction (u-WND) and v-direction (v-WND) Mediterranean wind speed data. Cumulative net heat fluxes were also calculated using the annual averages of HTFLX.

The magnitude of the annual wind speeds (WND) was also calculated using the annual directional wind speed averages u- and v-WND.

$$WND = \sqrt{(u\text{-}WND^2 + v\text{-}WND^2)} \qquad (1)$$

Annual anomalies for the SST, HTFLX, and WND datasets were obtained by calculating the overall mean for each dataset during 1985-2005, and then subtracting

the mean from each year of the corresponding dataset.

Empirical orthogonal function (EOF) analysis was performed on the annual anomalies of SST, on those of HTFLX, and on those of WND.

2.2.3. Empirical Orthogonal Function Theory

The Empirical Orthogonal Function (EOF) analysis allows the decomposition of a dataset based on analysis of the covariance matrix of the data (Cromwell, 2006; Emery and Thompson, 1997; Wilks, 1995) and is used to examine the spatial and temporal variability in the dataset (Wilson and Adamec, 2001). EOF analysis finds the spatial patterns of variability, their time variation, and gives a measure of the importance of each pattern (Björnsson and Venegas, 1997). Different patterns are projected as modes of variability, with each subsequent mode being orthogonal to the previous one.

Specifically, the EOF analysis takes all the variability in the time evolving field of the whole dataset and breaks it into n modes, where n is the length of the time series. In our case, n=21 since we are analyzing annual data from 1985 to 2005.

Every mode of variability is comprised of a standing oscillation pattern (the spatial eigenfunctions), which represent the spatial patterns of variability that vary with time. Each mode also includes a time series to go with the oscillation pattern (principal components) that shows how the spatial eigenfunctions vary with time (Björnsson and Venegas, 1997; Casey and Adamec, 2002).

While an EOF analysis calculates n modes, there are typically only a few modes that capture most of the variance. Usually the leading/first mode is the one upon which the data project most strongly, and the one that explains the most variance (Björnsson and Venegas, 1997). In the leading mode, the variations of the spatial and temporal fields are strongly coupled.

2.2.4. Data Organization for EOF Analysis

Overall, in order for the EOF analysis to be run on a dataset, the data must be placed in a matrix, so that the rows (y-dimension) indicate temporal development and the columns (x-dimension) are the spatial component. In our study since we are dealing with satellite data that are already in a 2-dimensional matrix with both dimensions (x-dimension of longitude and y-dimension of latitude) containing spatial data points, we organized our annual data into a 3-D matrix.

Our annual SST anomaly data, annual HTFLX anomaly data, and annual WND anomaly data, were each analyzed with EOF individually. Data of both variables were organized in 3-D matrices, in which the x- and y- dimensions contained spatial data points and the z-dimension indicated the temporal development in chronological order. Again the z-dimension of the matrices was equal to 21. Thus looking at each z-dimension, we see the spatial distribution of SST or HTFLX, or WND values across the Mediterranean during each year.

2.2.5. Analyses

Prior to performing EOF, a 10x10 pixel dilation of the coast line was performed on the SST annual data, in order to reduce some of the noise caused by the usually extreme temperatures of the coastal regions. Following the dilation, the SST annual data were run through a three-point spatial median filter to further reduce any noise in the data. All data (SST, HTFLX, and WND) were then normalized (dividing by the standard deviation) before performing the EOF analysis in order to further reduce the impact of locations with high variability. Here, we choose to show only the first two EOF results (modes) for SST, HTFLX and WND.

2.3. RESULTS AND DISCUSSION

Analyses of annual mean sea surface temperature (SST) data indicate that over the last two decades (1985-2005) a general warming has occurred over the entire Mediterranean Sea (Figs. 2.1a, 2.2). The overall warming during this period was approximately 0.7 °C, and occurred at an average rate of 0.036 °C per year (Fig. 2.1a). This is consistent with a 0.8 °C rate of increase recorded between 1985 and 2004 in the Mediterranean using the same Pathfinder data (Good et al., 2007). During the same period of time, global SST increased by 0.18 °C per decade, which is roughly half of the rate of increase we report in the Mediterranean (Good et al., 2007). A rapid increase in average SSTs occurred between 1993 and 1994, with average SST values being significantly higher than the overall mean (19.88 °C) in 1994-1995 and in1998 to 2005 (Fig. 2.1a). During these last 8 years, SSTs vary from year to year, but overall appear to be leveling-off (Fig. 2.1a). Spatial variability in the multi-decadal warming is depicted in the SST anomalies, with positive anomalies (higher than average SST values) dominating most of the Mediterranean after 1997, while negative anomalies existed from 1985 until about 1993 (Fig. 2.2).

The rise in SST from 1985 to 1994 and then the slowing down of that rise from 1998 until 2005, is consistent with the annual spatial average net surface heat flux (HTFLX) pattern that exhibits large positive values (heat gain by the ocean) from 1985-1994 and small positive or even negative values from 1995-2005 over the entire Mediterranean (Fig. 2.1b). The HTFLX decreased steadily at a rate of 1.27 W/m^2 per year, with the Mediterranean experiencing negative HTFLX values in 2001, 2003 and 2005 (Fig. 2.1b). The decrease in HTFLX over the Mediterranean, leads to an average

Figure 2.1. Annual averages and linear trends of oceanographic variables from 1985 to 2005. Annual mean values are shown in solid line with black dots. Standard error (s.e.m.) per year, are shown in vertical solid bars. (a) Mean values of sea surface temperature (SST) per year from 1985 to 2005. During the 21 year period the average value of SST was 19.88 ºC. (b) Mean annual values of net heat flux (HTFLX) over the Mediterranean Sea from 1985 to 2005. Between 1985 and 2005 there was an average positive net heat flux of 8.02 W/m^2. (c) Cumulative net heat fluxes across the Mediterranean from 1985 to 2005.

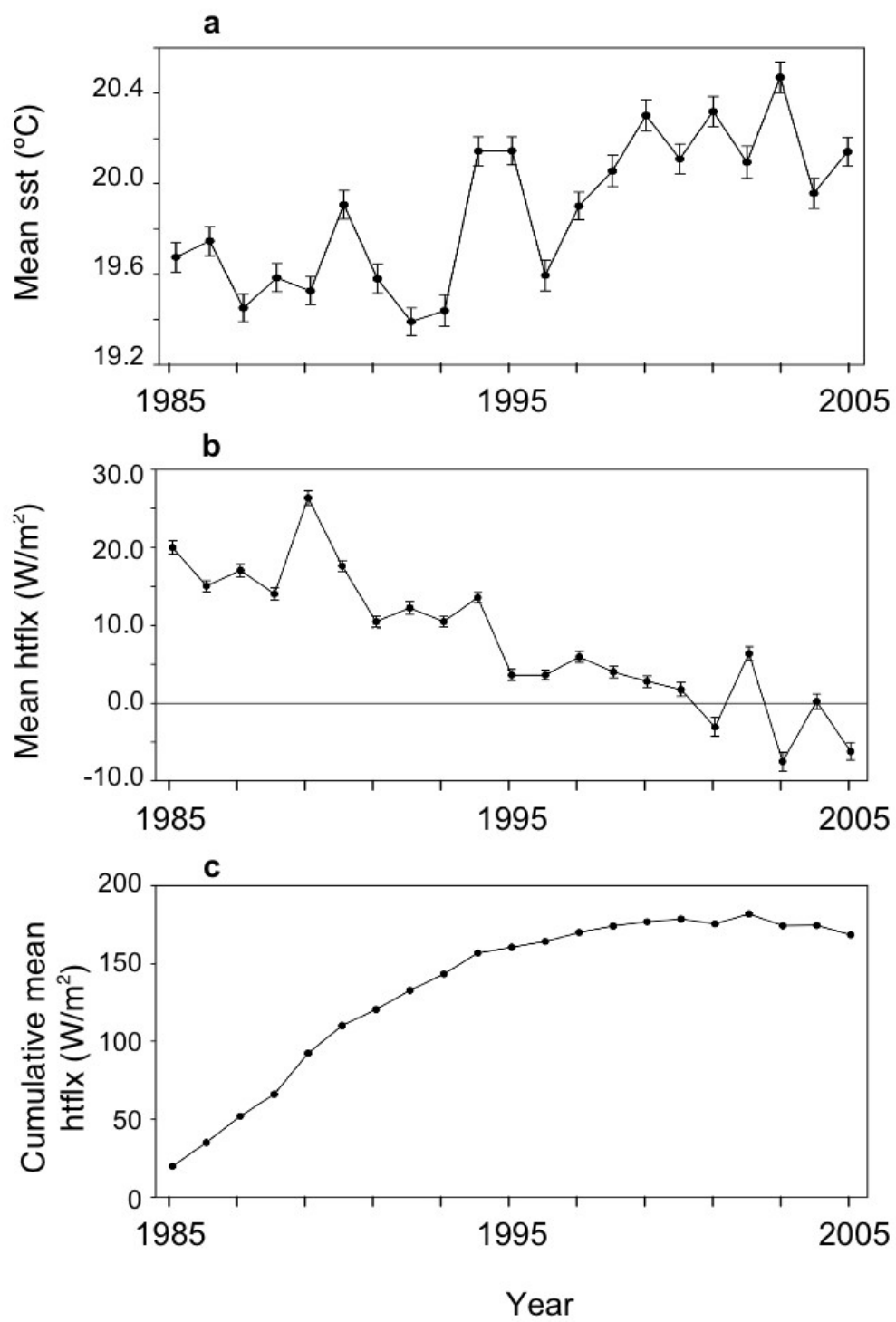Figure 2.2. Annual sea surface temperature (SST) anomalies across the Mediterranean Sea from 1985-2005. Annual anomalies are calculated by removing the overall mean from each year. Images are bound by the Mediterranean Sea coordinates of 46 ºN to 31 ºN, and 5.5 ºW to 36 ºE. Positive anomalies indicate higher than average SST values, while negative anomalies indicate lower than average SSTs.

Sea surface temperature anomaly (^{0}C)
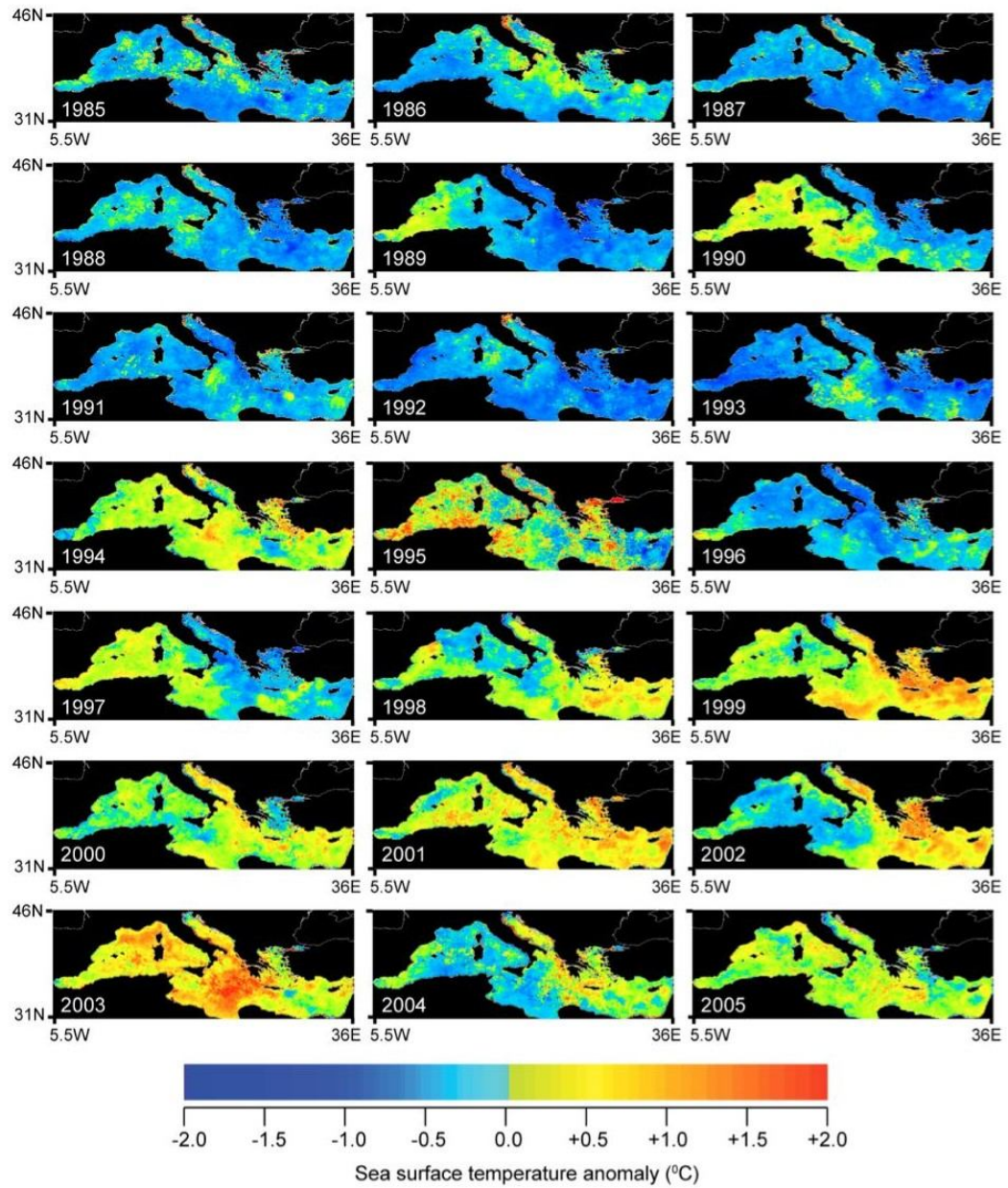
net heat flux of -2.04 ± 1.08 W/m^2 from 2001 to 2005, and this is consistent with decreases in heat content recently reported to occur across the earth's total surface (Bindoff et al., 2007), corresponding to net heat fluxes of -1.0 ± 0.3 W/m^2 from 2003 to 2005 (Lyman et al., 2006). Despite the decreasing trend in net heat fluxes over the later half of the present decade, the Mediterranean Sea experienced an average positive net surface heat flux of 8.02 W/m^2 over the past two decades (Fig. 2.1b), and remains approximately 0.7 °C warmer than it was in 1985 (Fig. 2.1a).

SST is a function of the steady accumulation of heat by the surface ocean and can be expressed as the integral of net heat fluxes (Garrett and Outerbridge, 1993). Consequently, it is more appropriate to compare SST with the cumulative net surface heat fluxes over the study period than with the annual averages of net heat fluxes. The heat loss experienced in the Mediterranean in 2001, 2003, and 2005 was not sufficient to cause large deviations from the overall basin warming, but it did contribute to the leveling-off of the cumulative mean heat fluxes after 1995 (Fig. 2.1c).

Empirical Orthogonal Function (EOF) analysis was performed on the annual SST data to examine their spatial and temporal patterns of variability from 1985 to 2005. The leading EOF mode (mode 1) of the SST data (without detrending) explains 57% of the original variance (Fig. 2.3a). The spatial eigenfunctions of mode 1 show that the SSTs across the entire Mediterranean share high positive eigenfunctions and thus varied in a spatially coherent manner over time (Fig. 2.3a). The principal component (PC) of the same mode (PC1), which depicts the time variation of the first mode, increased over the years supporting the fact that the Mediterranean experienced a basin-wide warming. The PC1 of SST is consistent with the patterns of spatially-averaged SST changes (Fig. 2.1a), and with the cumulative net surface heat flux (Fig. 2.1c).

Figure 2.3. Empirical orthogonal function (EOF) results from 1985 to 2005. (a) Spatial eigenfunction and principal component (PC) for mode 1 of sea surface temperature (SST) annual anomalies. Positive eigenfunctions during positive PC years indicate higher than average conditions occurred. Mode 1 of SST explains 57% of the original variance. (b) Spatial eigenfunction and PC for mode 2 of SST. Mode 2 of SST explains 12% variability. (c) Spatial eigenfunction and PC for mode 1 of annual anomaly net heat flux (HTFLX) data. Mode 1 of HTFLX explains 59% of the variability. (d) Spatial eigenfunction and PC for mode 2 of HTFLX. Mode 2 of HTFLX explains 9% of the original variance. (e) Spatial eigenfunction and PC for mode 1 of annual anomaly wind speed (WND) data. Mode 1 of WND explains 35% of the total variance. (f) Spatial eigenfunction and PC for mode 2 of WND. Mode 2 of WND explains 18% of the variability.
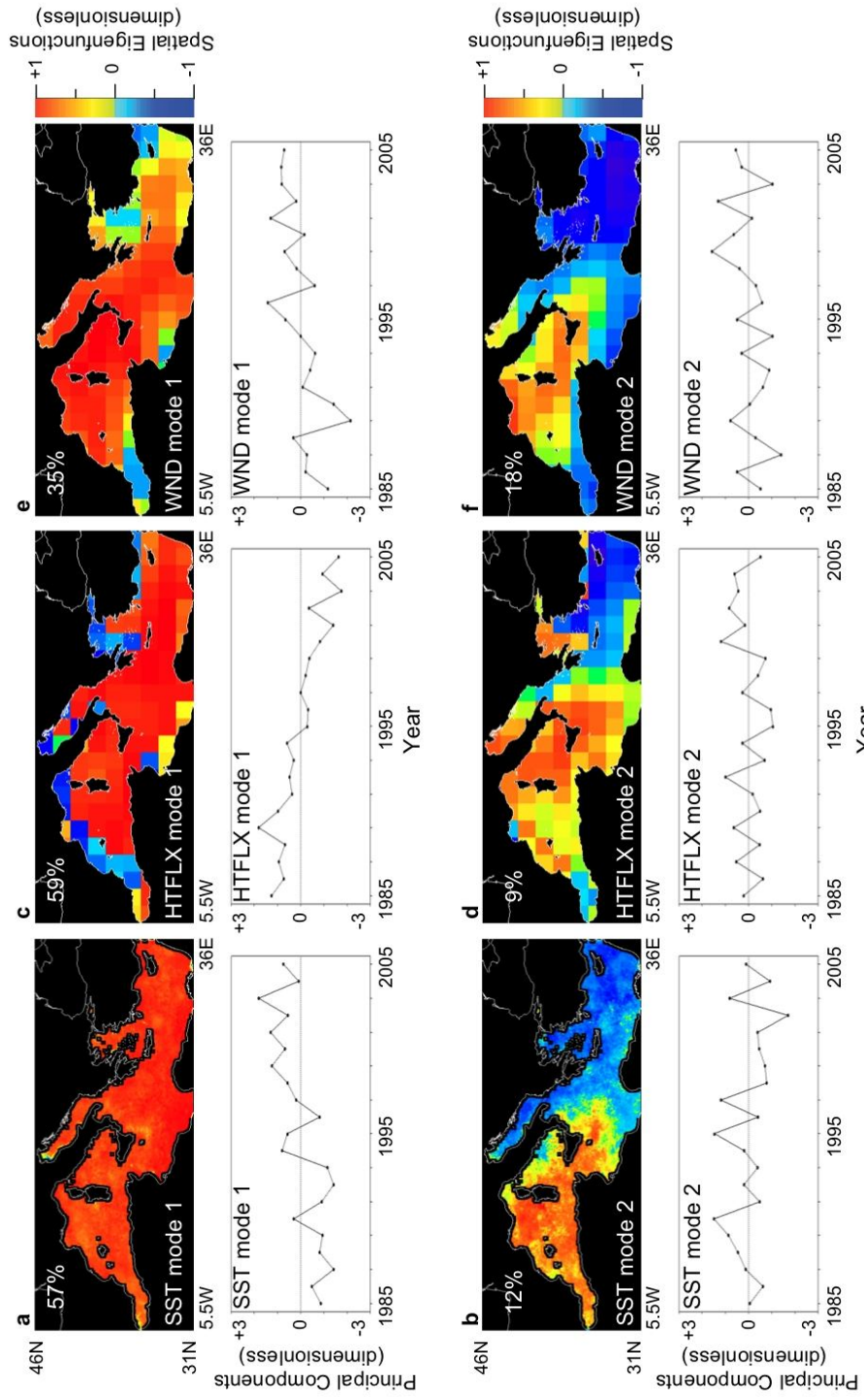
The second EOF mode of SSTs explains 12% of the original variance (Fig. 2.3b). An asymmetry in the NW-to-SE direction is depicted in the spatial eigenfunctions of mode 2. Areas in the western Mediterranean are out of phase from areas in the eastern parts of the Sea creating a dipole pattern of heating and cooling at interannual time scales (Fig. 2.3b).

Changes occurring in the eastern and western basins are frequently out of phase as a consequence of different processes that affect the climate of the two basins (Artale et al., 2006; Korres et al., 2000; Reddaway and Bigg, 1996). During the study period, areas in the western Mediterranean with positive spatial eigenfunctions experienced higher than average SSTs during years with positive PCs, and lower than average SSTs during years with negative PCs (Fig. 2.3b). In contrast, the eastern Mediterranean experienced higher than average SSTs during years of negative PCs, and lower than average SSTs during years of positive PCs (Fig. 2.3b). It is important to keep in mind that the dipole pattern depicted by mode 2 is superimposed on the longer low frequency changes exhibited by mode 1.

EOF analysis was also performed on the net surface heat flux data to examine its spatial and temporal patterns of variability in the context of the observed SST variability. Mode 1 explains 59% of the original variance (Fig. 2.3c). The spatial eigenfunction of mode 1 shows that the HTFLX across the entire Mediterranean, with the exception of some coastal areas in the northern Mediterranean, varied over time with strong spatial coherence. The PC1 of the HTFLX data exhibits a multidecadal trend that is similar to the PC1 of the SST data. The spatial eigenfunctions of mode 1 for HTFLX correspond to the basin-wide mode 1 spatial patterns for SST. The second mode of HTFLX EOF analysis, explains 9% of the variability (Fig. 2.3d). The dipole observed in the SST mode 2, is also seen in the HTFLX EOF spatial eigenfunctions of mode 2. As the western Mediterranean experiences an increase in HTFLX, at the same

time the eastern Mediterranean experiences a decrease in HTFLX (Fig. 2.3d). The PC2 of the HTFLX data shows interannual fluctuations, with the western Mediterranean experiencing higher than average heat flux from 2000 to 2004, while the eastern Mediterranean during the same period of time, experienced lower than average net surface heat fluxes (Fig. 2.3d).

In order to identify which one of the four components of net surface heat flux is driving the decreasing trend in HTFLX, we analyzed each component. Sensible heat flux, which has the smallest values, and net longwave radiation, make up a minor fraction to the net surface heat flux (Castellari et al., 1998; Garrett and Outerbridge, 1993; Josey, 2003). The net solar radiation component did not change significantly from year to year (Castellari et al., 1998). An investigation of the individual components of our net heat flux data showed no significant multidecadal trends for sensible heat fluxes (r^2=0.117, F=2.517, p=0.129), net solar radiation (r^2=0.001, F=0.025, p=0.877), and net longwave radiation (r^2=0.119, F=2.562, p=0.126). Moreover, all three of these components had only small fluctuations around their mean ($\pm$1.46, $\pm$1.88, $\pm$1.54 W/m^2). By contrast, a significant trend exists in the latent heat fluxes (r^2=0.822, F=87.871, p=1.47*10^{-8}), which varied $\pm$7.6 W/m^2 around their mean. Therefore, the decrease of heat gain in the Mediterranean can be concluded to be modulated during this period by variation in latent heat losses. This conclusion is confirmed by past studies (Castellari et al., 1998; Garrett and Outerbridge, 1993; Josey, 2003).

Latent heat loss is linearly related to wind speed (Garrett and Outerbridge, 1993; Matsoukas et al., 2005). Therefore, it can be said that the strong heating in the first decade of this study was due to low wind speeds and smaller than average latent heat losses. While the later decade experienced stronger winds with greater latent heat losses, that lead to either zero or negative net surface heat fluxes. To further explore

the modal patterns of variability in SST with variability in the latent heat losses caused by changes in wind speeds, we examined the modal pattern of wind speeds. Since latent heat loss is linearly related to wind speed, the modal patterns for latent heat loss and wind speed will be identical. Moreover, we chose to focus on wind speeds because we wanted to emphasize the importance of winds as the more direct causal mechanism that is driving the changes in SST.

An EOF analysis was performed on the annual mean wind speeds over the entire region. Mode 1 from the EOF analysis explains 35% of the original variance (Fig. 2.3e). The spatial eigenfunction of mode 1 shows once again that the whole basin, with the exception of some coastal areas, is fluctuating in phase over time. The PC1 of WND shares the linear multidecadal trend observed in the PC1s of SST and HTFLX. Wind speeds were low in the 1980s and trended upward during the past two decades (Fig. 2.3e). The second mode of the WND EOF explains 18% of the total variance (Fig. 2.3f). The dipole pattern observed in both modes 2 of the SST and HTFLX EOFs is similar to WND mode 2. Therefore, a reasonable explanation is that the winds are driving both the basin-wide multidecadal pattern and higher frequency dipole observed in mode 2 of the SSTs.

2.4. CONCLUSIONS

We have shown that an increase in the Mediterranean sea surface temperatures has taken place from 1985 to 2005. This increase is much higher than the globally recorded SST rise. A leveling-off observed in the second half of the record is due to increased latent heat loss caused by increasing wind speeds. As expected, the increasing trend in SST across the Mediterranean is strongly correlated with the cumulative heat fluxes over the region (r=0.624, p=0.003). SST variability is characterized by a broad, basin-wide multidecadal warming (mode 1) and a weaker

dipole pattern that fluctuates at interannual time scales (mode 2). The pattern of SST variability across the entire Mediterranean is shared by the patterns of HTFLX and WND. It is suggested that the observed patterns of SST are being forced by changes in latent heat losses brought about by changes in wind speeds over this period. Finally, it will be valuable to investigate future trends in SSTs to determine whether the recent leveling-off of SSTs and negative net surface heat fluxes represent a brief respite from a persistent warming or a new direction for an ever-changing Mediterranean Sea.

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CHAPTER THREE

THE FUTURE OF NORTHERN RIGHT WHALES (*Eubalaena glacialis*) IN THE NORTHWEST ATLANTIC OCEAN

Abstract – The northern right whale (*Eubalaena glacialis*) population in the North Atlantic is under threat of extinction, mostly due to anthropogenically related mortalities. Climate variability has also been affecting food availability for the whale population, which in turn potentially influences the reproductive rates. Here, I investigate the sensitivity of right whale population dynamics under different scenarios of food availability and mortality rates. Under climatically favorable feeding conditions, the female right whale population continues to grow into the future with positive specific growth rate and will double by the year 2475. However, when food availability is low, the population growth is negative. This decline is even more drastic if mortality rates are increased. A 30% increase in mortality rates will force the same food-limited population to go extinct by as early as year 2372. However, by protecting 1% of the total female population every year in which food concentrations are unfavorable, the population can grow slowly and avoid extinction. The future of northern right whales is dependent on food availability and therefore likely to be impacted by climate variability and change. The projections for population abundance are also very sensitive to mortality rates. Conservation efforts should take climate-related food variability as well as anthropogenic sources of mortality into consideration as we develop strategies to save this population from extinction.

3.1. INTRODUCTION

The North Atlantic right whale (*Eubalaena glacialis*) is among the world's rarest cetacean species, and with a population estimated to be approximately 300-350 individuals, is arguably one of the most threatened of all baleen whales (Clapham et al., 1999; Fairfield, 1990; IWC, 2001; Knowlton et al., 1994; Mayo et al. 2001). The right whale is a slow moving animal that frequents coastal and shelf habitats. It typically feeds in temperate or high latitudes during summer, and calves in warmer waters at low latitudes during winter. In the western North Atlantic, the feeding typically occurs in the Gulf of Maine and on the Scotian Shelf, while calving typically occurs in the coastal waters of Georgia and Florida (Clapham et al., 1999; Kraus et al., 1986; Winn et al. 1986).

The northern right whale was hunted intensively during the 17th century, the peak of the whaling years for this species (Reeves et al., 1978; Reeves and Mitchell, 1986). However, even with the cessation of commercial whaling, the species has failed to recover. The reason for this is most likely due to other anthropogenic sources of mortality, such as those from entanglement in fishing gear, ship strikes, habitat degradation, and pollution (IWC, 2001; Kenney and Kraus, 1993; Knowlton and Kraus, 2001; Kraus, 1990; Kraus and Rolland, 2006). In an attempt to save the species from extinction, most recent conservation efforts have focused on understanding the connections between right whales and these anthropogenic sources of direct mortality, while the relationship between right whales and the variable ocean environment in which they live has been given less attention. Future efforts to conserve the species will require a more ecosystem-based approach, since the relationship between the whales and their environment is a critical factor in their long-term chances of survival, and an important factor when predicting population trends in this species (Mayo et al., 2001).

The most obvious connection between the whale and its habitat is embodied in the whale's feeding activities and choices (Mayo et al., 2001). The baleen of the right whale is composed of closely spaced baleen plates with keratinaceous hairs that form a tight mesh for trapping small prey items, which enables animals to skim feed at the ocean's surface on copepods (Costa et al., 2006). North Atlantic right whales, which are found in the Gulf of Maine/Western Scotian Shelf region of the western North Atlantic, feed primarily on older life stages of the calanoid copepod, *Calanus finmarchicus* (Baumgartner et al., 2003; Baumgartner and Mate, 2005; Beardsley et al., 1996; Murison and Gaskin, 1989; Winn et al., 1986; Wishner et al., 1988). *Calanus* overwinters in a dormant stage (primarily copepodite V) throughout the western Gulf of Maine, especially in the deep basins, as a means of surviving through winter. Development is arrested during copepodite moult stages IV and V in late summer and fall, when the animals conduct an ontogenetic migration out of the surface waters (Heath et al., 2000; Hirche, 1996). Animals emerge from dormancy between December and March, and the stage VI copepodites migrate back to the surface to begin spawning (Beardsley et al., 1996; Heath et al., 2000).

As the principal source of nutrition for right whales, *Calanus finmarchicus*, plays a key role in determining when environmental conditions are favorable for right whale reproduction (Greene and Pershing, 2004). Modeling studies have shown that the stable calving rates of right whales observed during the 1980s can be attributed to the relatively high abundance of *Calanus* (Greene et al., 2003). Variability in prey abundance, via its effects on reproductive success, may place certain limits on the recovery of right whales (Kenney et al., 2001). An understanding of the linkages between climate, physical oceanography, plankton ecology, and cetacean reproductive biology are fundamental to understanding the whale population dynamics of right whales (Greene and Pershing, 2004; Leaper et al., 2006). Thus, forecasting the

consequences of climate change on pelagic ecosystems, as well as using modeling as a conservation and management tool for predicting changes in the distribution and abundance of right whales, are important tools for conservation and management (Baumgartner et al., 2003; Fujiwara and Caswell, 2001; Greene et al., 2003; Redfern et al., 2006).

Here I evaluate the sensitivity of northern right whale population dynamics to different food availability scenarios. I investigate the impacts that climate-associated food availability may have on reproductive rates. Further, I assess the sensitivity of predicted total female right whale population size to different mortality rates. Deterministic population dynamics matrix models are used throughout this chapter in an attempt to gain insights into possible future trajectories of the northern right whale population under varying food and anthropogenic mortality scenarios, and to point out some directions toward conservation measures. Hence, this chapter is an attempt to take an ecosystem-based modeling approach to assessing conservation objectives for right whales in the context of a changing climate.

3.2. METHODS

3.2.1. Northwest Atlantic Right Whale Life Cycle

The female population is represented in a 12-stage model, with the reproductively mature females in a 3-stage reproductive cycle, and immature females in the remaining nine stages (Fig. 3.1). The three reproductively mature female stages are: 1. resting – female is recovering from a previous pregnancy or nursing, 2. pregnant – female is currently pregnant, and 3. nursing – the female gives birth to a calf and is currently a mother nursing her newborn calf. An individual female is considered to be sexually mature when she first enters the resting stage for the first time, which is at least one year before her first pregnancy event. Sexual maturity in

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Figure 3.1. Life cycle graph for female northern right whales, *Eubalaena glacialis*. Circles represent different stages: 1, resting female; 2, pregnant female; 3, nursing female; age 0, new born female calf; age 1 through age 8, immature females of respective ages. Females in stages 1, 2, and 3 are sexually mature, while calves and immatures of ages 1 through 8 are sexually immature. The model assumes that a newborn calf has a 50% probability of being a female. Thus, out of all the newborn calves, only half of them are accounted for in the age-0 stage. Each arrow represents a possible stage transition from one year to the next. Arrows pointing away from circles represent mortality (m), which is stage specific. Females in the stage age -0 experience two probabilities of death; if a nursing mother dies, the newborn calf will also die (m_{41}), a newborn calf has an m_{42} probability of dying regardless of its mother's death. Transition rates "p" and "q" are dependent on food concentration.
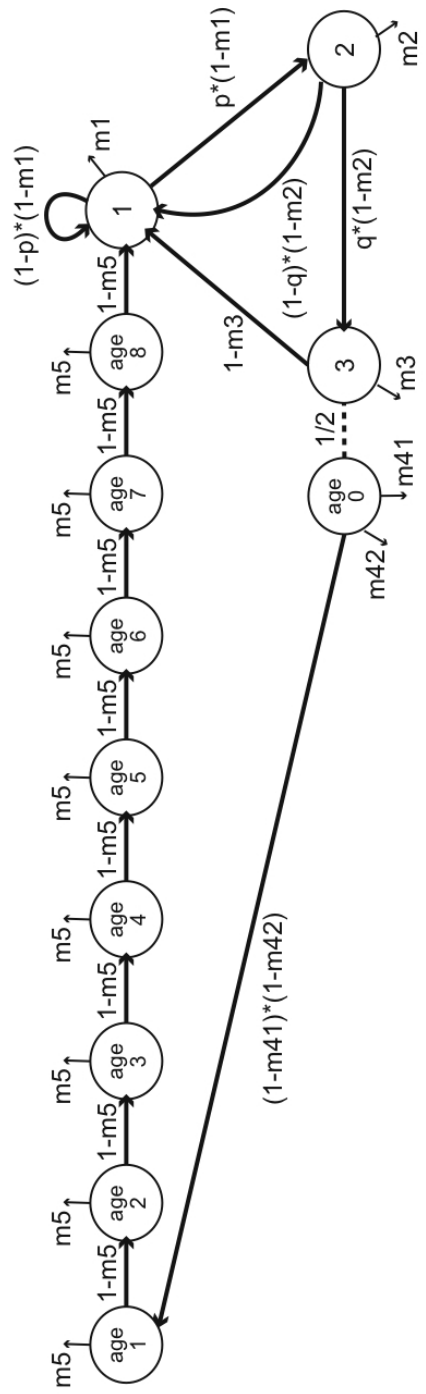
right whales is estimated to occur at approximately nine years of age (Fujiwara and Caswell, 2001; Hamilton et al., 1998; Kraus et al., 2001). For the southern right whales, age at first parturition ranges between 6 and 13 years old, with about 75% of females having their first calf at the age of 9 (Best et al., 2001; Cooke et al., 2001).

A sexually mature female right whale typically requires at least three years between births: one year for lactation, one year to build up fat stores to support the next pregnancy, and one year during the pregnancy (Knowlton et al., 1994). A calving interval of 3-3.35 years is observed in Southern right whales as well (Best and Kishino, 1998; Best et al., 2001; Cooke et al., 2001; Leaper et al., 2006). Therefore, I am assuming a one-year transition period between all stages. Further, the female sex ratio of newborn calves (stage age-0) is assumed to be 1:1 in our model. It is important though to recognize that all population dynamic parameters are density-dependent and are expected to fluctuate and change in nature as population size varies (Tang and Chen, 2002). However, I assume all parameters remain constant through time in this study.

I use the following mortality probabilities, which are stage-specific and time-invariant, as given by Fujiwara and Caswell's best sighting probability model (2001): mortality of a resting female, m_1, is 0.01 per year, mortality of a pregnant female, m_2, is 0.01 per year, mortality of a nursing mature female, m_3, is 0.17 per year, mortality of a newborn female calf is 0.17 per year if the calves' mother dies (m_{41}), and 0.16 per year if the calf dies independently of its mother (m_{42}). Mortality rates in each of the eight stages for immature females from age 1 until they enter the reproductive cycle, m_5, are 0.04 per year.

Transition probabilities, with the exception of those within the reproductive cycle (stages 1-3), are dependent only on survival. Both probabilities of transitioning within the reproductive cycle are dependent on survival and food availability (food

transition rate p between stages 1 and 2, and food transition rate q between stages 2 and 3). Food-dependent transitional rates (p and q), are linear functions and are based on parameters (slope and intercept) of *Calanus finmarchicus*-dependent transition functions from the previous year (t).

$$p_{(t+1)} = slope_{(p)} * Food_{(t)} + intercept_{(p)} \qquad (2)$$

$$q_{(t+1)} = slope_{(q)} * Food_{(t)} + intercept_{(q)} \qquad (3)$$

, where $slope_{(p)}$= 0.1059, $intercept_{(p)}$= 0.5353, $slope_{(q)}$= 0.1144, $intercept_{(q)}$= 0.3492. These slopes and intercepts were derived from the best fit model after running a genetic algorithm to find the set of parameters giving the best agreement between modeled numbers of calves (predicted when forced by a particular *Calanus* series) and observations on the numbers of calves (Pershing, in prep.).

3.2.2. *Calanus finmarchicus* Availability

In this study, I use three different scenarios for the availability of *Calanus finmarchicus*. The original *Calanus* availability data used to create the three different scenarios in this model were obtained from an anomaly abundance time series of *Calanus* that extends from 1981 to 1998 (Fig. 3.2). The anomaly values of *Calanus* abundance are from the May-June period of every year in the Western Gulf of Maine Region, and are of the largest stages of *Calanus finmarchicus*, the copepodite stages V and VI (Pershing et al., 2005). The time series of bi-monthly anomaly abundance of *Calanus* was computed by Pershing et al. (2005), using *Calanus* data collected from Continuous Plankton Recorder (CPR) surveys conducted in the center of the Gulf of Maine. A description of the CPR survey is provided by Pershing et al. (2005).

The first scenario used in the model is based on a high constant food concentration, equivalent to the average bi-monthly (May-June) anomaly value of *Calanus* abundance from the 1980s, which was calculated to be equal to 0.497
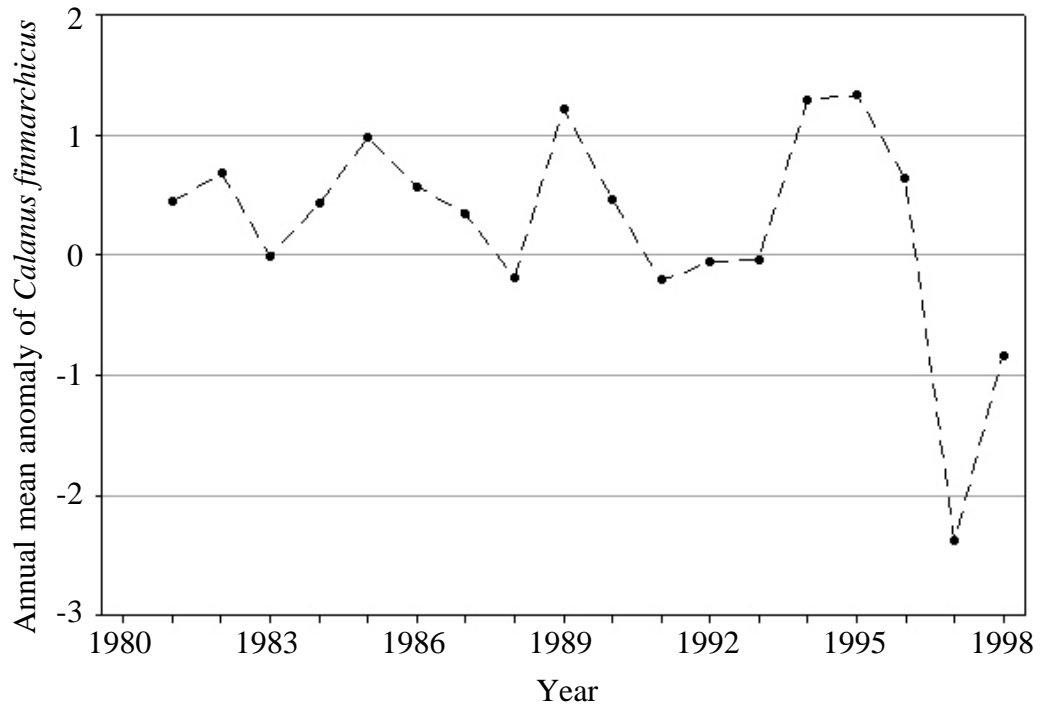
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Figure 3.2. Times-series of the calculated bi-monthly (May-June) *Calanus finmarchicus* abundance anomaly from 1981 until 1998. *Calanus* is the main food source for northern right whales. Abundance anomaly was determined from Continuous Plankton Recorder (CPR) surveys from the Western Gulf of Maine. Anomalies were calculated by Pershing et al. (2005).

(dimensionless abundance index). The 1980s were characterized by high abundances of *Calanus finmarchicus* with low interannual variability. This high-food scenario represents a realistic environment with plenty of *Calanus* to prey upon. The second scenario is a low constant food concentration corresponding to an abundance index of 0.0213, the average bi-monthly (May-June) anomaly value of *Calanus* abundance from the 1990s, which was a period of relative low abundance and high interannual variability for *Calanus*. The third scenario is the "worst-case" food concentration, corresponding to an abundance index of -0.530, the average of the seven lowest bi-monthly (May-June) anomaly values of *Calanus* abundance from the 1980s and 1990s.

3.2.3. Predicting the Future of Northern Right Whales from a Population Model

The population size of northern right whales in the Northwest Atlantic, extending for 500 years starting in 1980 was estimated (Appendix A.1-A.4). Previous estimates on the population size of northern right whales project that the species will go extinct in 200-300 years from now (Caswell et al., 1999; Fujiwara and Caswell, 2001). A 500-year projection time period was selected for this model since I wanted to determine whether accounting for food variability in the model would affect the projected extinction time.

Future predictions on the population size of northern right whales were based on an iterative application of a population projection matrix with transition probabilities described above. The matrix population model was applied to the right whale life cycle, and was initialized with a random distribution of 100 sexually mature female whales in the three reproductive stages (1, 2, and 3). Newborn female calves were assigned into stage age-0, during initialization of the model. The newborn female calves of stage age-0 were set equal to half of the mature females in stage 3 (nursing

females). The model predicts the number of females in the population under the three different food availability scenarios described previously, combined with the mortality rates as estimated by Fujiwara and Caswell (2001) (Appendix A.1). Under the high-food availability scenario, the food-dependent transition rates p and q are 0.5879 and 0.4061 respectively. Under the low-food availability scenario, the food-dependent transition rates p and q are 0.5376 and 0.3516 respectively. And under our worst-case scenario, the food-dependent transition rates p and q are 0.4792 and 0.2886 respectively.

The model was also used to estimate the average number of years required for females to become pregnant again and successfully give birth to calves under the different food availabilities (H_{33}) (Appendix A.2). This was done by applying a Markov chain recurrence solution to the transition matrix (P) of the reproductive life cycle, while also calculating the entropy rate H(X) (Ekroot and Cover, 1993). Recurrence is also dependent on the stage-specific population size ratio (μ_i, where i is a stage in the reproductive cycle).

$$H(X) = - \Sigma (\mu_i) * \Sigma (P_{ij} * Log_2 (P_{ij})) , \quad i=j=1 \text{ (resting), 2 (pregnant), 3(nursing)} \quad (4)$$
, where P_{ij} is the transition probability from stage i to stage j.

$$H_{33} = H(X) / \mu_3 , \qquad\qquad i=3 \text{ for nursing stage} \qquad\qquad (5)$$

Future population growth under different scenarios of increasing mortality rates (in percentages) was estimated to determine the sensitivity of the model to changes in mortality rates (Appendix A.3).

Finally, I estimated the number of females, independent of age and stage that need to be protected every year under the three different food availability scenarios to stabilize the population (Appendix A.4). Each model was run 100 times with different initial random distributions of 100 mature female whales in the three reproductive stages, and the average of the results from all runs was calculated.

3.3. RESULTS AND DISCUSSION

As expected from the structure of the model, future projections of the numbers and stage composition of the sexually mature females in the right whale population are dependent on food availability (Fig. 3.3). The numbers of mature female whales all increase in the high-food scenario, when anomaly abundance of *Calanus* is held constant at the 1980s average abundance index value of 0.497 (Fig. 3.3a). However, in the low-food scenario, when anomaly abundance of *Calanus* is held constant at the1990s average value of 0.0213, the population of mature female whales declines in all reproductive stages (Fig. 3.3b). The decline in the population of females is even more rapid and larger in our worst-case scenario, when anomaly abundance of *Calanus* is held constant at -0.530 (Fig. 3.3c). Regardless of food availability levels, after an approximately 10-year period, which is needed for the model to stabilize, more females are found in the resting stage per year than in the pregnant stage (Fig. 3.3). The fewest females are always found in the nursing stage, which perhaps indicates the difficulty of becoming pregnant and successfully giving birth to a calf that must subsequently be nursed (Fig. 3.3).

The success of giving birth and nursing a calf is also dependent on food availability. In the high-food scenario, similar to the average from the 1980s, a mature female will require on average 3.48 ± 0.206 years between successfully giving birth to calves (Fig. 3.4). The typical inter-calving interval for right whales is 3-4 years, and assumes a one-year transition period between the mature female stages of resting, pregnant, and nursing (Hamilton et al., 1998; Knowlton et al., 1994; Knowlton and Kraus, 2001). Recently, the interval between successful reproductions has been recorded at 5 years, presumably as a result of low *Calanus* concentrations (Knowlton and Kraus, 2001). In the low-food scenario of the model, similar to the average from the 1990s, a mature female will require on average 4.50 ± 0.286 years between

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Figure 3.3. Projected population of sexually mature female right whales based on three different food concentration scenarios. Solid lines represent the number of females in the resting stage, long dashed lines represent females in the pregnant stage, and short dashed lines represent females in the nursing stage. (a) *Calanus* abundance anomaly in the 1980s averaged 0.497 (dimensionless) per year (high-food scenario), (b) mean *Calanus* abundance anomaly in the 1990s was 0.0213 per year (low-food scenario), and (c) the average of the seven lowest *Calanus* abundance anomalies from the 1980s and 1990s was -0.530 per year (worst-case scenario). Initial whale distribution conditions in 1980 were the same under all three different food availability scenarios. All projections start with 100 sexually mature females, randomly distributed in the three stages of sexually mature females.
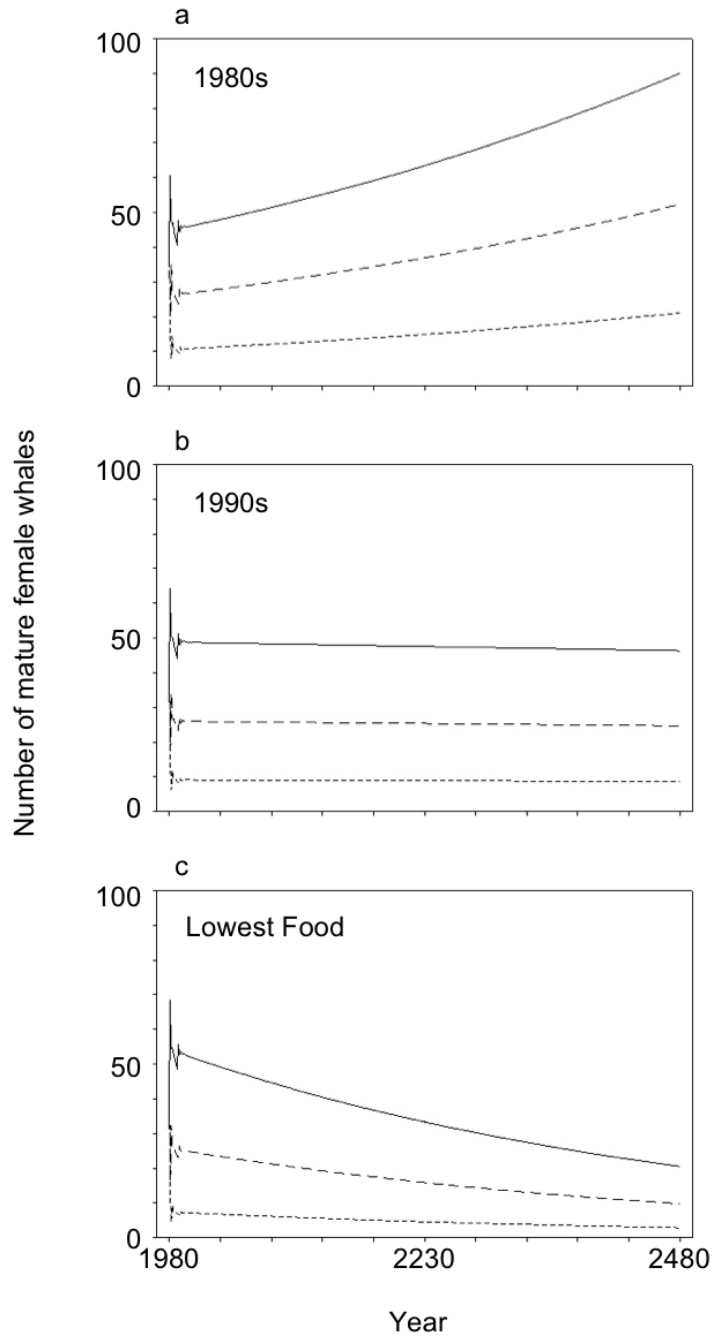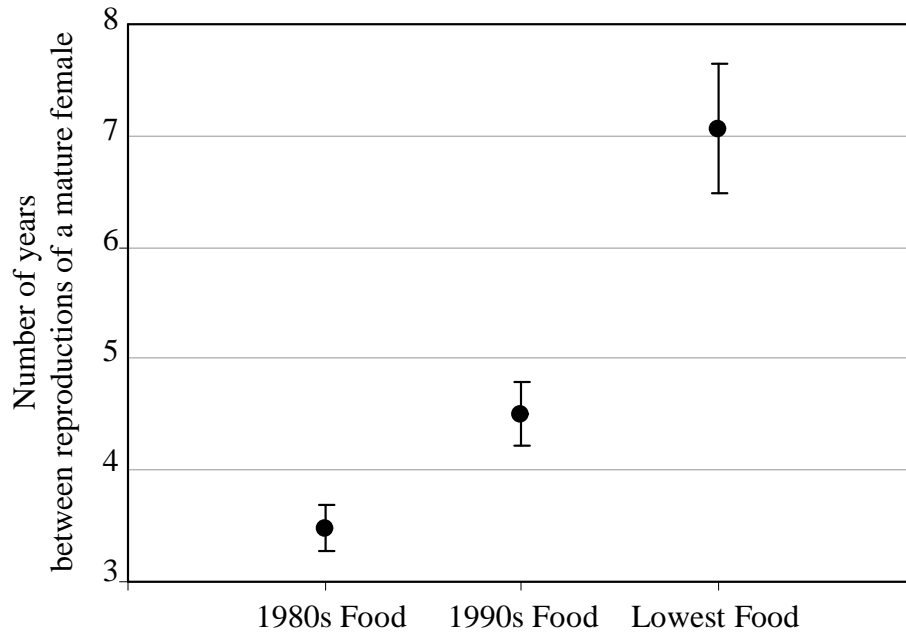
Figure 3.4. Calving interval during three different food availability scenarios. Dots represent the mean value of the number of years between giving birth; calculated from projecting the population for 500 years from 1980, and re-running the model 100 times. Vertical lines with horizontal bars above and below the mean value represent one standard deviation. Mean *Calanus* abundance anomaly values used for each scenario were: 0.497 per year for the 1980s, 0.0213 per year for the 1990s and -0.530 per year for the seven lowest values from the 1980s and 1990s.

successfully giving birth to calves (Fig. 3.4). In our worst-case scenario, similar to the average of the worst seven years of the 1980s and 1990s, a mature female will require on average 7.06 ± 0.577 years between successfully giving birth to calves (Fig. 3.4). As food availability declines, more mature females remain in the resting stage, awaiting better feeding conditions. It is also possible that more unsuccessful pregnancies occur during limited food availability years relative to when food is plentiful.

Food availability also affects the projected size of the total female population, including both mature and immature females, as well as the population's growth rate. Starting with an initial population of 100 mature females, over the 500-year projection, the total female right whale population increases only under the high-food scenario, whereas this hypothetical population declines under the low-food and worst-case scenarios (Fig. 3.5a). The specific growth rate (slope of the natural log of the total female population) under the high-food scenario is $+1.40*10^{-3}$ (ln(animals)/year) (Table 3.1), and the population will double in approximately 500 years; where

$$\text{doubling time} = (\ln 2) / (\text{specific growth rate}) \qquad (6)$$

Under the low-food and worst-case scenarios, the specific growth rates are $-0.11*10^{-3}$ (ln(animals)/year) and $-1.95*10^{-3}$ (ln(animals)/year), respectively (Fig. 3.5a, Table 3.1). The total female population could continue to grow if food availability corresponds to the average *Calanus* abundance anomaly value from the 1980s and 1990s (0.2591 - (dimensionless index)), with a specific growth rate of $+0.65*10^{-3}$ (ln(animals)/year) (Table 3.1). In this scenario, it will take the female right whale population approximately 1075 years to double in size from its estimated level in 1980. Regardless of what food availability scenario I consider, the population is right on the knife edge of viability, since even under the most optimistic feeding conditions, the population requires about 500 years to double.

Figure 3.5. Projections of total female population on a logarithmic scale (natural log) for 500 years starting in 1980 under the three different food availability scenarios, and under different percentile increases in mortality at all stages of the life cycle. Average anomaly food conditions from the 1980s were 0.497 (solid lines), average anomaly food conditions from the 1990s were 0.0213 (dashed lines), and average anomaly food concentrations for our "worst-case scenario" were -0.530 (dotted lines). (a) Projected total population of female right whales under the three different food conditions with mortality rates from Fujiwara and Caswell (2001) with 0 % increase; (b) projected population as in (a) but with 10% increased mortality rates at all life stages; (c) projected population as in (a) but with 20% increased mortality rates at all life stages; and (d) projected population as in (a) but with 30% increased mortality rates at all life stages.
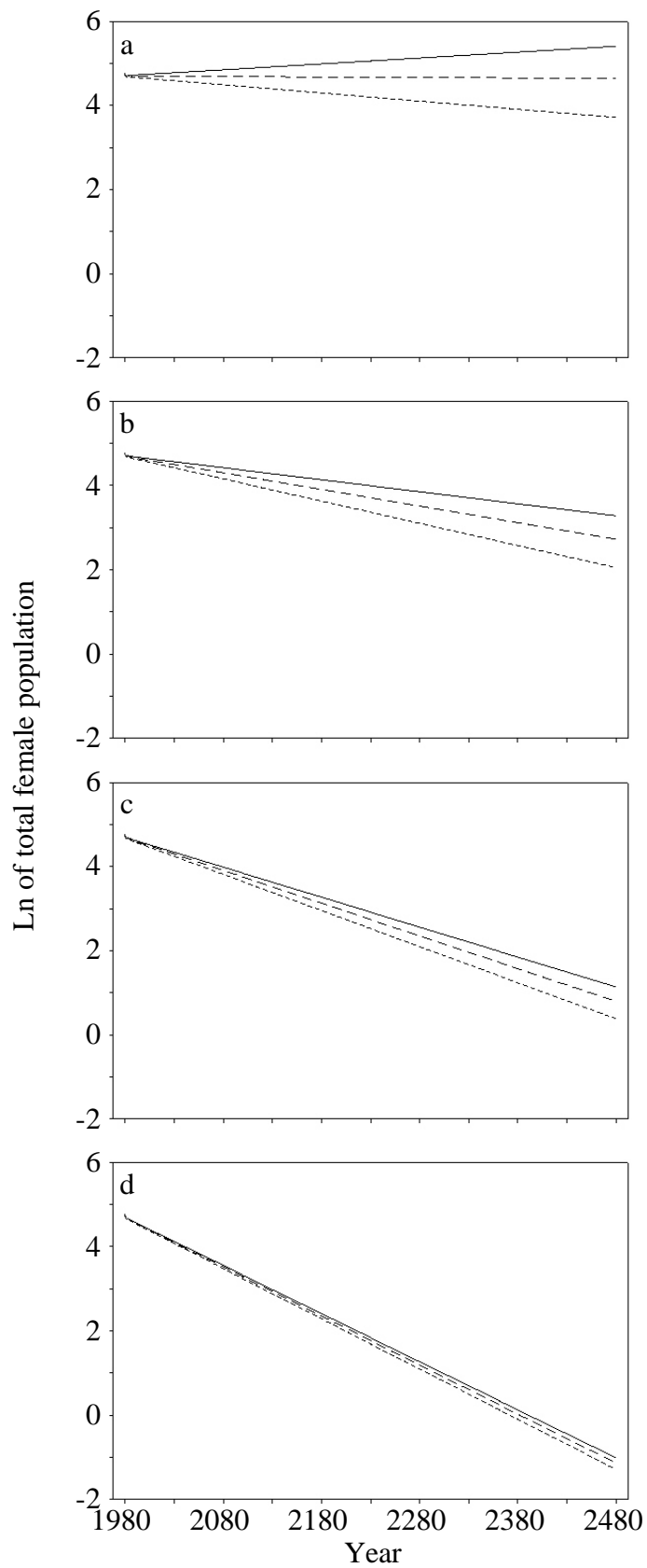
Table 3.1. Specific growth rates per year of the total female right whale population as predicted over the next 500 years under three different food availability scenarios and four different percent increases in all model mortality rates. Mortality rate increase is proportional to the mortality rates given by Fujiwara and Caswell (2001). The specific growth rate is the slope of the linear regression equation that was applied to the natural log of the total female population size from 1980 until 2480. The mean value for *Calanus finmarchicus* anomaly abundance from 1981 until 1998 is based on Continuous Plankton Recorder (CPR) data (Pershing et al., 2005).

Food availability condition	Mean anomaly food abundance	Mortality rate increase (%)	Specific growth rate ($*10^{-3}$)
1980s (high-food scenario)	0.497	0	+ 1.40
		10	- 2.86
		20	- 7.13
		30	- 11.40
1990s (low-food scenario)	0.0213	0	- 0.11
		10	- 3.95
		20	- 7.80
		30	- 11.70
1980s and 1990s lowest abundance (worst-case scenario)	- 0.530	0	- 1.95
		10	- 5.27
		20	- 8.60
		30	- 11.90
1981-1998 average	0.259	0	+ 0.65

It is important to recognize that the projected specific growth rates described above were calculated using the constant, time-invariant, annual mortality rates derived from a best sighting probability model of Fujiwara and Caswell (2001). It can reasonably be expected that these mortality rates will vary in time due to natural environmental variability, but also because of changes in mortalities from anthropogenic sources. Mortality rates for the southern right whale population, a population that is growing rapidly, have been estimated to be between 0.017 per year and 0.042 per year for the sexually mature stages (Best and Kishino, 1998; Cooke et al., 2001; Best et al., 2001), and up to 0.087 per year for juveniles (Best et al., 2001). Given that the southern right whale population is facing much lower mortality due to anthropogenic sources such as ship strikes, fishing gear entanglement and habitat loss than the northern population, I would expect lower mortality rates for the southern right whale population compared to the northern population. Therefore, it is quite possible that the mortality rates I am using in the northern right whale model (especially those for resting and pregnant females) are lower than those occurring in nature.

To investigate the potential effects of higher natural mortality rates on the model projections, the net population growth was determined for cases of mortality rates that were, respectively, 10%, 20%, and 30% higher across all stages of the life cycle, than the values provided by Fujiwara and Caswell (2001). When mortality rates were increased by 10% ($m_1=m_2=0.011$, $m_3=m_{41}=0.187$, $m_{42}=0.176$, $m_5=0.044$), the total female population declined faster for all food availability scenarios, relative to the decline with no increase in mortality rates (Fig. 3.5b, Table 3.1). When mortality rates increased by 20% ($m_1=m_2=0.012$, $m_3=m_{41}=0.204$, $m_{42}=0.192$, $m_5=0.048$), the total female population declined even further with only 3 female whales remaining in the population (out of the initial 116 mature females and newborn calves) by 2480

even under the high-food scenario (Fig. 3.5c, table 3.1). When mortality rates were increased by 30% ($m_1=m_2=0.013$, $m_3=m_{41}=0.221$, $m_{42}=0.208$, $m_5=0.052$), the population was projected to go extinct by the year 2391 under the high-food scenario, by the year 2382 under the low-food scenario, and by the year 2372 under our worst-case scenario (Fig. 3.5d, Table 3.1). In these calculations, I used the Fujiwara and Caswell (2001) definition of extinction time as the time when the total female population size drops to a single individual.

Since the current right whale population in the northwest Atlantic is very small and estimated to be less than 400 individuals, of which about 200 are expected to be females, even slight increases in mortality rates can have strong detrimental effects on the population's likelihood of survival. Therefore, I used the model to estimate what additional percentage of the total female population needed to be retained in the population (i.e. protected from death by an anthropogenic cause) every year to prevent the population from declining under the different food availability scenarios. With a total population of 100 mature females and approximately 16 newborn calves used to initialize the model, the average annual growth rate (N_{t+1}/N_t; where N is the total population size) under the high-food scenario is 1.001, under the low-food scenario is 0.9999, and under our worst-case scenario is 0.9981 (Fig. 3.6). Linear growth rates are used here instead of specific growth rates, in order to be consistent with the method of data presentation used by Fujiwara and Caswell (2001) for this particular analysis. Growth rates greater than one indicate a growing population, whereas growth rates lower than one indicate a population that is in decline. Therefore, under this model, by protecting just 1% of the female population annually, the population growth rate under the low-food scenario increases to 1.009 and under our worst-case scenario increases to 1.007 (Fig. 3.6). Hence, conservation measures that can protect only a few
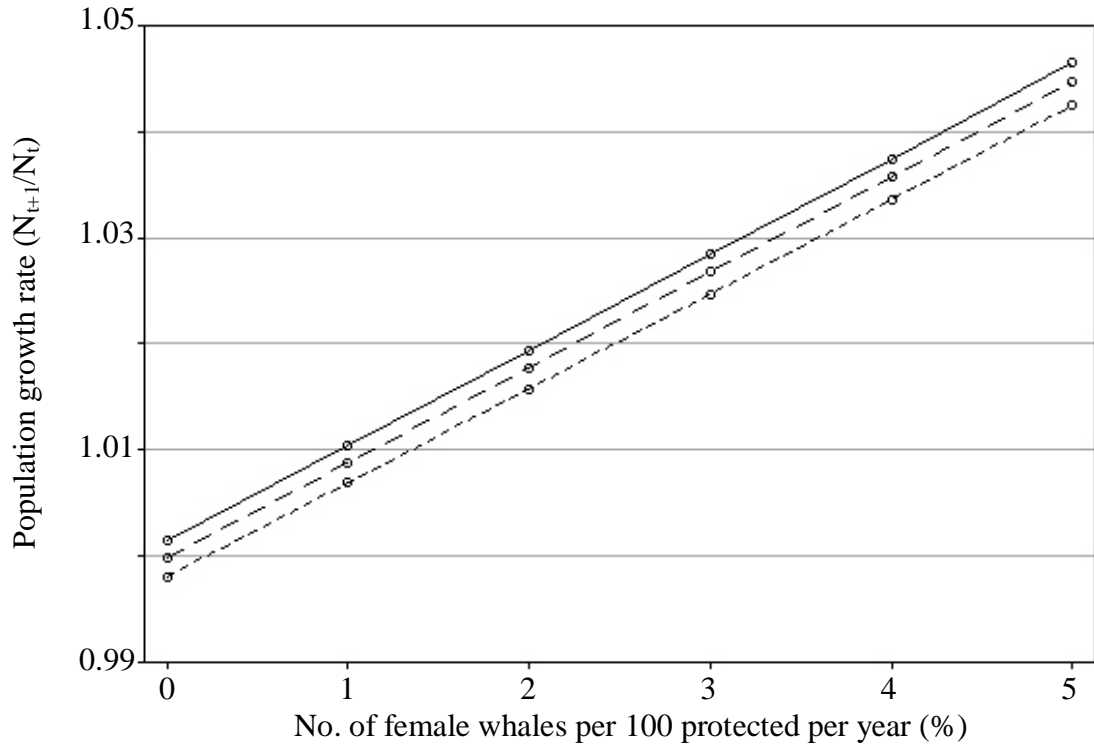
Figure 3.6. Average predicted population growth rate (N_{t+1}/N_t) resulting from protecting female right whales based on percentages of the total female population, and regardless of their stage in the life cycle under the three different food availability scenarios. Average food abundance anomaly from the 1980s (solid line), average food abundance anomaly from the 1990s (dashed line), and average food abundance anomaly for our "worst-case" scenario (dotted line).

additional female whales per year have the potential to save the population from eventual extinction under a realistic range of feeding conditions.

3.4. CONCLUSIONS

Future projections of the northwest Atlantic right whale population should take into account variations in food availability. If the future *Calanus* abundance index persists at levels equal to those experienced during the 1980s (high-food scenario), when the average abundance index value was 0.497 per year, the female right whale population is expected to grow and even double in size over the next 500 years. If however, future *Calanus* abundance anomaly levels persist at levels seen in the 1990s (low-food scenario), or the lowest seven from the 1980s and 1990s (worst-case scenario), the population will decline and eventually go extinct. Importantly, if future *Calanus* abundance anomaly values persist at an average level equal to the mean food conditions that existed over the combined period of 1980s and 1990s, the population will have a slow positive growth.

As food availability declines, mature females spend more time in the resting stage, as they require longer period of time to build up their minimum fat stores in order to support another pregnancy. This results in longer intervals between consecutive births. In addition to these considerations about food availability, the population projections for the right whales are very sensitive to mortality rates. Even slight increases in mortality can force the population on a descending trajectory. To improve the accuracy of our population projections, it is critical to cross-validate the mortality rates used in the models with those estimated from empirical field data. One encouraging finding is that my projections suggest that protecting just 1% of the female population per year may be sufficient to save the population from eventual extinction under a realistic range of feeding conditions.

With the reality that our climate is changing rapidly in response to anthropogenic forcing, it is important that conservation efforts not get locked into a static view of the world. Food availability to right whales will continue to vary; however, it is certainly conceivable that the extent of this variability may be greater than I have observed in the past. It is also possible that new trends in food availability to right whales will emerge as the climate changes. Conservation efforts should take into consideration the relationship between right whales and the variability of their marine environment. Further, it is important to obtain precise and accurate mortality rates that reflect reality for all stages of the right whale life cycle. These empirical mortality rates, coupled with data on food resources, are critical for realistic model projections. Demographic models that can explore the dynamic interplay between reproduction and mortality in a changing environment will lead to better management and conservation decisions affecting the survival and preservation of the North Atlantic right whale.

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CHAPTER FOUR

OVERVIEW AND CONCLUSIONS

Climatic impacts on ocean ecosystems are occurring globally. Climate change is a fact, affecting different parts of the world in a variety of ways. All components of the ocean ecosystem, from the physical environment to the biology are being impacted by climate change. Satellite remote sensing is an excellent tool in helping us identify the spatial and temporal variabilities occurring in the physical ocean environment as a result of climate change. It can also help in identifying the sources and causes of the variability, as well as the connections with other parts of the world. Impacts from climate change on ocean biology are easily observable through the shifts in the distributions and abundances of species. Such shifts can have a domino effect, typically starting from the primary producers and reaching the top of the food chain with a time delay. At these higher trophic levels though, there are a lot of species which are currently endangered or threatened with extinction. Thus, changes in the availability of their prey can have detrimental effects on their survival.

I have shown in chapter two, that the entire Mediterranean Sea has undergone an increase in temperatures from 1985 until 2005. A leveling-off observed in the second half of the record is due to increases of latent heat losses caused by increasing wind speeds. This warming in the Mediterranean, which is almost double that of the global oceans, is characterized by a broad, basin-wide multidecadal warming and a weaker dipole pattern that fluctuates at interannual time scales. This warming is driven primarily by changes in annual net surface heat flux, specifically by latent heat losses due to variability in regional wind speeds.

It will be valuable to investigate future trends in Mediterranean SSTs to

determine whether the recent leveling-off of sea surface temperatures and negative net surface heat fluxes represent a brief respite from a persistent warming or a new direction for an ever-changing Mediterranean Sea. Since changes occurring in the Mediterranean Sea are interconnected with changes in the Atlantic Ocean, understanding the trends in the Mediterranean can help us understand changes in the Atlantic Ocean. By studying the Mediterranean, we can also understand how the climatic changes occurring in the Mediterranean can affect the composition of water masses, circulation, and deep water formation in the Atlantic Ocean, an important part in the global meridional overturning circulation.

In chapter three, we have shown that the future of North Atlantic right whales is dependent on food availability and climate variability. Climate variability has been affecting food availability for the whale population, which in turn potentially influences the reproductive rates. Under favorable climatic conditions and high *Calanus finmarchicus* availability, the female right whale portion of the population continues to grow into the future with positive specific growth rate. However, when food availability is low, the growth of the female portion of the population turns negative. Further, when *Calanus finmarchicus* abundance is low, female whales spend more time in the resting stage, which results in longer intervals between consecutive births. In contrast, when food abundance is high, inter-calving intervals are shorter. The decline of the female population is even more drastic if mortality rates increase. Even slight increases in mortality, can force the population on to a declining path with extinction possible within the next 300 years. Hope for the survival of the species still exists, as by protecting just 1% of the female population every year, even under some of the worst feeding conditions observed recently, the population can still grow slowly and avoid extinction.

As we develop strategies to save this population from extinction, conservation

efforts should take climate-related food variability as well as anthropogenic sources of mortality into consideration. Further, it is important to obtain precise and accurate mortality rates for all stages of the right whale life cycle. These empirical mortality rates, coupled with data on food resources, are critical for realistic population projections. Demographic models that can explore the dynamic interplay between reproduction and mortality in a changing environment will lead to better management and conservation decisions affecting the survival and preservation of the species.

Climate change does not recognize national and political boundaries. The problem cannot be solved by one country in isolation of others. All countries need to be involved in tackling the global problem of climate change on all fronts. We have the capability of observing and analyzing many environmental and biological changes occurring worldwide in near real-time. We are also slowly gaining the ability to hindcast and forecast past and future impacts of the ocean environment and its populations. However, even as our predictive understanding improves, we must make the hard decisions necessary to diminish man's impacts on global ocean ecosystems.

This dissertation demonstrates that we have the mechanisms to document climate change and its impacts on the earth's ecosystems. Tragically, the question still remains as to whether we have the will, discipline and commitment, individually and collectively, to change our behaviors in hopes of reversing and improving the situation.

APPENDIX

A.1. Script written in MATLAB to predict and estimate the population size of

northern right whales in the Northwest Atlantic, extending for 500 years from 1980

under three different food availability conditions, using mortality rates as estimated by

Fujiwara and Caswell (2001).


```
function
[whales, calves_per_yr, avg_calves_per_rep_fem, mean_calves_per_rep_fem] =
RWfwdFcst_mortal_new(Food, moms99const, params, runtime)

%load GOMgaExp
%load GOMdata99
%load FoodProj

y= length(Food(:,1));
'time series length='
y

t=length(Food(1,:));

a=runtime;

whales=zeros(y+1,4);
whl_std=zeros(y+1,4);

yr_restin_avg= zeros(y+1,a);
yr_pregna_avg= zeros(y+1,a);
yr_mother_avg= zeros(y+1,a);
yr_calves_avg= zeros(y+1,a);
yr_1_avg= zeros(y+1,a);
yr_2_avg= zeros(y+1,a);
yr_3_avg= zeros(y+1,a);
yr_4_avg= zeros(y+1,a);
yr_5_avg= zeros(y+1,a);
yr_6_avg= zeros(y+1,a);
yr_7_avg= zeros(y+1,a);
yr_8_avg= zeros(y+1,a);

calves_per_rep_fem= zeros(y+1,a);
tl_pop= zeros(y+1,a);
tl_pop_gr_rate= zeros(y+1,1);
```

```matlab
rep_pop_gr_rate= zeros(y+1,1);
ratio_1= zeros(y+1,1);
ratio_2= zeros(y+1,1);
ratio_3= zeros(y+1,1);
rep_ratio_1= zeros(y+1,1);
rep_ratio_2= zeros(y+1,1);
rep_ratio_3= zeros(y+1,1);

food_avg_80s=  0.4968;
food_avg_90s=  0.0213;
food_avg_bad= -0.5304;

Food(:,2:end)= food_avg_bad;

food_avg= mean(Food(:,2:end),2);

m1=  0.01;
m2=  0.01;
m3=  0.17;
m41= 0.17;
m42= 0.16;
m5=  0.04;

for b=1:runtime
   b

   GOMwhls0=zeros(y+1,12);
   all_whls=zeros(y+1,12,t-1);

      for j= 1:moms99const(1,2)
         c= rand(1);
         s= fix(c*3)+1;
         GOMwhls0(1,s)= GOMwhls0(1,s)+1;
      end

   GOMwhls0(1,4)= GOMwhls0(1,3)*0.5;


   for z=1:t-1

      for j=2:2
         pnew= params(1)*Food(j-1,z+1) + params(2);
         qnew= params(3)*Food(j-1,z+1) + params(4);

         GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
                  + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
                  + GOMwhls0(j-1,3)*(1-m3);
```

```
      GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
      GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
      GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
      GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
    end


for j=3:3
      pnew= params(1)*Food(j-1,z+1) + params(2);
      qnew= params(3)*Food(j-1,z+1) + params(4);

      GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
                + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
                + GOMwhls0(j-1,3)*(1-m3);
      GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
      GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
      GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
      GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
      GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
    end

for j=4:4
      pnew= params(1)*Food(j-1,z+1) + params(2);
      qnew= params(3)*Food(j-1,z+1) + params(4);

      GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
                + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
                + GOMwhls0(j-1,3)*(1-m3);
      GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
      GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
      GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
      GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
      GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
      GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
    end

for j=5:5
      pnew= params(1)*Food(j-1,z+1) + params(2);
      qnew= params(3)*Food(j-1,z+1) + params(4);

      GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
                + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
                + GOMwhls0(j-1,3)*(1-m3);
      GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
      GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
      GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
      GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
```

```
    GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
    GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
    GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
end

for j=6:6
    pnew= params(1)*Food(j-1,z+1) + params(2);
    qnew= params(3)*Food(j-1,z+1) + params(4);

    GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
             + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
             + GOMwhls0(j-1,3)*(1-m3);
    GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
    GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
    GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
    GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
    GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
    GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
    GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
    GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
end

for j=7:7
    pnew= params(1)*Food(j-1,z+1) + params(2);
    qnew= params(3)*Food(j-1,z+1) + params(4);

    GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
             + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
             + GOMwhls0(j-1,3)*(1-m3);
    GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
    GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
    GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
    GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
    GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
    GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
    GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
    GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
    GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
end

for j=8:8
    pnew= params(1)*Food(j-1,z+1) + params(2);
    qnew= params(3)*Food(j-1,z+1) + params(4);

    GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
             + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
             + GOMwhls0(j-1,3)*(1-m3);
```

```
        GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
        GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
        GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
        GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
        GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
        GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
        GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
        GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
        GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
        GOMwhls0(j,11)= GOMwhls0(j-1,10)*(1-m5);
    end

    for j=9:9
        pnew= params(1)*Food(j-1,z+1) + params(2);
        qnew= params(3)*Food(j-1,z+1) + params(4);

        GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
                + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
                + GOMwhls0(j-1,3)*(1-m3);
        GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
        GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
        GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
        GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
        GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
        GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
        GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
        GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
        GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
        GOMwhls0(j,11)= GOMwhls0(j-1,10)*(1-m5);
        GOMwhls0(j,12)= GOMwhls0(j-1,11)*(1-m5);
    end

    for j=10:y+1
        pnew= params(1)*Food(j-1,z+1) + params(2);
        qnew= params(3)*Food(j-1,z+1) + params(4);

        GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
                + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
                + GOMwhls0(j-1,3)*(1-m3) ...
                + GOMwhls0(j-1,12)*(1-m5);
        GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
        GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
        GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
        GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
        GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
        GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
        GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
```

```
      GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
      GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
      GOMwhls0(j,11)= GOMwhls0(j-1,10)*(1-m5);
      GOMwhls0(j,12)= GOMwhls0(j-1,11)*(1-m5);
    end


    all_whls(:,:,z)=GOMwhls0(:,:);
  end


  yr_restin_avg(:,b)= mean(all_whls(:,1,:),3);
  yr_pregna_avg(:,b)= mean(all_whls(:,2,:),3);
  yr_mother_avg(:,b)= mean(all_whls(:,3,:),3);
  yr_calves_avg(:,b)= mean(all_whls(:,4,:),3);
  yr_1_avg(:,b)= mean(all_whls(:,5,:),3);
  yr_2_avg(:,b)= mean(all_whls(:,6,:),3);
  yr_3_avg(:,b)= mean(all_whls(:,7,:),3);
  yr_4_avg(:,b)= mean(all_whls(:,8,:),3);
  yr_5_avg(:,b)= mean(all_whls(:,9,:),3);
  yr_6_avg(:,b)= mean(all_whls(:,10,:),3);
  yr_7_avg(:,b)= mean(all_whls(:,11,:),3);
  yr_8_avg(:,b)= mean(all_whls(:,12,:),3);

  for z=1:y+1
    tl_pop(z,b)= sum(yr_restin_avg(z,b)+ yr_pregna_avg(z,b)...
          + yr_mother_avg(z,b)+ yr_calves_avg(z,b)+ yr_1_avg(z,b)...
          + yr_2_avg(z,b)+ yr_3_avg(z,b)+ yr_4_avg(z,b) ...
          + yr_5_avg(z,b)+ yr_6_avg(z,b)+ yr_7_avg(z,b)...
          + yr_8_avg(z,b));
    rep_fem_pop(z,b)= sum(yr_restin_avg(z,b)+ yr_pregna_avg(z,b)…
          + yr_mother_avg(z,b));
    calves_per_rep_fem(z,b)= yr_calves_avg(z,b)/rep_fem_pop(z,b);
  end

  avg_calves_per_rep_fem= mean(calves_per_rep_fem,1);
  mean_calves_per_rep_fem= mean(calves_per_rep_fem,2);

  calves_per_yr= mean(yr_calves_avg,1);

end

avg_tl_pop= mean(tl_pop,2);

whales(1:end,1)=mean(yr_restin_avg,2);
whales(1:end,2)=mean(yr_pregna_avg,2);
whales(1:end,3)=mean(yr_mother_avg,2);
whales(1:end,4)=mean(yr_calves_avg,2);
```

```
whl_std(1:end,1)=std(yr_restin_avg,0,2);
whl_std(1:end,2)=std(yr_pregna_avg,0,2);
whl_std(1:end,3)=std(yr_mother_avg,0,2);
whl_std(1:end,4)=std(yr_calves_avg,0,2);

avg_rep_fem_pop(:,1)= mean(rep_fem_pop, 2);
avg_tl_pop(:,1)=mean(tl_pop,2);

for z=2:y+1
   tl_pop_gr_rate(z,1)= (avg_tl_pop(z)-avg_tl_pop(z-1))/avg_tl_pop(z-1);
   rep_pop_gr_rate(z,1)= (avg_rep_fem_pop(z)- avg_rep_fem_pop(z-1))
                        /avg_rep_fem_pop(z-1);
end


mean_tl_pop_gr_rates= mean(tl_pop_gr_rate);
mean_rep_pop_gr_rate= mean(rep_pop_gr_rate);
mean_calves_per_yr= mean(whales(:,4),1);

for z=1:y+1
   ratio_1(z,1)=whales(z,1)/avg_tl_pop(z);
   ratio_2(z,1)=whales(z,2)/avg_tl_pop(z);
   ratio_3(z,1)=whales(z,3)/avg_tl_pop(z);
   rep_ratio_1(z,1)=whales(z,1)/avg_rep_fem_pop(z);
   rep_ratio_2(z,1)=whales(z,2)/avg_rep_fem_pop(z);
   rep_ratio_3(z,1)=whales(z,3)/avg_rep_fem_pop(z);
end


%mkdir RWFwdResults_best
cd RWFwdResults_best
   %mkdir whales_500y
   cd whales_500y
      %mkdir Food_avg_80s
      %mkdir Food_avg_90s
      %mkdir Food_avg_worst
      cd Food_avg_worst

figure(1)
clf
plot(Food(1:end,1), whales(1:y,1), 'g'); hold on
plot(Food(1:end,1), whales(1:y,2), 'b'); hold on
plot(Food(1:end,1), whales(1:y,3), 'r'); hold on
xlabel('Year');
ylabel('Number of whales');
dlmwrite(['whales.txt'], whales, 'delimiter','\t', 'newline', 'pc');
```

```
dlmwrite(['whales_std.txt'], whl_std, 'delimiter','\t', 'newline', 'pc');


figure(2)
clf
plot(Food(1:end,1), avg_rep_fem_pop(1:y,1), 'r'); hold on
plot(Food(1:end,1), avg_tl_pop(1:y,1), 'k');
dlmwrite(['avg_rep_fem_pop.txt'], avg_rep_fem_pop, 'delimiter','\t', 'newline', 'pc');
dlmwrite(['avg_tl_pop.txt'], avg_tl_pop, 'delimiter','\t', 'newline', 'pc');


figure(3)
clf
hist(avg_calves_per_rep_fem)
xlabel('Avg Growth Rates');
title('Histogram of Average Growth Rates');
dlmwrite(['calves_per_rep_fem.txt'], avg_calves_per_rep_fem, 'delimiter','\t',
'newline', 'pc');


figure(4)
clf
x1= Food(1:end,1);
y1=mean_calves_per_rep_fem(1:y,1);
y2= food_avg(1:end);
hl1=line(x1,y1,'color', 'k');
ax1=gca;
ylabel('Average Growth Rates')
set(ax1,'XColor','k','YColor','k')
ax2=axes('Position',get(ax1,'Position'), ...
      'YAxisLocation', 'right', ...
      'Color', 'none', ...
      'YColor', 'k');
hl2=line(x1,y2, 'Color', 'g', 'Parent', ax2);
ylabel('Average Food')
xlabel('Year');
title('Average Yearly Calves_per_rep_fem');
dlmwrite(['avg_yr_calves_per_rep_fem.txt'], mean_calves_per_rep_fem,
'delimiter','\t', 'newline', 'pc');


figure(5)
clf
hist(calves_per_yr)
xlabel('Calves per year');
title('Histogram of Calves per Year');
dlmwrite(['calves_per_yr.txt'], calves_per_yr, 'delimiter','\t', 'newline', 'pc');
```

```
figure(6)
clf
plot(Food(1:end,1), tl_pop_gr_rate(1:y,1), 'k'); hold on
plot(Food(1:end,1), rep_pop_gr_rate(1:y,1), 'r');
xlabel('Year');
ylabel('Total & Reproductive Population Growth Rates');
dlmwrite(['tl_pop_gr_rates.txt'], tl_pop_gr_rate, 'delimiter','\t', 'newline', 'pc');
dlmwrite(['rep_pop_gr_rates.txt'], rep_pop_gr_rate, 'delimiter','\t', 'newline', 'pc');
dlmwrite(['avg_tl_pop.txt'], avg_tl_pop, 'delimiter','\t', 'newline', 'pc');
dlmwrite(['avg_rep_pop.txt'], avg_rep_fem_pop, 'delimiter','\t', 'newline', 'pc');

figure(7)
clf
plot(Food(1:end,1), ratio_1(1:y), 'g'); hold on
plot(Food(1:end,1), ratio_2(1:y), 'b'); hold on
plot(Food(1:end,1), ratio_3(1:y), 'r'); hold on
xlabel('Year');
ylabel('Ratio of whales with total population');
dlmwrite(['bm_whales.txt'], whales, 'delimiter','\t', 'newline', 'pc');
dlmwrite(['bm_whales_std.txt'], whl_std, 'delimiter','\t', 'newline', 'pc');




cd ..
cd ..
cd ..
```

A.2. Script written in MATLAB to estimate the average number of years it takes for one female to become pregnant again and successfully give birth to a calf under the different food availabilities.

```matlab
function [calving_int_arr]=RWfwdFcst_int(Food, moms99const, params, runtime);

%load GOMgaExp
%load GOMdata99
%load FoodProj

y= length(Food(:,1));
'time series length='
y


a=runtime;

    food_avg_80s=  0.4968;
    food_avg_90s=  0.0213;
    food_avg_bad= -0.5304;

Food(:,2)=food_avg_bad;


pnew= params(1)*Food(1,2)+params(2)
qnew= params(3)*Food(1,2)+params(4)

H_resting=  -(log2(pnew)*pnew)
H_pregnant= -(log2(qnew)*qnew)
H_nursing=  0;


calving_int_arr= zeros(a,2);
overall_yr_int= zeros(1,2);

for b=1:runtime
    b

    GOMwhls0=zeros(y+1,3);
    resting_ratio=zeros(y,1);
    pregnant_ratio=zeros(y,1);
    nursing_ratio =zeros(y,1);



    for j= 1:moms99const(1,2)
```

```
        c= rand(1);
        s= fix(c*3)+1;
        GOMwhls0(1,s)= GOMwhls0(1,s)+1;
    end

    for j=2:y+1
        [GOMwhls0(j,:),r]= RWfwd(Food(j-1,2),GOMwhls0(j-1,:),params);
    end

    GOMwhls0 ;
    no_mothers=find(GOMwhls0(:,3)==0);
    GOMwhls0(no_mothers,3)=0.01;

    for j=2:y+1
        resting_ratio(j-1,1)=  GOMwhls0(j-1,1)/100;
        pregnant_ratio(j-1,1)= GOMwhls0(j-1,2)/100;
        nursing_ratio(j-1,1)=  GOMwhls0(j-1,3)/100;

        HX(j-1,1)= (resting_ratio(j-1,1)*H_resting) +
                    (pregnant_ratio(j-1,1)*H_pregnant);

        H33(j-1,1)= HX(j-1,1)/nursing_ratio(j-1,1);

    end


    H33;
    calving_int_arr(b,1)= mean(calving_int);
    calving_int_arr(b,2)= std(calving_int,0);

end

overall_yr_int(1,1)= mean(calving_int_arr(:,1));
overall_yr_int(1,2)= std(calving_int_arr(:,2),0);

%mkdir RWFwdResults_best_yr_int
cd RWFwdResults_best_yr_int
    %mkdir Food_80s_yr_int
    %mkdir Food_90s_yr_int
    %mkdir Food_worst_yr_int
    cd Food_worst_yr_int

figure(1)
clf
hist(calving_int_arr(:,1))
xlabel('Avg Years Between Births');
title('Histogram of Time between Reproduction');
```

```
figure(2)
clf
plot(overall_yr_int(1,1), 'sr'); hold on
plot(overall_yr_int(1,1)+overall_yr_int(1,2), 'sb'); hold on
plot(overall_yr_int(1,1)-overall_yr_int(1,2), 'sb');

ylim([0 20])
ylabel('Overall no. of Years between Births');
dlmwrite(['overall_yr_int.txt'], overall_yr_int, 'delimiter','\t', 'newline', 'pc');


figure(3)
clf
plot(1:b, calving_int_arr(:,1), '-*r'); hold on
plot(1:b, calving_int_arr(:,1)+calving_int_arr(:,2), '-b'); hold on
plot(1:b, calving_int_arr(:,1)-calving_int_arr(:,2), '-b');

ylim([0 20])
xlim([0 101])
ylabel('Years between Births');
dlmwrite(['avg yrs bw births.txt'], calving_int_arr,'delimiter','\t', 'newline', 'pc');

cd ..
cd ..
```

A.3. Script written in MATLAB to investigate the projections for the population under

different mortality increases (in percentages).

```
function
[whales, calves_per_yr, avg_calves_per_rep_fem, mean_calves_per_rep_fem] =
RWfwdFcst_mortal_new_incr(Food, moms99const, params, runtime)

%load GOMgaExp
%load GOMdata99
%load FoodProj

y= length(Food(:,1));
'time series length='
y

t=length(Food(1,:));

a=runtime;

whales=zeros(y+1,4);
whl_std=zeros(y+1,4);

yr_restin_avg= zeros(y+1,a);
yr_pregna_avg= zeros(y+1,a);
yr_mother_avg= zeros(y+1,a);
yr_calves_avg= zeros(y+1,a);
yr_1_avg= zeros(y+1,a);
yr_2_avg= zeros(y+1,a);
yr_3_avg= zeros(y+1,a);
yr_4_avg= zeros(y+1,a);
yr_5_avg= zeros(y+1,a);
yr_6_avg= zeros(y+1,a);
yr_7_avg= zeros(y+1,a);
yr_8_avg= zeros(y+1,a);

calves_per_rep_fem= zeros(y+1,a);
tl_pop= zeros(y+1,a);
tl_pop_gr_rate= zeros(y+1,1);
rep_pop_gr_rate= zeros(y+1,1);
ratio_1= zeros(y+1,1);
ratio_2= zeros(y+1,1);
ratio_3= zeros(y+1,1);
rep_ratio_1= zeros(y+1,1);
rep_ratio_2= zeros(y+1,1);
rep_ratio_3= zeros(y+1,1);

    food_avg_80s=  0.4968;
    food_avg_90s=  0.0213;
    food_avg_bad= -0.5304;
```

```
Food(:,2:end)=food_avg_bad;

food_avg=mean(Food(:,2:end),2);

m1=  (0.01 + (0.01*10/100));
m2=  (0.01 + (0.01*10/100));
m3=  (0.17 + (0.17*10/100));
m41= (0.17 + (0.17*10/100));
m42= (0.16 + (0.16*10/100));
m5=  (0.04 + (0.04*10/100));


for b=1:runtime
   b

   GOMwhls0=zeros(y+1,12);
   all_whls=zeros(y+1,12,t-1);

    for j= 1:moms99const(1,2)
       c= rand(1);
       s= fix(c*3)+1;
       GOMwhls0(1,s)= GOMwhls0(1,s)+1;
    end


   GOMwhls0(1,4)= GOMwhls0(1,3)*0.5;

   for z=1:t-1

     for j=2:2
        pnew= params(1)*Food(j-1,z+1) + params(2);
        qnew= params(3)*Food(j-1,z+1) + params(4);

        GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
                + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
                + GOMwhls0(j-1,3)*(1-m3);
        GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
        GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
        GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
        GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
     end


     for j=3:3
        pnew= params(1)*Food(j-1,z+1) + params(2);
        qnew= params(3)*Food(j-1,z+1) + params(4);

        GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
                + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
                + GOMwhls0(j-1,3)*(1-m3);
        GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
```

```
   GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
   GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
   GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
   GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
end

for j=4:4
   pnew= params(1)*Food(j-1,z+1) + params(2);
   qnew= params(3)*Food(j-1,z+1) + params(4);

   GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
            + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
            + GOMwhls0(j-1,3)*(1-m3);
   GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
   GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
   GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
   GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
   GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
   GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
end

for j=5:5
   pnew= params(1)*Food(j-1,z+1) + params(2);
   qnew= params(3)*Food(j-1,z+1) + params(4);

   GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
            + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
            + GOMwhls0(j-1,3)*(1-m3);
   GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
   GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
   GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
   GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
   GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
   GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
   GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
end

for j=6:6
   pnew= params(1)*Food(j-1,z+1) + params(2);
   qnew= params(3)*Food(j-1,z+1) + params(4);

   GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
            + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
            + GOMwhls0(j-1,3)*(1-m3);
   GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
   GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
   GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
   GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
   GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
   GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
   GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
   GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
```

```matlab
end

for j=7:7
    pnew= params(1)*Food(j-1,z+1) + params(2);
    qnew= params(3)*Food(j-1,z+1) + params(4);

    GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
            + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
            + GOMwhls0(j-1,3)*(1-m3);
    GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
    GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
    GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
    GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
    GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
    GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
    GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
    GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
    GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
end

for j=8:8
    pnew= params(1)*Food(j-1,z+1) + params(2);
    qnew= params(3)*Food(j-1,z+1) + params(4);

    GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
            + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
            + GOMwhls0(j-1,3)*(1-m3);
    GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
    GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
    GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
    GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
    GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
    GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
    GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
    GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
    GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
    GOMwhls0(j,11)= GOMwhls0(j-1,10)*(1-m5);
end

for j=9:9
    pnew= params(1)*Food(j-1,z+1) + params(2);
    qnew= params(3)*Food(j-1,z+1) + params(4);

    GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
            + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
            + GOMwhls0(j-1,3)*(1-m3);
    GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
    GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
    GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
    GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
    GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
    GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
```

```
         GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
         GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
         GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
         GOMwhls0(j,11)= GOMwhls0(j-1,10)*(1-m5);
         GOMwhls0(j,12)= GOMwhls0(j-1,11)*(1-m5);
     end

     for j=10:y+1
        pnew= params(1)*Food(j-1,z+1) + params(2);
        qnew= params(3)*Food(j-1,z+1) + params(4);

        GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
                  + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
                  + GOMwhls0(j-1,3)*(1-m3) ...
                  + GOMwhls0(j-1,12)*(1-m5);
        GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
        GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
        GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
        GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
        GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
        GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
        GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
        GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
        GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
        GOMwhls0(j,11)= GOMwhls0(j-1,10)*(1-m5);
        GOMwhls0(j,12)= GOMwhls0(j-1,11)*(1-m5);
     end

     all_whls(:,:,z)=GOMwhls0(:,:);

  end


  yr_restin_avg(:,b)= mean(all_whls(:,1,:),3);
  yr_pregna_avg(:,b)= mean(all_whls(:,2,:),3);
  yr_mother_avg(:,b)= mean(all_whls(:,3,:),3);
  yr_calves_avg(:,b)= mean(all_whls(:,4,:),3);
  yr_1_avg(:,b)= mean(all_whls(:,5,:),3);
  yr_2_avg(:,b)= mean(all_whls(:,6,:),3);
  yr_3_avg(:,b)= mean(all_whls(:,7,:),3);
  yr_4_avg(:,b)= mean(all_whls(:,8,:),3);
  yr_5_avg(:,b)= mean(all_whls(:,9,:),3);
  yr_6_avg(:,b)= mean(all_whls(:,10,:),3);
  yr_7_avg(:,b)= mean(all_whls(:,11,:),3);
  yr_8_avg(:,b)= mean(all_whls(:,12,:),3);

  for z=1:y+1
     tl_pop(z,b)=sum(yr_restin_avg(z,b)+ yr_pregna_avg(z,b)...
              + yr_mother_avg(z,b)+ yr_calves_avg(z,b)+ yr_1_avg(z,b)...
              + yr_2_avg(z,b)+ yr_3_avg(z,b)+ yr_4_avg(z,b) ...
              + yr_5_avg(z,b)+ yr_6_avg(z,b)+ yr_7_avg(z,b)...
              + yr_8_avg(z,b));
```

```
      rep_fem_pop(z,b)= sum(yr_restin_avg(z,b)+ yr_pregna_avg(z,b) …
            + yr_mother_avg(z,b));
      calves_per_rep_fem(z,b)= yr_calves_avg(z,b)/rep_fem_pop(z,b);
   end

   avg_calves_per_rep_fem= mean(calves_per_rep_fem,1);
   mean_calves_per_rep_fem= mean(calves_per_rep_fem,2);

   calves_per_yr= mean(yr_calves_avg,1);

end

avg_tl_pop= mean(tl_pop,2);

whales(1:end,1)=mean(yr_restin_avg,2);
whales(1:end,2)=mean(yr_pregna_avg,2);
whales(1:end,3)=mean(yr_mother_avg,2);
whales(1:end,4)=mean(yr_calves_avg,2);

whl_std(1:end,1)=std(yr_restin_avg,0,2);
whl_std(1:end,2)=std(yr_pregna_avg,0,2);
whl_std(1:end,3)=std(yr_mother_avg,0,2);
whl_std(1:end,4)=std(yr_calves_avg,0,2);

avg_rep_fem_pop(:,1)= mean(rep_fem_pop, 2);
avg_tl_pop(:,1)=mean(tl_pop,2);

for z=2:y+1
   tl_pop_gr_rate(z,1)= (avg_tl_pop(z)-avg_tl_pop(z-1))/avg_tl_pop(z-1);
   rep_pop_gr_rate(z,1)= (avg_rep_fem_pop(z)-avg_rep_fem_pop(z-1))
                         /avg_rep_fem_pop(z-1);
end


mean_tl_pop_gr_rates= mean(tl_pop_gr_rate);
mean_rep_pop_gr_rate= mean(rep_pop_gr_rate);
mean_calves_per_yr= mean(whales(:,4),1);

for z=1:y+1
   ratio_1(z,1)=whales(z,1)/avg_tl_pop(z);
   ratio_2(z,1)=whales(z,2)/avg_tl_pop(z);
   ratio_3(z,1)=whales(z,3)/avg_tl_pop(z);
   rep_ratio_1(z,1)=whales(z,1)/avg_rep_fem_pop(z);
   rep_ratio_2(z,1)=whales(z,2)/avg_rep_fem_pop(z);
   rep_ratio_3(z,1)=whales(z,3)/avg_rep_fem_pop(z);
end


%mkdir RWFwdResults_best_incr
cd RWFwdResults_best_incr
   %mkdir whales_500y_10perc
   cd whales_500y_10perc
```

```
%mkdir Food_avg_80s_10perc
%mkdir Food_avg_90s_10perc
%mkdir Food_avg_worst_10perc
cd Food_avg_worst_10perc


figure(1)
clf
plot(Food(1:end,1), whales(1:y,1), 'g'); hold on
plot(Food(1:end,1), whales(1:y,2), 'b'); hold on
plot(Food(1:end,1), whales(1:y,3), 'r'); hold on
xlabel('Year');
ylabel('Number of whales');
dlmwrite(['whales.txt'], whales, 'delimiter','\t', 'newline', 'pc');
dlmwrite(['whales_std.txt'], whl_std, 'delimiter','\t', 'newline', 'pc');




figure(2)
clf
plot(Food(1:end,1), avg_rep_fem_pop(1:y,1), 'r'); hold on
plot(Food(1:end,1), avg_tl_pop(1:y,1), 'k');
dlmwrite(['avg_rep_fem_pop.txt'], avg_rep_fem_pop, 'delimiter','\t', 'newline', 'pc');
dlmwrite(['avg_tl_pop.txt'], avg_tl_pop, 'delimiter','\t', 'newline', 'pc');




figure(3)
clf
hist(avg_calves_per_rep_fem)
xlabel('Avg Growth Rates');
title('Histogram of Average Growth Rates');
dlmwrite(['calves_per_rep_fem.txt'], avg_calves_per_rep_fem, 'delimiter','\t',
'newline', 'pc');


figure(4)
clf
x1= Food(1:end,1);
y1=mean_calves_per_rep_fem(1:y,1);
y2= food_avg(1:end);
hl1=line(x1,y1,'color', 'k');
ax1=gca;
ylabel('Average Growth Rates')
set(ax1,'XColor','k','YColor','k')
ax2=axes('Position',get(ax1,'Position'), ...
     'YAxisLocation', 'right', ...
     'Color', 'none', ...
     'YColor', 'k');
hl2=line(x1,y2, 'Color', 'g', 'Parent', ax2);
ylabel('Average Food')
xlabel('Year');
title('Average Yearly Calves_per_rep_fem');
```

```
dlmwrite(['avg_yr_calves_per_rep_fem.txt'], mean_calves_per_rep_fem,
'delimiter','\t', 'newline', 'pc');


figure(5)
clf
hist(calves_per_yr)
xlabel('Calves per year');
title('Histogram of Calves per Year');
dlmwrite(['calves_per_yr.txt'], calves_per_yr, 'delimiter','\t', 'newline', 'pc');


figure(6)
clf
plot(Food(1:end,1), tl_pop_gr_rate(1:y,1), 'k'); hold on
plot(Food(1:end,1), rep_pop_gr_rate(1:y,1), 'r');
xlabel('Year');
ylabel('Total & Reproductive Population Growth Rates');
dlmwrite(['tl_pop_gr_rates.txt'], tl_pop_gr_rate, 'delimiter','\t', 'newline', 'pc');
dlmwrite(['rep_pop_gr_rates.txt'], rep_pop_gr_rate, 'delimiter','\t', 'newline', 'pc');
dlmwrite(['avg_tl_pop.txt'], avg_tl_pop, 'delimiter','\t', 'newline', 'pc');
dlmwrite(['avg_rep_pop.txt'], avg_rep_fem_pop, 'delimiter','\t', 'newline', 'pc');

figure(7)
clf
plot(Food(1:end,1), ratio_1(1:y), 'g'); hold on
plot(Food(1:end,1), ratio_2(1:y), 'b'); hold on
plot(Food(1:end,1), ratio_3(1:y), 'r'); hold on
xlabel('Year');
ylabel('Ratio of whales with total population');
dlmwrite(['bm_whales.txt'], whales, 'delimiter','\t', 'newline', 'pc');
dlmwrite(['bm_whales_std.txt'], whl_std, 'delimiter','\t', 'newline', 'pc');


cd ..
cd ..
cd ..
```

A.4. Script written in MATLAB to estimate the number of female whales (in percentages) that needs to be protected every year under the three different food availability scenarios in order for the population to grow.

```
function
[whales, calves_per_yr, avg_calves_per_rep_fem, mean_calves_per_rep_fem]=
RWfwdFcst_mortal_new_save(Food, moms99const, params, runtime)

%load GOMgaExp
%load GOMdata99
%load FoodProj

y= length(Food(:,1));
'time series length='
y

t=length(Food(1,:));

a=runtime;

whales=zeros(y+1,4);
whl_std=zeros(y+1,4);

yr_restin_avg= zeros(y+1,a);
yr_pregna_avg= zeros(y+1,a);
yr_mother_avg= zeros(y+1,a);
yr_calves_avg= zeros(y+1,a);
yr_1_avg= zeros(y+1,a);
yr_2_avg= zeros(y+1,a);
yr_3_avg= zeros(y+1,a);
yr_4_avg= zeros(y+1,a);
yr_5_avg= zeros(y+1,a);
yr_6_avg= zeros(y+1,a);
yr_7_avg= zeros(y+1,a);
yr_8_avg= zeros(y+1,a);

calves_per_rep_fem= zeros(y+1,a);
tl_pop= zeros(y+1,a);
tl_pop_gr_rate= zeros(y+1,1);
rep_pop_gr_rate= zeros(y+1,1);
ratio_1= zeros(y+1,1);
ratio_2= zeros(y+1,1);
ratio_3= zeros(y+1,1);
rep_ratio_1= zeros(y+1,1);
rep_ratio_2= zeros(y+1,1);
rep_ratio_3= zeros(y+1,1);
gr_rate= zeros(y+1,1);
```

```
   food_avg_80s=  0.4968;
   food_avg_90s=  0.0213;
   food_avg_bad= -0.5304;

Food(:,2:end)= food_avg_80s;

food_avg=mean(Food(:,2:end),2);
m1=  0.01;
m2=  0.01;
m3=  0.17;
m41= 0.17;
m42= 0.16;
m5=  0.04;

for b=1:runtime
   b

   GOMwhls0=zeros(y+1,12);
   all_whls=zeros(y+1,12,t-1);

      for j= 1:moms99const(1,2)
         c= rand(1);
         s= fix(c*3)+1;
         GOMwhls0(1,s)= GOMwhls0(1,s)+1;
      end


   GOMwhls0(1,4)= GOMwhls0(1,3)*0.5;


u=2;

   for z=1:t-1

      for j=2:2
         pnew= params(1)*Food(j-1,z+1) + params(2);
         qnew= params(3)*Food(j-1,z+1) + params(4);

         GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
                  + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
                  + GOMwhls0(j-1,3)*(1-m3);
         GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
         GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
         GOMwhls0(j,4)=  GOMwhls0(j-1,3)*0.5;
         GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
         for d= 1:1
            c= rand(1);
            s= fix(c*5)+1 ;
            GOMwhls0(j,s)= GOMwhls0(j,s)+((u/100)*sum(GOMwhls0(j,:),2));
         end
      end
```

```
for j=3:3
   pnew= params(1)*Food(j-1,z+1) + params(2);
   qnew= params(3)*Food(j-1,z+1) + params(4);

   GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
             + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
             + GOMwhls0(j-1,3)*(1-m3);
   GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
   GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
   GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
   GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
   GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
   for d= 1:1
      c= rand(1);
      s= fix(c*6)+1 ;
      GOMwhls0(j,s)= GOMwhls0(j,s)+((u/100)*sum(GOMwhls0(j,:),2));
   end
end

for j=4:4
   pnew= params(1)*Food(j-1,z+1) + params(2);
   qnew= params(3)*Food(j-1,z+1) + params(4);

   GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
             + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
             + GOMwhls0(j-1,3)*(1-m3);
   GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
   GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
   GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
   GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
   GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
   GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
   for d= 1:1
      c= rand(1);
      s= fix(c*7)+1 ;
      GOMwhls0(j,s)= GOMwhls0(j,s)+((u/100)*sum(GOMwhls0(j,:),2));
   end
end

for j=5:5
   pnew= params(1)*Food(j-1,z+1) + params(2);
   qnew= params(3)*Food(j-1,z+1) + params(4);

   GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
             + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
             + GOMwhls0(j-1,3)*(1-m3);
   GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
   GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
   GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
   GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
   GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
```

```
     GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
     GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
     for d= 1:1
        c= rand(1);
        s= fix(c*8)+1 ;
        GOMwhls0(j,s)= GOMwhls0(j,s)+((u/100)*sum(GOMwhls0(j,:),2));
     end
end

for j=6:6
   pnew= params(1)*Food(j-1,z+1) + params(2);
   qnew= params(3)*Food(j-1,z+1) + params(4);

   GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
              + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
              + GOMwhls0(j-1,3)*(1-m3);
   GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
   GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
   GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
   GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
   GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
   GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
   GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
   GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
   for d= 1:1
      c= rand(1);
      s= fix(c*9)+1 ;
      GOMwhls0(j,s)= GOMwhls0(j,s)+((u/100)*sum(GOMwhls0(j,:),2));
   end
end

for j=7:7
   pnew= params(1)*Food(j-1,z+1) + params(2);
   qnew= params(3)*Food(j-1,z+1) + params(4);

   GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
              + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
              + GOMwhls0(j-1,3)*(1-m3);
   GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
   GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
   GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
   GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
   GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
   GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
   GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
   GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
   GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
   for d= 1:1
      c= rand(1);
      s= fix(c*10)+1 ;
      GOMwhls0(j,s)= GOMwhls0(j,s)+((u/100)*sum(GOMwhls0(j,:),2));
   end
```

```
end

for j=8:8
    pnew= params(1)*Food(j-1,z+1) + params(2);
    qnew= params(3)*Food(j-1,z+1) + params(4);

    GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
               + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
               + GOMwhls0(j-1,3)*(1-m3);
    GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
    GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
    GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
    GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
    GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
    GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
    GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
    GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
    GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
    GOMwhls0(j,11)= GOMwhls0(j-1,10)*(1-m5);
    for d= 1:1
        c= rand(1);
        s= fix(c*11)+1 ;
        GOMwhls0(j,s)= GOMwhls0(j,s)+((u/100)*sum(GOMwhls0(j,:),2));
    end
end

for j=9:9
    pnew= params(1)*Food(j-1,z+1) + params(2);
    qnew= params(3)*Food(j-1,z+1) + params(4);

    GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
               + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
               + GOMwhls0(j-1,3)*(1-m3);
    GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
    GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
    GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
    GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
    GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
    GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
    GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
    GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
    GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
    GOMwhls0(j,11)= GOMwhls0(j-1,10)*(1-m5);
    GOMwhls0(j,12)= GOMwhls0(j-1,11)*(1-m5);
    for d= 1:1
        c= rand(1);
        s= fix(c*12)+1 ;
        GOMwhls0(j,s)= GOMwhls0(j,s)+((u/100)*sum(GOMwhls0(j,:),2));
    end
end

for j=10:y+1
```

```
        pnew= params(1)*Food(j-1,z+1) + params(2);
        qnew= params(3)*Food(j-1,z+1) + params(4);

        GOMwhls0(j,1)=  GOMwhls0(j-1,1)*(1-m1)*(1-pnew) ...
                + GOMwhls0(j-1,2)*(1-m2)*(1-qnew) ...
                + GOMwhls0(j-1,3)*(1-m3) ...
                + GOMwhls0(j-1,12)*(1-m5);
        GOMwhls0(j,2)=  GOMwhls0(j-1,1)*(1-m1)*(pnew);
        GOMwhls0(j,3)=  GOMwhls0(j-1,2)*(1-m2)*(qnew);
        GOMwhls0(j,4)=  GOMwhls0(j,3)*0.5;
        GOMwhls0(j,5)=  GOMwhls0(j-1,4)*(1-m41)*(1-m42);
        GOMwhls0(j,6)=  GOMwhls0(j-1,5)*(1-m5);
        GOMwhls0(j,7)=  GOMwhls0(j-1,6)*(1-m5);
        GOMwhls0(j,8)=  GOMwhls0(j-1,7)*(1-m5);
        GOMwhls0(j,9)=  GOMwhls0(j-1,8)*(1-m5);
        GOMwhls0(j,10)= GOMwhls0(j-1,9)*(1-m5);
        GOMwhls0(j,11)= GOMwhls0(j-1,10)*(1-m5);
        GOMwhls0(j,12)= GOMwhls0(j-1,11)*(1-m5);
        for d= 1:1
           c= rand(1);
           s= fix(c*12)+1 ;
           GOMwhls0(j,s)= GOMwhls0(j,s)+((u/100)*sum(GOMwhls0(j,:),2));
        end
    end

   all_whls(:,:,z)=GOMwhls0(:,:);

end

yr_restin_avg(:,b)= mean(all_whls(:,1,:),3);
yr_pregna_avg(:,b)= mean(all_whls(:,2,:),3);
yr_mother_avg(:,b)= mean(all_whls(:,3,:),3);
yr_calves_avg(:,b)= mean(all_whls(:,4,:),3);
yr_1_avg(:,b)= mean(all_whls(:,5,:),3);
yr_2_avg(:,b)= mean(all_whls(:,6,:),3);
yr_3_avg(:,b)= mean(all_whls(:,7,:),3);
yr_4_avg(:,b)= mean(all_whls(:,8,:),3);
yr_5_avg(:,b)= mean(all_whls(:,9,:),3);
yr_6_avg(:,b)= mean(all_whls(:,10,:),3);
yr_7_avg(:,b)= mean(all_whls(:,11,:),3);
yr_8_avg(:,b)= mean(all_whls(:,12,:),3);

for z=1:y+1
   tl_pop(z,b)=sum(yr_restin_avg(z,b)+ yr_pregna_avg(z,b)...
           + yr_mother_avg(z,b)+ yr_calves_avg(z,b)+ yr_1_avg(z,b)...
           + yr_2_avg(z,b)+ yr_3_avg(z,b)+ yr_4_avg(z,b) ...
           + yr_5_avg(z,b)+ yr_6_avg(z,b)+ yr_7_avg(z,b)...
           + yr_8_avg(z,b));
   rep_fem_pop(z,b)=sum(yr_restin_avg(z,b)+yr_pregna_avg(z,b)...
           + yr_mother_avg(z,b));
   calves_per_rep_fem(z,b)= yr_calves_avg(z,b)/rep_fem_pop(z,b);
end
```

```matlab
    avg_calves_per_rep_fem= mean(calves_per_rep_fem,1);
    mean_calves_per_rep_fem= mean(calves_per_rep_fem,2);

    calves_per_yr= mean(yr_calves_avg,1);

end

avg_tl_pop= mean(tl_pop,2);

whales(1:end,1)=mean(yr_restin_avg,2);
whales(1:end,2)=mean(yr_pregna_avg,2);
whales(1:end,3)=mean(yr_mother_avg,2);
whales(1:end,4)=mean(yr_calves_avg,2);

whl_std(1:end,1)=std(yr_restin_avg,0,2);
whl_std(1:end,2)=std(yr_pregna_avg,0,2);
whl_std(1:end,3)=std(yr_mother_avg,0,2);
whl_std(1:end,4)=std(yr_calves_avg,0,2);

avg_rep_fem_pop(:,1)= mean(rep_fem_pop, 2);
avg_tl_pop(:,1)=mean(tl_pop,2);

for z=2:y+1
    tl_pop_gr_rate(z,1)= (avg_tl_pop(z)-avg_tl_pop(z-1))/avg_tl_pop(z-1);
    rep_pop_gr_rate(z,1)= (avg_rep_fem_pop(z)-avg_rep_fem_pop(z-1))
                          /avg_rep_fem_pop(z-1);
end




mean_tl_pop_gr_rates= mean(tl_pop_gr_rate);
mean_rep_pop_gr_rate= mean(rep_pop_gr_rate);
mean_calves_per_yr= mean(whales(:,4),1);

for z=1:y+1
    ratio_1(z,1)=whales(z,1)/avg_tl_pop(z);
    ratio_2(z,1)=whales(z,2)/avg_tl_pop(z);
    ratio_3(z,1)=whales(z,3)/avg_tl_pop(z);
    rep_ratio_1(z,1)=whales(z,1)/avg_rep_fem_pop(z);
    rep_ratio_2(z,1)=whales(z,2)/avg_rep_fem_pop(z);
    rep_ratio_3(z,1)=whales(z,3)/avg_rep_fem_pop(z);
end

for j=2:y+1
    gr_rate(j,1)=avg_tl_pop(j,1)/avg_tl_pop(j-1,1);
end

avg_gr_rate=mean(gr_rate(21:end,1))


%mkdir RWFwdResults_best
```

```
%cd RWFwdResults_best
  %mkdir whales_500y
  %cd whales_500y
      %mkdir Food_avg_80s
      %mkdir Food_avg_90s
      %mkdir Food_avg_worst
      %cd Food_avg_worst

figure(1)
clf
plot(Food(1:end,1), avg_tl_pop(1:y,1), 'k');
%dlmwrite(['avg_tl_pop.txt'], avg_tl_pop, 'delimiter','\t', 'newline', 'pc');

figure(2)
clf
plot(Food(1:end,1), gr_rate(2:y+1,1), 'k');

%cd ..
%cd ..
%cd ..
```