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Investigation of the Population Dynamics of Endangered Whooping Cranes In The Breeding Ground Wood Buffalo National Park: An Agent-Based Modelling Approach

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by

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A THESIS

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Abstract

For rare species to be saved for a self-sustaining ecology, it is crucial to understand how their populations work, especially in important locations like their breeding grounds. This study digs deep into the lives of the Whooping Cranes (Grus Americana) that only breed in the environment of Wood Buffalo National Park (WBNP) located in NWT/AB and are highly endangered and on the verge of extinction. Using a novel modelling technique called Agent-Based Modelling (ABM), this study gives a detailed look at how individual behaviours, relationships between species, and their environment all affect the population dynamics of endangered cranes.

This research, which can be located at the intersection of ecology and computer modelling, employs actual population data of whooping cranes that are obtained from Canadian Wildlife Service (CWS), and ABM-ing approach to untangle the complex web of factors that affect the fate of whooping crane populations. This includes the biological features of whooping cranes, and the effect of climate change on reproduction success in Wood Buffalo National Park. Through rigorous ABM simulations, this approach not only catches the complexity of these correlations, but it also provides a flexible tool for simulating and testing different scenarios, which makes it possible to look at what might happen with different conservation tactics.

ABM has given us some early insights that show how important it is for whooping cranes to understand breeding dynamics in Wood Buffalo National Park. These results show where conservation efforts should be directed and how important it is to protect and fix up these areas. Also, the dynamic nature of ABM shows how biological effects ripple through the ecosystem, giving a full picture of how various parts of this complex environment depend on each other.

In short, this examination not only shows how the threatened whooping crane's population changes in the unique breeding ground in Wood Buffalo National Park, but it also shows how

agent-based modelling in ecology could change things for the better for this species. By figuring out how the complex relationships and behaviours of whooping cranes work, this study not only helps to protect the species, but it also paves the way for more widespread uses of computational methods in ecological research. With the knowledge gained from this research, adaptive conservation methods could be employed to help the endangered whooping cranes have a self-sustaining population in their breeding ground.

Preface

This thesis is original, unpublished, independent work by the author, Mikail Kipirti

Acknowledgements

Completing my Master of Science (MSc) thesis has been a transformative journey, and I am sincerely thankful to all those who have been part of this remarkable endeavor.

To my thesis advisor, Prof. Emmanuel Stefanakis, you have been more than a guide; you have been a beacon of knowledge and a pillar of unwavering encouragement. Your belief in my potential and your patient guidance have illuminated my path, allowing me to navigate the intricate maze of research with newfound confidence. I am forever indebted to you for the lessons learned, both in the realm of engineering science and in life itself.

I extend my sincere gratitude to the faculty members of the Geomatics Engineering Department for fostering a vibrant academic community where innovation and intellectual exploration thrive. Their dedication to teaching and research has been a constant source of motivation.

My heartfelt appreciation goes to my family and especially to my father who have stood beside me with unwavering encouragement and boundless belief in my abilities. His words of wisdom, support, and understanding have propelled me forward during moments of challenge and triumph.

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This thesis is a testament to the collective effort, support, and inspiration I have received from mentors, peers, family, and institutions. It is an honor to have been part of a community that values knowledge, exploration, and growth.

Thank you.

Mikail Kipirti

January 2024

Dedication

This dissertation is dedicated to the intersection of intellectual ambition, scientific investigation, and unshakable family support—three unchangeable pillars that have determined the trajectory of my knowledge-seeking journey.

This work is dedicated to the never-ending pursuit of knowledge and wisdom. It exemplifies the limitless curiosity that drives our investigation of the natural world and search of deeper understanding.

To my family, especially to my father, whose unwavering support and belief in my academic ambitions served as the foundation of my academic journey. Your support and sacrifice have been important in propelling me forward, and I mostly dedicate this work to him with deep thanks.

My heartfelt gratitude goes to my supervisor, Prof. Emmanuel Stefanakis, whose support, when heavily needed, have been lifesaving in keeping my science journey.

This work is humbly dedicated to the scientific community of the East and the West and of past, present, and future as an affirmation of our joint quest for knowledge and truth.

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List of Abbreviation

WCs ----- The Whooping Cranes

ABM -- --Agent-Based Model

WBNP -- Wood Buffalo National Park

ODD ----- Overview, Design concepts, and Details

SA ------- Sensitivity Analysis

CWS ------Canadian Wildlife Service

PDE -------Differential Equations

GA --------Genetic Algorithm

ING -------Individual Based Neural Network Genetic Algorithm

ANN ------Artificial Neural Network

SIR -------The Susceptible-Infected-Recovered Model

EBM -----Equation-Based Model

NWT ----Northwest Territories

COSEWIC – Committee on the Status of Endangered Wildlife in Canada

SARA ---- (Canadian) Species at Risk Act

AB -------Alberta

SK --------Saskatchewan

MB -------Manitoba

LCT ----- Lower Critical Temperature

NRC ----- National Research Council

EPA ----- Environmental Protection Agency

CHAPTER 1: INTRODUCTION

1.1 Research Objective

The present study is motivated by predefined set of research objectives, with the primary goal of conducting a comprehensive investigation into the population dynamics of the endangered Whooping Cranes (WCs) in their nesting habitat located in Wood Buffalo National Park (WBNP). The utilization of an Agent-Based Modelling (ABM-ing) methodology is employed to structure these aims, with the aim of acquiring a comprehension of the various factors that have influence on the populations of Whooping Cranes in this crucial habitat. Additionally, this approach offers insights that may be utilized to facilitate the conservation and recovery efforts for these species.

The main goal of this study is to construct an advanced and contextually relevant Agent-Based Model (ABM) that is specifically designed to simulate the ecological dynamics of whooping cranes. This model will primarily focus on the breeding ground of Whooping Cranes in Wood Buffalo National Park, considering their unique ecological characteristics. The task at hand entails the development of a computational framework using NetLogo software that accurately models the behaviours, interactions, and crucial life history processes of Whooping Cranes at the individual level within the designated ecosystem. Also, this model will establish the basis for future research aims.

The second aim of this research is to evaluate the significant impact of habitat quality in Wood Buffalo National Park on the population dynamics of Whooping Cranes during their nesting period. In this study, Agent-Based Modelling (ABM-ing) is employed to conduct a comprehensive analysis of the effects of habitat availability and appropriateness on important demographic factors, including breeding success, chick survival, and overall population increase, within this critical breeding area. In this sense the consideration for conducting this research is to quantitatively assess the complex correlation between habitat quality and the population dynamics of the Whooping Crane.

A conservation project that has been successful up until now is facing a new challenge that has the potential to undermine all the hard work that has been done in the past by ecologists: climate change. The reproductive success of Whooping Cranes is significantly endangered by one of the world's biggest threats. To address this issue, this study also aims to integrate climate-related factors, such as temperature and precipitation, into an Agent-Based Model (ABM). The study evaluates the potential impact of climate change on the reproductive outcomes of this species in Wood Buffalo National Park during their breeding season. This objective holds significant importance in comprehending the susceptibility of Whooping Cranes to climate change within this particular environment.

The utilization of Agent-Based Modelling (ABM-ing) for the purpose of simulating the impacts of different management scenarios implemented in Wood Buffalo National Park is another essential research aspect. In this study, *what-if* scenarios are employed in modelling to evaluate the effects of various interventions, including habitat quality, predator control, and birth rate on the breeding season populations of Whooping Cranes. This study offers empirically supported perspectives on the efficacy of various scenarios and their capacity to inform conservation initiatives in breeding grounds.

Another highly important aspect of this study is to generate practical knowledge and empirical data that may effectively inform, and lead conservation and management initiatives focused on the preservation of the endangered Whooping Cranes residing in Wood Buffalo National Park.

To summarize, the study aims comprise a thorough and multifaceted examination of the population dynamics of the endangered Whooping Cranes within their nesting habitat in Wood Buffalo National Park. This study seeks to gain a comprehensive understanding of the ecological dynamics and conservation requirements of this iconic species within a specific context by utilizing Agent-Based Modelling.

Additionally, it aims to contribute to the existing body of knowledge on the conservation of keystone species of wildlife in crucial habitats.

1.2 Organizational Framework of Thesis

This thesis is carefully structured into several chapters, each of which has a particular function to effectively convey about the research. The goals and content of each chapter are briefly described as follows:

Chapter 1 establishes the foundation for the whole of the thesis. The provision of background and context is essential in elucidating the research problem. The research questions are expressed clearly. It emphasises the meaning of the study and usefulness of its findings.

Chapter 2 reviews the research topic's literature in detail. It introduces study-related concepts and theories to give the theoretical framework. Focusing on the whooping crane as a central aspect of the research, this section provides an in-depth exploration of the species, its habitat, behavior, biology, and threads. It also details the research area's geography and ecology. Another piece of information that Chapter 2 provides is an explanation of the data gathering procedure and software tool. It covers details regarding the sources of the employed data and a brief description of NetLogo.

In Chapter 3, the methods and approach to the research are discussed. It provides an overview of the research design, including an explanation of the reasoning behind its selection.

In Chapter 4, the process of constructing the model and the detailed explanations of the ODD protocol have been provided in great depth. Tables and flowcharts are utilized to enhance comprehension of the model parameters.

In Chapter 5, the research findings are methodically presented. The results are analyzed, and the model is evaluated. This chapter offers an analysis of the study's empirical findings.

Chapter 6 summarizes the findings of the study. The limitations of the study are acknowledged, and directions for future research are suggested. The following section includes both the references and the appendices.

CHAPTER 2: LITERATURE REVIEW AND DESCRIPTION OF MODEL COMPONENTS

2.1 Literature Review of Related Studies

Through history, human beings have never quit seeking and wondering about the things around their environment and events happening in nature. In order to comprehend the complexity of the environment, systematic methods that can capture, analyze, and, if necessary, regenerate the characteristics of complex systems are needed. Our comprehension must encompass the microscopic, mesoscopic, and macroscopic elements of these phenomena (Crooks et al., 2018), in order to obtain an extensive and meaningful descriptions of these systems. Modelling is the most effective instrument that is available to achieve this purpose.

According to U.S. National Research Council (NRC), a model is defined " simplification of reality that is constructed to gain insights into select attributes of a particular physical, biological, economic, or social system." (Gaber et al., 2009).

A modeller, who makes theoretical descriptions of systems, establishes boundaries(limitations), prioritizes methods, chooses which parts of the system to model, and decides how to represent these processes, making assumptions, mathematically. As a result, models are unable to fully represent the complexity that exists in the natural world because they are predicated on simplifying assumptions. Despite these, modelling serves a variety of functions, including explanation, description, understanding the patterns, and prediction of a system`s behaviour to forecasting future changes.

Experimentation is not always applicable to the study of real-world systems because these systems are frequently either too complicated or develop too slowly. In this sense, Railsback & Grimm, 2012 give an example of how and why modelling are important: To understand how cities expand and land uses change over a period of time via experimentation alone would be very challenging and time-consuming for scientist. To formulate, generate, and conduct experiments to understand answers to related questions, it is recommended to use computer programs to create a simplified version of the system, a model, that enables us to manipulate and analyze the behaviour or patterns.

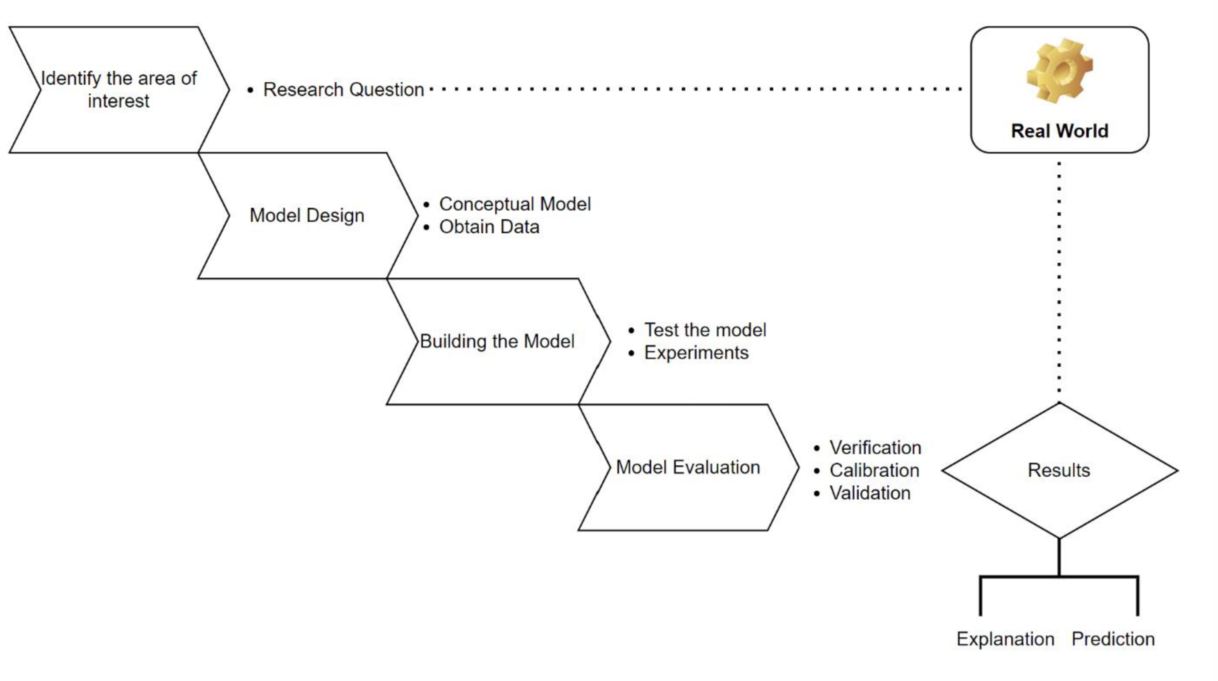

Figure 1 Generalized Modelling Steps

The iterative progression depicted in figure 1 is typically followed when creating and implementing a model to meet a given decision-making requirement. (Gaber et al., 2009)

A highly particular research question is the first step in the modelling process since it acts as the main compass and filter during the model's design. Spatiotemporal scales, parameters and their values, and data collection should all be carefully planned for in the model design phase. These procedures are frequently depicted in conceptual models, that describes the most important behaviors of the system, rules, object, or process relevant to the problem of interest. The most technical part of the modelling process is implementation, where the model specifications are converted into computer language using appropriate formulas and software.

The evaluation of a model encompasses the assessment of the scientific validity of the underlying principles, the extent to which the model aligns with observed conditions, and the suitability of the model for a specific application.

When deciding to develop a model, it is crucial that all components of the modelling process are considered before moving forward with model development.

Several methods exist for producing results from environmental models. The first of these is scenario-based(Kelly (Letcher) et al., 2013), where the model is constructed to consider the impacts of various components implementing *what if* scenarios, which is also known as agent-based modelling. ABM is intended to enable the user to examine the outcomes of various actions or policies, as well as their effects and associated trade-offs.

Environmental models have long faced criticism for being either overly complicated or too basic, or for being constrained by calculations based on traditional mathematics. About 20 years ago, criticisms of aggregation brought agent-based modelling to light. ABM-ing aims to overcome challenges on aggregate versus disaggregate, individual versus system by presenting simulation frameworks that are far more adaptable and less formal.

These models (ABMs) remove the lines between macro and micro, aggregate and disaggregate, but they also incorporate time into their formulation (Crooks et al., 2018). The inclusion of this element was of great importance within the field of ecological modelling as well.

Agent-based models (ABMs) have been employed in various domains over recent years, encompassing fields such as economics, science (Kelly (Letcher) et al., 2013), game theory, traffic simulations (Zhang, n.d.), and environmental studies (Zhu, n.d.). These models have been particularly useful in addressing issues related to water, forest, and agro-ecosystem management, as well as ecology, specifically in the context of population dynamics (McLane et al., 2011). Additionally, ABMs have contributed to our understanding of how animals perceive, learn, and adapt to changes in their environment.

The field of wildlife management is progressively adopting a multidisciplinary approach (McLane et al., 2011), and agent-based models (ABMs) serve as an effective tool in this context. ABMs facilitate the incorporation of expertise from diverse disciplines, enhancing the effectiveness of wildlife management strategies.

For instance, (Testa et al., 2012) indicate in their research that the dynamics of a population cannot be adequately described by traditional predator-prey models, and there is an absence of population level data suitable for parameterizing these model. Following the ODD protocol for their ABM, the study aims to simulate the distinctive emergent patterns in the size of groups, consumption of prey, and demographics of killer whales and their prey. The research mostly focuses on revealing critical conceptual concepts and real-world data required to comprehend core aspects of the killer whale predator-prey system in the NE Pacific Ocean by implementing ABM approach.

Another example where ABM excels over the classical ecological model is from the very first ABM designed to simulate grazing behaviour on a realistic scale conducted by (Jablonski et al., 2018). The goal of the research is to develop an ABM that is particularly helpful for simulating intricate systems like livestock grazing management. The model tries to enable accurate representation of cattle behaviour from a detailed perspective. The research concludes that ABM has been found to be a reliable approach to evaluating alternative management strategies in a simulation platform without endangering cattle.

On the other hand, endangered species, which are defined as “any species which is in danger of extinction throughout all or a significant portion of its range” (Costante et al., 2023), are of important position in wildlife populations and face significant challenges arising from a combination of natural and human-related factors, encompassing changes in the climate, contamination, as well as habitat loss and fragmentation (McLane et al., 2011).

According to (Intergovernmental Panel On Climate Change, 2022), species extinction in forests, coral reefs, and Arctic regions could lead to the irreversible loss of biodiversity ecosystems worldwide, taking with them their critical services like food, carbon storage, and disease control. If temperatures rise above 1.5°C and reach 4.0°C, many land and sea spots might become uninhabitable to up to 100% of their native species (Intergovernmental Panel On Climate Change, 2022).

The endangered whooping cranes, which are rare and rely on wetland habitats throughout their life cycle, are among the animal species that are severely impacted by global warming. Their limited population size and unique breeding habitat make them more vulnerable to climate change than other cranes.

Butler et al., (2017) indicated that the breeding grounds of whooping cranes in Canada could dry up just enough by 2050 because of climate change, and this enables predators to get to the birds' shallow-water nests and important eggs and hatchlings. The study, which was written by U.S. Fish and Wildlife Service researchers, says that the wild population would start to drop again if just one juvenile crane for every 200 adults died. Whooping cranes are only capable of having one chick a year, apart from very rare circumstances; as a result, there is a significant risk of predation for that chick; consequently, their recruitment is inherently low overall (Platt, 2017), which makes recovery a very difficult task.

In the actual world, carrying out experimentation on the population dynamics of endangered species, except by employing proper modelling techniques that use what-if scenarios to get a better picture about them, is a challenging and time-consuming endeavour.

Although several scientists studied and predicted an increase in the population of this endangered species considering a 10-year cycle (Butler et al., 2013), they lacked information on the likelihood of extinction and sensitivity analysis of population dynamics on the breeding ground (WBNP), but this time iterating the model yearly, and most importantly, did not use the agent-based modelling (ABM) approach, an underutilized modelling technique in the field of computational ecology that allows modellers to easily examine the importance of various components in the population.

2.2 Whooping Cranes

The whooping crane, a species native to North America and also known as *Grus Americana*, is recognized as one of the rarest birds in North America, continues to face significant threats to its survival, and is still considered a highly endangered species.(figure-3) (Buzek, n.d.)

The USFWS and the Committee on the Status of Endangered Wildlife (COSEWIC) both designated the whooping crane as endangered in the United States and Canada, respectively, in 1970 and 1978. (*Canadian Wildlife Service and U.S. Fish and Wildlife Service. 2005. International Recovery Plan for the Whooping Crane. Ottawa: Recovery of Nationally Endangered Wildlife (RENEW), and U.S. Fish and Wildlife Service*, 2007)

The Whooping Crane has been widely studied over the past half-century, and there is much information available on its biology and history. It is known that the Whooping Crane is a "flagship species" of wildlife protection in North America, and that it is the tallest bird in the area (Classen & McCracken, 2010). Canada is home to all the wild breeding populations of this species around the world. Early in the 20th century, there were only 14 grown birds left and at that time, the species was at the brink of extinction (Classen & McCracken, 2010). To help make sure the species doesn't go extinct and have a self-sustaining wild population, ecologists have been trying for several decades to release into the wild birds that were raised in captivity outside of Canada. But Canada's breeding population is still very small, and they can only breed in a small area of Wood Buffalo National Park (WBNP) located in the Northwest Territories (NWT) and northern Alberta. What is more, they are vulnerable to catastrophic weather events like droughts, heavy precipitations, and storms that happen more frequently with the changing climate. The population of this species is weak in terms of its ability to survive or reproduce because it has a low yearly rate of reproduction.

To fully comprehend how WCs reproduce in the wild and improve how they are managed in captivity, it helps to know how they reproduce in the wild. Whooping Cranes are socially monogamous, and usually stay with the same partner for life (Songsasen, n.d.), although couples have been known to split up if they are not able to have chicks.

Figure 2 An adult Whooping Crane - Photo: Krabben Hoft/Audubon Photography Awards

Habitat: WCs breed in a unique wetland complex in WBNP, in open waters, allowing them to be easily detected by predators. The nesting habitat of Whooping Cranes predominantly consists of bulrush, sedges, or other emergent plants found in shallow regions of stagnant bodies of water, such as ponds, small lakes, or wet meadows (White, 2001). The whooping crane is highly susceptible to changes in breeding ground habitat conditions due to its small population size, limited distribution, wetland habitat needs, and twice-yearly 4,000-kilometer migration path(Chavez-Ramirez & Wehtje, 2012).

Breeding: The only nesting area for the cranes in Canada is the WBNP, which is in the Boreal Plains ecozone. The population lives and breeds there from late April to mid-September for summer. It is uncommon to see a WC flying during the spring and summer, unless it is in the immediate proximity of its nest (Kuyt, 1992). The explanation may vary; from April to early August, breeding cranes are engaged in nesting and caring for their young that are unable to fly. Most of the breeding area is in Wood Buffalo National Park (WBNP), near the Little Buffalo rivers, Sass, Klewi, and Nyarling, which are on the border between northern Alberta and southern Northwest Territories (figure-2) (Classen & McCracken, 2010). The breeding range of the cranes in WBNP has significantly expanded since the initiation of breeding ground surveys in 1966, in conjunction with the notable increase in population size (Wilson, n.d.).

Figure 3 Map of WCs nesting areas in and around WBNP (Adapted from the COSEWIC Report).

Life Cycle and Reproduction: Whooping cranes are birds that live a long time, up to 28 years in the wild. Like other cranes, WCs stay with the same partner for a long time and may stay together for life (Stratton, n.d.). Both the males and females are responsible for taking care of the eggs and feeding the chicks. Even though each female lays two eggs, mostly each parent can raise only one single young. Most birds start having babies when they are 4 or 5 years old (Johns et al., n.d.). When they get to WBNP in late April, they start nesting. The eggs undergo an incubation period lasting around 30 to 35 days (Classen & McCracken, 2010). Clutch happens soon after, and the nesting process is usually finished by mid-May. The adults and young birds come back to the nest for the first three to four nights after the hatch. The family normally stays within 2 km of the nest for the first 20 days after the egg(s) hatch and usually stay close to their nesting area during the summer. Chicks may swim soon after they hatch and generally can keep doing it until they are about two months old. Juveniles can fly for a long time after about three months (May, 1994). Pairs commonly exhibit a high degree of dedication to their breeding territory, often choosing to nest in the same spot every year (May, 1994).

Diet: Throughout the year, WCs have an omnivorous feeding behaviour (Classen & McCracken, 2010), based on freshwater invertebrates and vertebrates on the breeding grounds (Chavez-Ramirez & Wehtje, 2012). Plant items, especially fruits and grains, are also consumed to varying degrees throughout the year. Additional food items that are potentially significant within the breeding grounds encompass blue crabs, snakes, and frogs (Classen & McCracken, 2010).

Threats: The significant factors influencing the number of whooping cranes is habitat quality and food availability, particularly in the breeding grounds. The Whooping Crane relies on blue crabs for food during the winter. This means that things that affect crab numbers may have significant impacts on cranes. Lack of food on the wintering grounds can make it very hard for WCs to nest in WBNP (Classen & McCracken, 2010). Inadequate chick production along with low survivorship are additionally linked to dry situations on their breeding areas (Johns, n.d.-b). In the year 1994, following a period of reduced blue crab populations during the winter season, the quantity of subsequent nesting endeavours in WBNP experienced a decline from 43, to an only 28. The breeding grounds have minimal human disruption due to the absence of outside access to the breeding area from April to September, with the exception of authorized park personnel and scientific researchers.

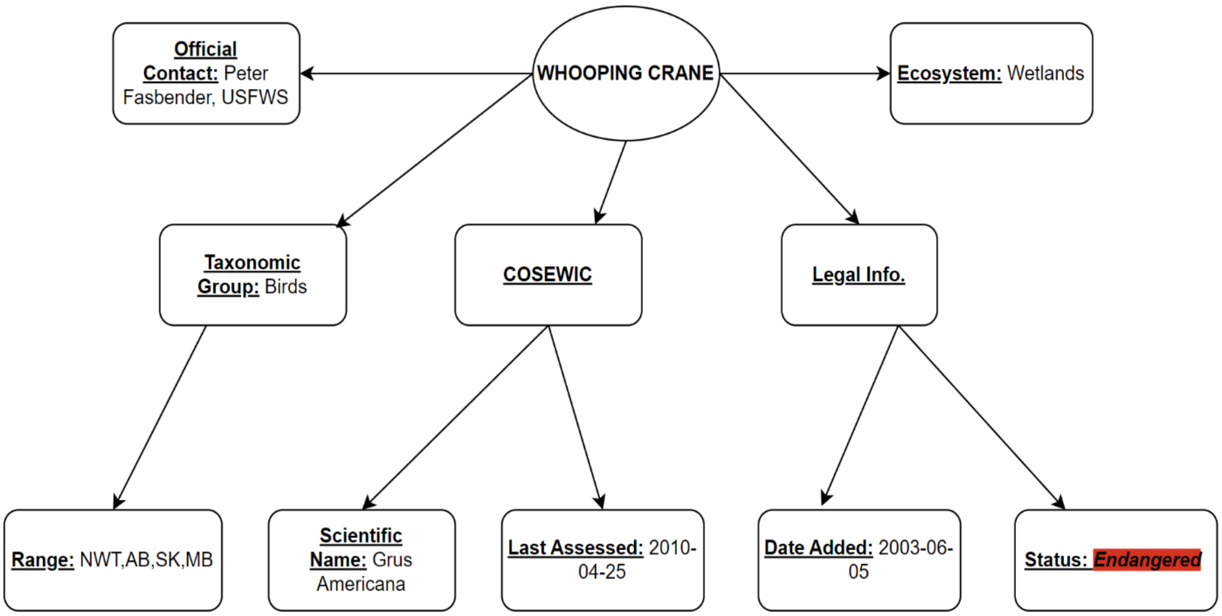

Figure 4: Whooping Crane Species at Risk Act (SARA)Schema (official contact information can be found here)

2.3 Study Area Description

Wood Buffalo National Park (WBNP) is the largest national park in Canada, encompassing a greater land area than the country of Switzerland (*Wood Buffalo National Park*, 2011). The park was established in 1922 to protect the world's largest herd of free-roaming wood bison ("Wood Buffalo National Park," 2023) As an UNESCO World Heritage site, it is the home of the world's largest beaver dam, the nesting habitat of endangered whooping cranes, and one of the last remaining herds of free-roaming wood bison (*Wood Buffalo National Park*, 2011).

The world's only breeding site for the endangered whooping crane is found in Wood Buffalo National Park. The park's few breeding pairs have been carefully managed to save the species from extinction. The 4.5 million hectares of the park, the entirety of its ecosystems, and its preservation are crucial for the whooping crane's in-situ conservation (Centre, n.d.).

The nesting and summering grounds of WCs are in the northeastern region of Wood Buffalo National Park, as well as the surrounding areas of Alberta (figure-3) and the Northwest Territories (NWT) (60°0.33' N, 111°52.88' W) (Johns, n.d.-a). Most cranes are found in a 600 km2 area adjacent to the Sass and Klewi rivers (Johns et al., n.d.), as well as in a few smaller concentrations in nearby areas.

Figure 5 Whooping Crane (white and in the middle) habitat on Wood Buffalo National Park. Photo by Jane Peterson

2.4 Data Gathering

No model cannot be constructed, calibrated, or evaluated without having preliminary data to work with. In many instances, having reliable data will be essential to the process of developing the model (Crooks et al., 2018). It is important to fully understand the data's strengths, limits, biases, and gaps before utilizing it, since these will highly affect how well the model represents real-world phenomena.

As (Kelly (Letcher) et al., 2013) indicate in their research that to build a model two primary categories of data are available: quantitative and qualitative data. Survey, geographical, and time series data are examples of quantitative data, which is defined as the measurable features or quantities in a system. Expert judgment, stakeholder opinions, and certain information obtained through surveys and interviews are examples of qualitative data or information.

Beginning 1950, the US Fish and Wildlife has been carrying out aerial survey of the Aransas-Wood Buffalo Park wintering habitats during November and April each year (Butler et al., 2013), despite the fact that these abundance counts are not an actual census of the population, many scientist believe that they offers a good indication of abundance of WCs.

Due to the remoteness of the AWBP breeding grounds and the difficulty of capturing and marking individuals (Wilson, n.d.), it has been hard to get detailed statistical data, such as sex ratio, on the population of WCs.

For this study, the Canadian Wildlife Service (CWS) provided the population data (table 1) of WCs, which includes the total number of populations in which young and nests numbers exist as well. These data are gathered through aerial surveys conducted in May and June by CWS staff (Weir, 2006). Every survey covers around 927 km2 of WBNP and surrounding areas and takes about 25 hours to complete.

Endangered Whooping Crane Aransas Wood Buffalo Park Population 1966-2022				
Year	**Nest Count**	**Total Cranes**	**Young**	**Adults**
1966	5	43	5	38
1967	9	48	9	39

1968	10	50	6	44
1969	12	56	8	48
1970	15	57	6	51
1971	13	59	5	54
1972	16	51	5	46
1973	14	49	2	47
1974	15	49	2	47
1975	16	57	8	49
1976	16	69	12	57
1977	17	72	10	62
1978	15	75	7	68
1979	19	76	6	70
1980	19	78	6	72
1981	17	73	2	71
1982	17	73	6	67
1983	24	75	7	68
1984	29	86	15	71
1985	28	97	16	81
1986	29	110	21	89
1987	32	134	25	109
1988	31	138	19	119
1989	30	146	20	126
1990	32	146	13	133

1991	33	132	8	124
1992	40	136	15	121
1993	45	143	16	127
1994	28	133	8	125
1995	49	158	28	130
1996	45	160	16	144
1997	51	182	30	152
1998	50	183	18	165
1999	48	188	17	171
2000	50	180	9	171
2001	53	176	15	161
2002	50	185	16	169
2003	61	194	25	169
2004	54	217	34	183
2005	58	220	30	190
2006	62	237	45	192
2007	65	266	39	227
2008	66	270	38	232
2009	62	264	22	242
2010	74	283	45	238
2011	77	254	39	215
2012	66	257	35	222
2013	74	304	39	265

2014	82	308	39	269
2015	68	463	38	425
2016	79	489	50	439
2017	98	505	49	456
2018	87	504	13	491
2019	97	506	39	467
2020	Winter survey not conducted due to COVID-19			
2021	102	543	31	512
2022	96			

Table 1 Population data from CWS, including adults, nest, and young annually.

The actual population data presented in table-1 above is an example of the time series of WCs abundance that spans 55 years, from 1966 to 2021, except for 2020 owing to Covid-19.

The number of WCs has been increasing for the last decades. However, according to the recovery plan for the WCs (B. Johns et al., 2007) recovery is characterized by a phase of stable or growing population sizes, as well as the capacity of the species to adapt to typical environmental fluctuations and rare adverse years. A target of self-sustaining 1,000 individuals in the wild is established for the Aransas/Wood Buffalo population of cranes.

Another type of data taken into account during the modelling process is monthly climate data. This type of data focuses mostly on the lowest temperature, maximum temperature, average temperature, and total precipitation during the months of May to September, from 1966 to 2007, since the WCs spend their time in WBNP during these months. Following a search based on the station's location to the study region, it was determined that the Birch Mountain Lo station was the one the closest to the study area, with a distance of 11.60 km. These data, a piece of which is shown in table-2, were then obtained from the website for historical climate data provided by Environment Canada (Canada, 2011) and organized in an MS Excel spreadsheet.

Station Information						Climate Factors Influencing Whooping Cranes							
Longitude (x)	Latitude (y)	Name	Climate ID	Date/Time	Year	Mean Max Temp (°C)	Mean Min Temp (°C)	Mean Temp (°C)	Extr Max Temp (°C)	Extr Min Temp (°C)	Total Rain (mm)	Total Snow (cm)	Total Precip (mm)
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	May-66	1966	12.3	2.3	7.3	21.7	-10	55.1	2.5	57.7
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jun-66	1966	15.4	6.9	11.2	24.4	0	44.5	0	44.5
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jul-66	1966	17.5	9.8	13.7	23.3	3.9	136.1	0	136.1
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Aug-66	1966	16.4	8.2	12.3	28.3	0	86.4	0	86.4
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Sep-66	1966	13.9	4.8	9.4	23.3	-3.9	23.9	0	23.9
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	May-67	1967	10.3	-0.2	5.1	25	-11.7	2.8	2.5	5.3
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jun-67	1967	15.8	5.1	10.5	27.8	-6.1	62.2	0.3	62.5
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jul-67	1967	18.8	9	13.9	26.1	1.1	170.4	0	170.4
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Aug-67	1967	19	9.2	14.1	28.3	2.2	63.2	0	63.2
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Sep-67	1967	14.5	5.6	10.1	27.8	-3.9	58.4	17.3	75.7
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	May-68	1968	10.4	0.6	5.5	23.3		26.2	7.9	34
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jun-68	1968	15.7	6.6	11.2	23.3	-1.7	90.2	0	90.2
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jul-68	1968	16.1	7.5	11.8	29.4	1.7	101.1	0	101.1
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Aug-68	1968	15.3	6.6	11	22.2	0	20.3	0	20.3
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Sep-68	1968	9.6	2.7	6.2	18.9	-1.7	73.9	7.9	81.8
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	May-69	1969	10.7	0.7	5.7	20.6	-8.9	17.8	4.1	21.8
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jun-69	1969	15	4.9	10	26.1	-6.1	15.7	0	15.7
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jul-69	1969	19	9.4	14.2	27.8	5	30.7	0	30.7
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Aug-69	1969	18	8.7	13.4	25.6	3.3	66	0	66
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Sep-69	1969	7.4	2.2	4.8	19.4	-3.3	75.7	25.9	101.6
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	May-70	1970	11.3	1.6	6.5	20	-5.6	55.6	17.3	72.9
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jun-70	1970	18.5	9.4	14	31.1	1.1	86.9	0	86.9
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jul-70	1970	19.5	10.1	14.8	27.8	3.3	68.6	0	68.6
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Aug-70	1970	18.7	8.4	13.6	28.3	1.7	22.1	0	22.1
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Sep-70	1970		2.2			-5			
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	May-71	1971	15.7	4.2	10	28.3	-8.9	32.5	0	32.5
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jun-71	1971	17.7	8.7	13.2	26.7	3.9	178.8	0	178.8
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Jul-71	1971	18.6	9.7	14.2	26.1	2.2	45.5	0	45.5
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Aug-71	1971	19.3	10.3	14.8	25.6	0.6	153.4	0	153.4
-111.85	57.72	BIRCH MOUNTAIN LO	3060700	Sep-71	1971	9.8	2.7	6.3	21.1	-3.9	85.6	4.6	90.2

Table 2 Climate Parameters between 1966 – 2007

2.5 Simulation Platform: NetLogo Primitives

NetLogo is a powerful and user-friendly agent-based simulation tool that is widely used in various fields for modeling and exploring complex systems. It was developed at the Center for Connected Learning and Computer-Based Modeling at Northwestern University. NetLogo is specifically designed to simulate and study the dynamics of individual agents and their interactions within a given environment (*Wilensky, U. (1999). NetLogo. Http://Ccl.Northwestern.Edu/Netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.*, n.d.). NetLogo is primarily known for its support of agent-based modeling, where individual entities (*agents*), interact with each other and their environment to produce emergent behaviors at the system level. These models are particularly useful for simulating and understanding complex systems in social sciences, biology, ecology, economics, and more. In NetLogo, agents are represented as "turtles" (mobile entities) and "patches" (grid cells or locations). Turtles can move, interact, and have individual properties, while patches provide a static background for agents.

NetLogo comes with a rich collection of pre-built models spanning various domains, such as biology, social sciences, economics, and ecology. These models can be used as templates, references, or starting points for creating new simulations.

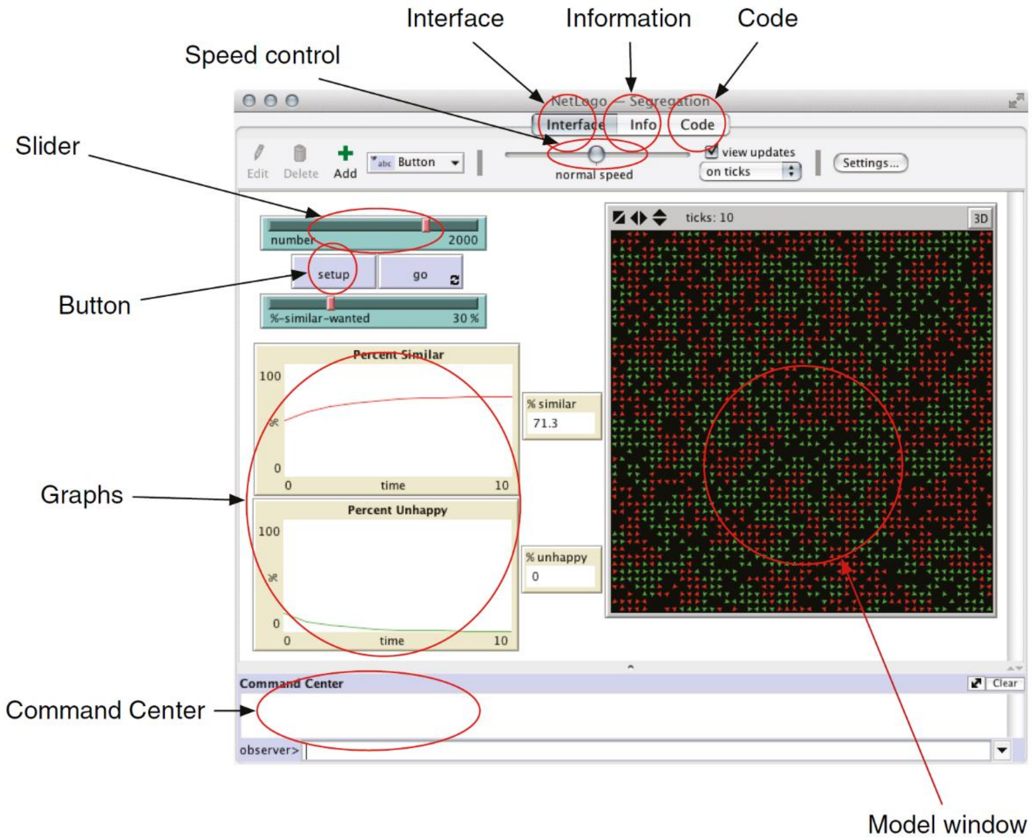

Figure 6 NetLogo interface and main components (Crooks et al., 2018)

A more detailed code used in the model can be found in the Appendix section at the end. The following is a description of the primary components that make up the latest version of NetLogo 6.4:

Interface: The primary UI is chosen using this tab. Here's where you add controls (buttons, sliders, switches, etc.) to operate the model and see the output.

Code: On this tab, the computer code that directs the model's behaviour is written.

Info: This tab gives users information about the model that is loaded into the session. The following are the question titles: What is it? How does it operate?

NetLogo has a built-in GIS extension that allows us to read data files from GIS and copy the values to patches or turtles for simulation. It also has *primitives* that serve as the foundational elements in NetLogo programming. These are the basic and concise predefined keywords that can be combined to create more extensive algorithms, forming the essential building blocks for constructing intricate agent-based models.

Some of the main primitives in the model are listed below;

Globals: globals is a primitive that we use to define custom global variables in NetLogo. A global variable is a variable that has the same value for all the agents in the model across all procedures. Keep in mind that if you would like to create a variable that is only needed temporarily and within just one specific procedure, you should use the let primitive instead. In WCs model, temperature and precipitation have been designed as globals.

If: if is a primitive that allows us to define conditional agent behaviors. If the given condition is true, NetLogo will run the provided code within the brackets. If the given condition is false, NetLogo will not do anything.

CHAPTER 3: METHODOLOGY

3.1 Agent-Based Modelling

Agent-based modelling (ABM) is a computational modelling approach that encompasses a system composed of autonomous and heterogeneous agents that interact with each other based on rules (Macal & North, 2008). The official proposal of agent-based models occurred in the early 1990s (Heppenstall et al., 2020), and since then, they have gained significant popularity as a research tool across various disciplines. ABM is based technically on the science of artificial intelligence (AI) and rooted in complexity theories, and describes a modelling idea that is closely related to the object orientation modelling technique, which is used to model the interactions between the various components of a system (Nourqolipour & shariff, 2010).

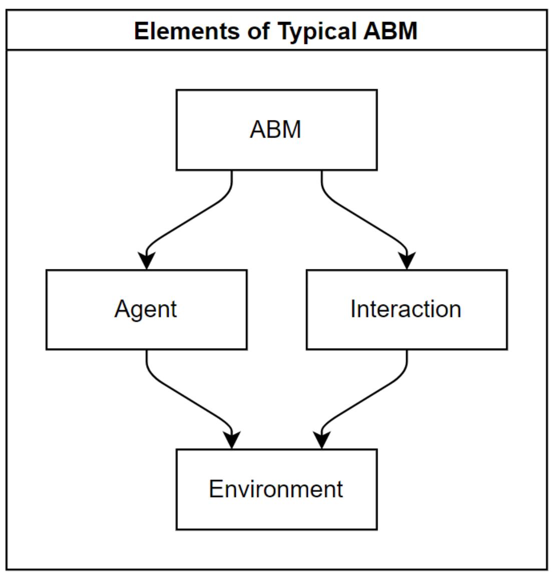

Figure-7 An ABM consists of three main components: agents, interactions, and environment.

Above figure shows the main three elements of a standard ABM, which are basically agents, interactions, and environment.

Although there is no universal agreement as to what an agent represents in ABM (Macal & North, 2008), it can be defined as any *entity* in the real-world that is discrete and identifiable, heterogenous, highly autonomous, exhibiting non-linear behaviours, and self-directed, social and goal-directed, and is able to make decisions based on given rules. Living or non-living anything can be an agent such as human, buildings, taxi drivers. These features and flexibility make them active components of the modelled system rather than passive elements.

In ABM, the spatial context in which an agent interacts is referred to as the environment. It is usually a grid of raster cells with variables that are subject to temporal change.

Fundamentally, the goal of an ABM is to simulate patterns at the system level that arise from the interactions between individual agents, their surrounding agents (agent to agent), and the surrounding environment (agent to environment). These interactions reflect the behaviour of a systems by utilizing *rules*, not calculus like in equation-based approaches (Wallentin, n.d.). Rules are defines as “set of commands that are assigned to each agent to guide their behaviour and decision-making” (Crooks et al., 2018). As a result, the successful deployment of agent-based models necessitates proficiency in programming languages (e.g., NetLogo, GAMA, AnyLogic etc.) for encoding the rules, instead of just having a comprehension of conventional calculus.

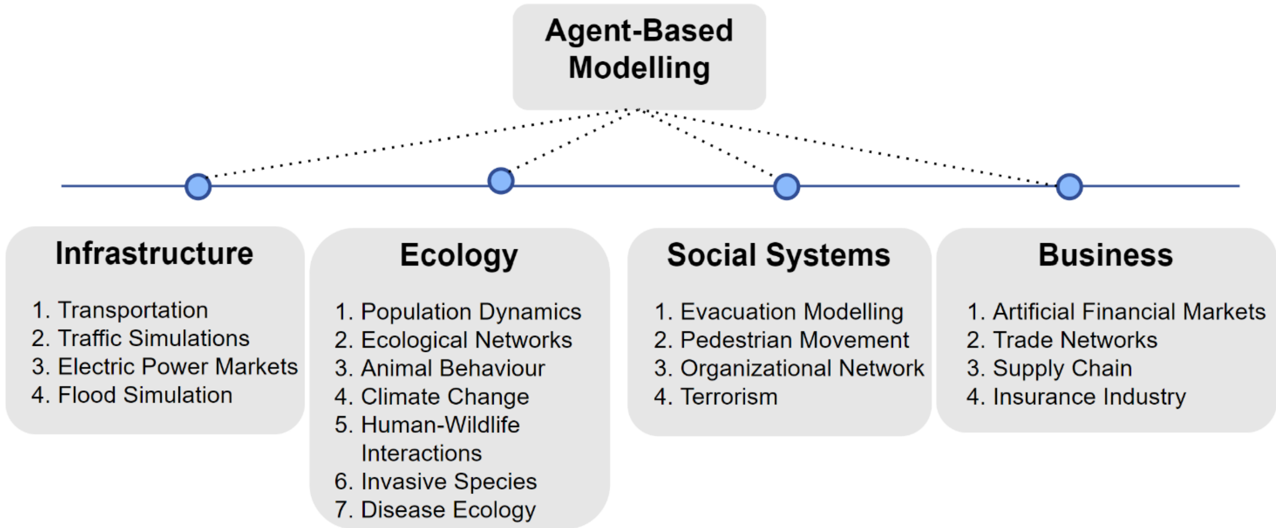

Figure 8 Application Areas of ABM with subtitles. Adapted from (Macal & North, 2008)

The application domains of ABM exhibit a wide range of complexity, owing to last two decades advancements in data collecting and computing advancements. These fields span from minimal models that utilize hypothetical data to more intricate models that leverage large-scale datasets. As seen in figure 9, it can be utilized in a variety of applications such as economy (Turrell, 2016), city planning (Crooks et al., 2021), transportation (Zhang, n.d.), environmental phenomena (Pooyandeh, 2014), animal movement (Tang & Bennett, 2010), population dynamics modelling (Crevier et al., 2021), human behavior (Kwon & Silva, 2019), science (Prins et al., 2008), and exploring complexity (Sun et al., 2016).

ABM has also become increasingly multidisciplinary, interdisciplinary, and transdisciplinary in its applications. In a multidisciplinary context, ABM is utilized within individual disciplines, and experts from these disciplines use agent-based models to study specific aspects within their own domains. Each discipline may contribute its unique perspective to understanding a complex system.

a) b)

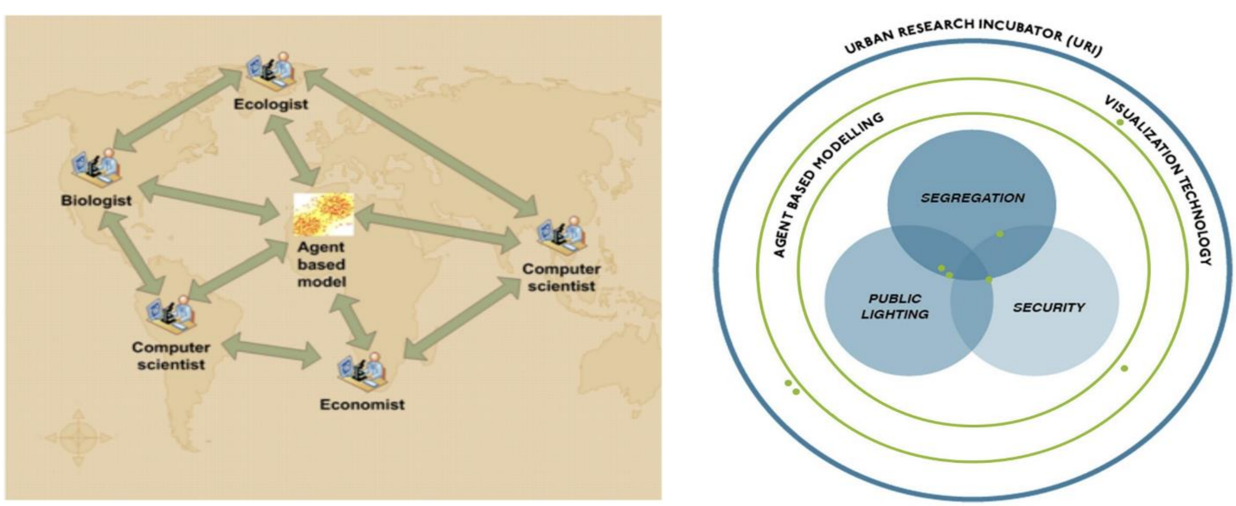

Figure 9 A multidisciplinary (a) and transdisciplinary (b) ABMs (Adapted from (Nguyen et al., 2011) and (Gebert, 2022))

ABM is often used in an interdisciplinary manner when researchers collaborate across disciplines to develop models that incorporate insights from different fields. For example, economists and ecologists might collaborate to model the economic and ecological aspects of a particular system using ABM. The integration of diverse expertise enriches the model and provides a more comprehensive understanding.

In a transdisciplinary context, ABM may involve not only collaboration between researchers from different disciplines but also engagement with practitioners, policymakers, and other stakeholders. The modeling process becomes a collaborative effort that integrates academic knowledge with real-world experiences and insights. This can lead to more contextually relevant and applicable models that address the concerns of various stakeholders.

3.2 Comparison of ABM with Other Modelling Approaches

ABM is a computational modeling technique used to simulate complex systems by representing individual agents and their interactions within an environment. However, it has distinct characteristics that set it apart from traditional equation-based modelling (EBM) methodologies. A summary of these differences can be seen in table 3, where ABM shines over traditional modelling techniques in many ways.

ABM competes with EBM approaches in many research areas. Equation-based methods find system variables and evaluate or combine sets of equations that show how these variables are related over a constant period. Both ways create a model of the system and run it on a computer to simulate it. The model and how it is used are what make them different. (Van Dyke Parunak et al., 1998) In ABM, the model is made up of a group of agents that represent the behaviours of every individual within the simulated the system, and when the model is run, these behaviours are imitated by the agents, while EBM is a set of equations, and the process of putting the model into action is to evaluate those equations over a specified time.

Criterias	Agent-Based Models	Other Modelling
Heterogeneity	Highly available	Heavily homogeneity
Focus	Individuals	System
Interactions / Rules	Non-linear and based on expertise, statistics, and logic	Linear equations are used.
Scenarios Testing	Easy	Difficult
Multiple Entities	Easily applicable	Difficult
Reusability	The ODD protocol	Needs calculus
Approach	Bottom-up / disaggregate	Top-down / aggregate
Complexity Level	High	Medium to low
Emergence	Micro level	Macro level
Model Structure	Adaptive to Changes	Constant
Computing / Software	Easy Coding (NetLogo)	Complicated programming languages (C++)
Application Areas	Multidisciplinary (see figure 9)	Over Specialization
Dimension	High Spatiotemporal Resolution	Continuous/Discrete Temporal Scale

Representation	Complete real-world representation	Reductionist approach to real-world phenomena
Result and Purpose	Hypothesis testing and detailed scenarios comparison with real/unreal data	Generalized system patterns
Users	Scientist, non-scientist	Expertise required
Data Sources	Qualitative and Quantitative	Mostly quantitative
Projections	Holistic	Aggregate mathematical approaches

Table 3 Comparison of ABM with Traditional Modelling Methods. Adapted and reorganized from (Schieritz, 2002), (Hunt et al., 2007), and (Milling & Schieritz, 2003) and Author

Another advantage of ABM over classic analytic modelling methods is that it enables individuals to be different from each other in terms of its heterogeneous structure. The model is able to reflect diverse and adaptable populations because agents can have different interactions, behaviours, and rules. Conventional methods, on the other hand, tend to assume that system components are all the identical (homogeny) and, are lacking the ability to represent heterogeneous and detailed complexity of the modelled phenomena and use simplifying assumptions to make the math easier to be understood.

ABM shines best in areas where details of localization and distribution and where discrete choices are most important. EBM works best with systems that can be modelled centrally and whose behaviour is driven by concrete physical rules instead of processing information. (Van Dyke Parunak et al., 1998)

More generally, ABMs are particularly well-suited for addressing ecological and evolutionary inquiries (An et al., 2021) due to their ability to readily incorporate intra-specific variation, learning, and adaptation, which was exceedingly uncommon in the case of other model types.

3.3 Agent-Based Modelling in Wildlife

By creating the Overview, Design concepts, Details (ODD) standard protocol, a common framework for model formulation and communication, ecologists have remarkably contributed to the development of agent-based modelling science (An et al., 2021).

ABMs can mimic thousands of individuals in realistic environments with a great amount of the detailed internal physiology, perception, and the ability to process those perceptions and follow the rules based on those and their internal states (DeAngelis & Diaz, 2019). This extensive range of capabilities positions ABMs as useful tools in the study of wildlife dynamics, as depicted in figure 10.

In population ecology, important actions such as when and where to move, when and what to eat, and whether to start a fight for food resources or run away from a predator are all choices that members of species must make for maximising growth and minimizing survival, and the way those actions are modelled by classical mathematical models of ecology, such as the Lotka-Volterra prey-predator model, is lacking the capture realism of the modelled world.

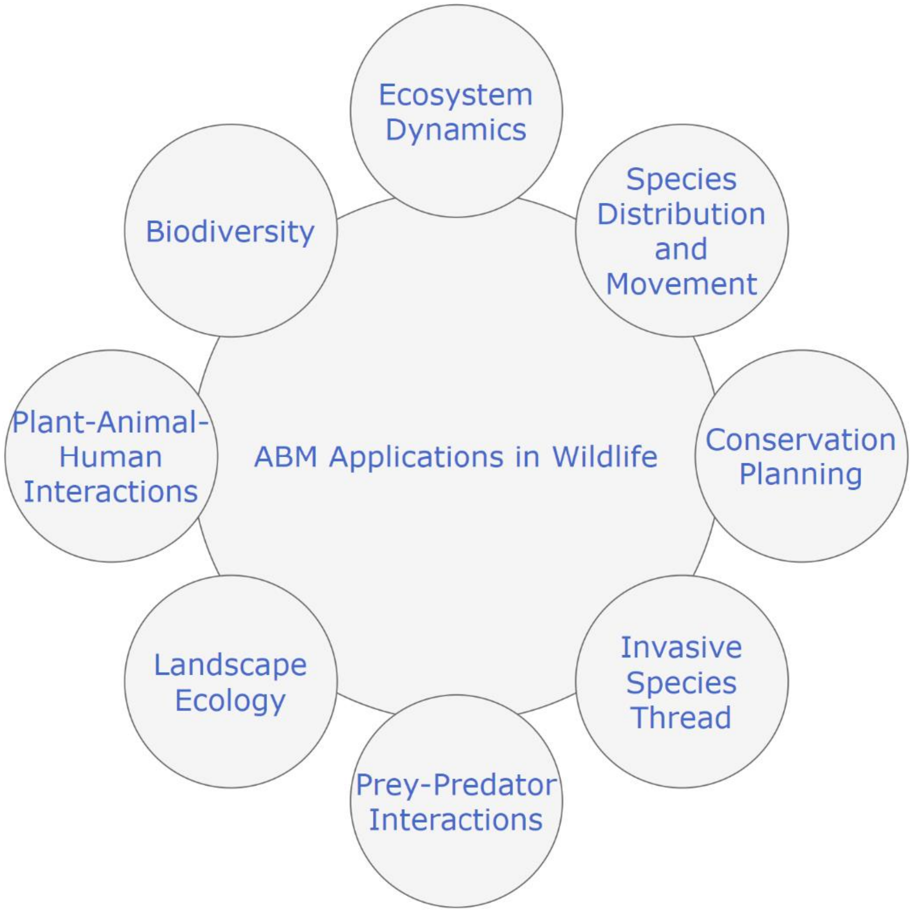

Figure 10 ABM Application in Wildlife

All the choices and the rules that govern individuals in population have been hard to incorporate into the traditional models of ecology, although modelling the way individuals look for things, choose what to eat, or deal with conflicts within social hierarchy has been studied for a long time by population ecologist. When all agents are given a few simple rules to follow when making decisions, the population-level models that come out of this have led to important level of *homogeneity* in patterns and *generalizations* (DeAngelis & Diaz, 2019). It is additionally acknowledged that these models fail to capture the way individuals in real world act. Figure 11 is an example of a prey-predator ecosystem that contains a higher level of complexity than what can be provided by traditional equation-based modelling. Also, many of the movement patterns of individuals or herds are significantly more complex than ones in differential equation (PDE) models. ABMs can follow rules that range from simple (what-if scenarios) to very complicated (DeAngelis & Diaz, 2019); meaning that an agent can make adaptive decisions about what to do by using reasonable and simple "*if-then*" rules or more complex neural networks and genetic algorithms.

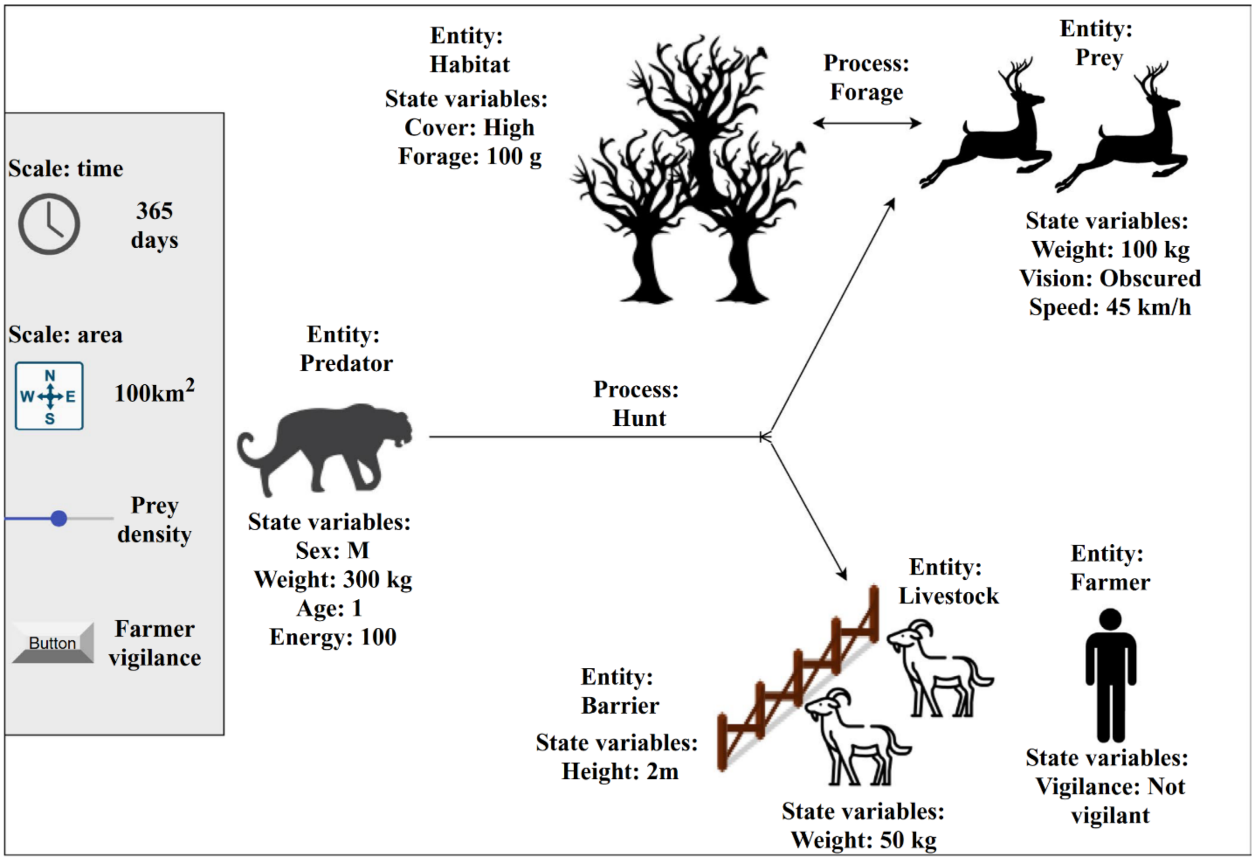

Figure 11 Typical prey-predator ecosystem within ABM (Murphy et al., 2020)

3.4 Modelling the Population Growth

Modeling population growth is a common task in ecology, sociology, and related fields. In ecology, modeling population growth is essential for understanding the dynamics of species populations within ecosystems. There are various mathematical models to describe population growth over time. Among them, one classic model is well-known: the exponential growth model. When a population experiences exponential growth, its per capita (per individual) growth rate remains constant regardless of population size, causing the population to become exponentially larger. Exponential population growth gives a fundamental understanding of how population increases or decreases over time, and other population modelling, such as logistic population growth, is basically derived from it (Gotelli, 2008). In this modelling, the population is not exposed to external factors; meaning that any change in population size is only based on births and deaths, which does not represent the complexity of the natural world where population growth can experience exponential growth for a while (*Exponential Growth & Logistic Growth (Article)*, n.d.), but eventually, the availability of resources will limit it.

Agent-based models, however, can provide a more detailed and flexible approach, allowing for the consideration of various factors and interactions within a population. Modelling population growth with such combined approaches will help to predict the population size at any given time. Typically, a population's size can be altered by just four methods. Births and immigration can lead to an expansion in the population, while deaths and emigration can lead to an overall decrease (Stratton, n.d.).

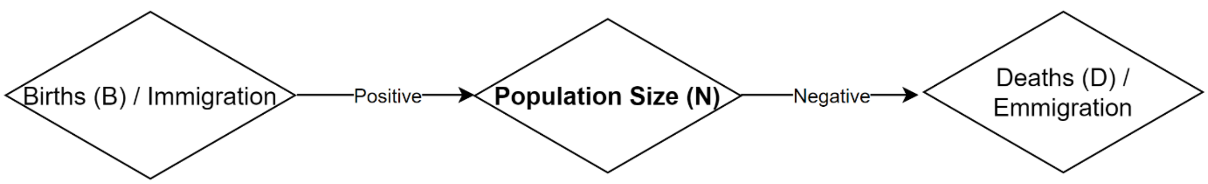

Figure 12 An illustration of how population changes

Since there is just one natural population of WCs in the wild (WBNP), immigration and emigration have ignorable impacts on the species. Consequently, it is possible to write a straightforward formula that illustrates how the population will fluctuate yearly:

$$N_1 = N_o + B - D$$

D: represent the number of deaths,

B: represents the number of newborns,

N_o: represent initial number of the population,

N_1: represents the number of populations at t time (after 1 year)

The overall number of births and deaths will vary depending on the size of the population. For simple reasons such as when they begin with more parents, large populations are likely to have more births overall than small populations. However, the likelihood that an individual will give birth or die within a specific time frame is probably rather stable. These are referred to as the birth rate (b) and death rates (d).

$$b = \frac{Births}{Population} \quad \text{and } d = \frac{Deaths}{Population}$$

Considering the first equation;

$$N_{t+1} = N_t + bN_t - dN_t \Rightarrow N_{t+1} = (1+b-d)\, N_t$$

In population ecology, it is often assumed that birth and death rates are constant, therefore (1+b-d) is considered constant multiplier of the population, and the Greek letter λ *(lambda)* is used to symbolize this.

$$N_{t+1} = \lambda\, N_t \Rightarrow \lambda = \frac{Nt+1}{Nt}$$

Lambda (λ) is defined finite population growth rate. It can be understood from the above formula that if $\lambda > 1.0$, then the population is increasing and if $\lambda < 1.0$, it has a decreasing trend (Stratton, 2010).

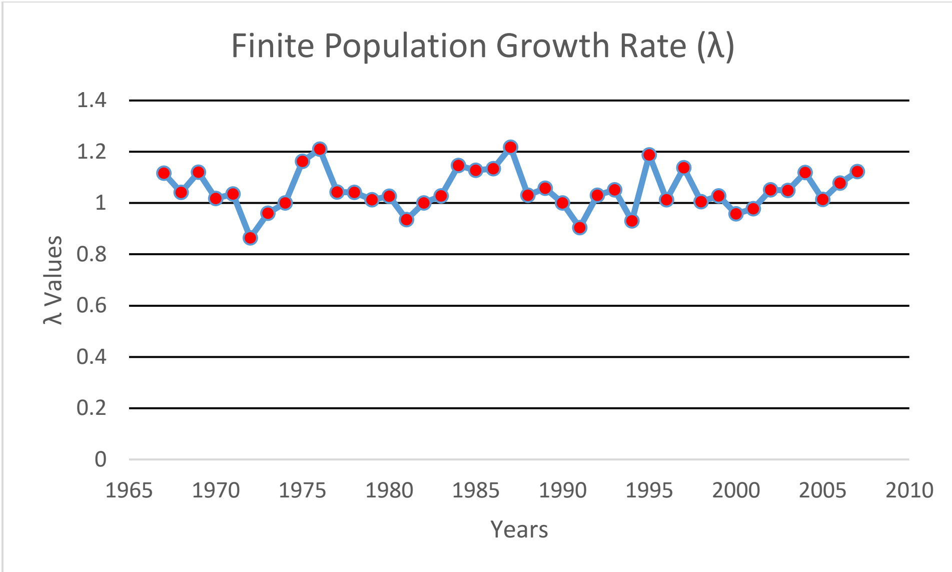

Figure 13 Finite Growth Rates of WCs during 1967-2007

Based on available demographic statistics, the λ values of WCs varied with a largely positive growth rate between 1967 and 2007, going from 0.86 to 1.21. However, the population did decline in a few years, including 1972–1974, 1981–1982, 1990–1991, and 2000–2001.

CHAPTER 4: MODEL CONSTRUCTION

4.1 Overview-Design-Detail (ODD) Protocol

Agent-based models enable researchers to examine the emergence of system-level features resulting from the adaptive behaviour of individuals, as well as the impact of the system on individuals (Grimm et al., 2006). However, the potential of ABM technology is not without its associated drawbacks. ABM systems are inherently more intricate in their structure compared to analytical and/or mathematical modelling approaches. The execution and operation of these models demand their implementation and utilization on computer systems. ABMs present a greater level of complexity in terms of analysis, comprehension, and communication compared to conventional analytical models. The issue of communication is of particular significance. Analytical models possess a high degree of communicability due to their formulation in the universal language of mathematics, so the description typically exhibits comprehensiveness, clarity, and reader-friendliness for many modellers and even for non-technical individuals. On the other hand, the publicly available descriptions of ABMs frequently exhibit characteristics such as being challenging to comprehend, lacking in comprehensive details, and exhibiting ambiguity and uniqueness, so reducing their accessibility for those who are not familiar with them.

In their early days, agent-based models received a lot of interest, because it was a fundamentally new approach with which individual behaviour and interactions could be studied on a system level. However, considerable critique was formulated by the research community. Finally, 28 researchers, who cover a wide range of fields within ecology, came together to publish a joint paper with an agreed standard protocol for the reporting of agent-based models: the ODD protocol (Grimm et al., 2006).

The Overview, Design concepts, and Details (ODD) protocol, utilized for delineating ABM, has gained substantial acceptance and usage for the purpose of documenting these models within scholarly articles from various science fields (Grimm et al., 2020a). The ODD serves as a standardized means of communication, ensuring that the process of model development remains comprehensible and reproducible within the scientific community. It requires the followings as (Murphy et al., 2020) states:

>> <u>Overview:</u> General information and context of the model,

>> <u>Design concepts:</u> Strategic considerations and internal methods,

>> <u>Details:</u> Technical methodology and details of their use in the model.

Since its inception, the ODD protocol has been extensively employed, ensuring that model development adheres to the rigorous standards of ecological research. Incorporating these criteria into the process results in well-structured elements that enhance the value of both basic and advanced ABMs. This framework guarantees the integration of theoretical underpinnings into computational aspects and prevents arbitrary programming, thereby rendering the model a genuine and practical system for applied research (Murphy et al., 2020).

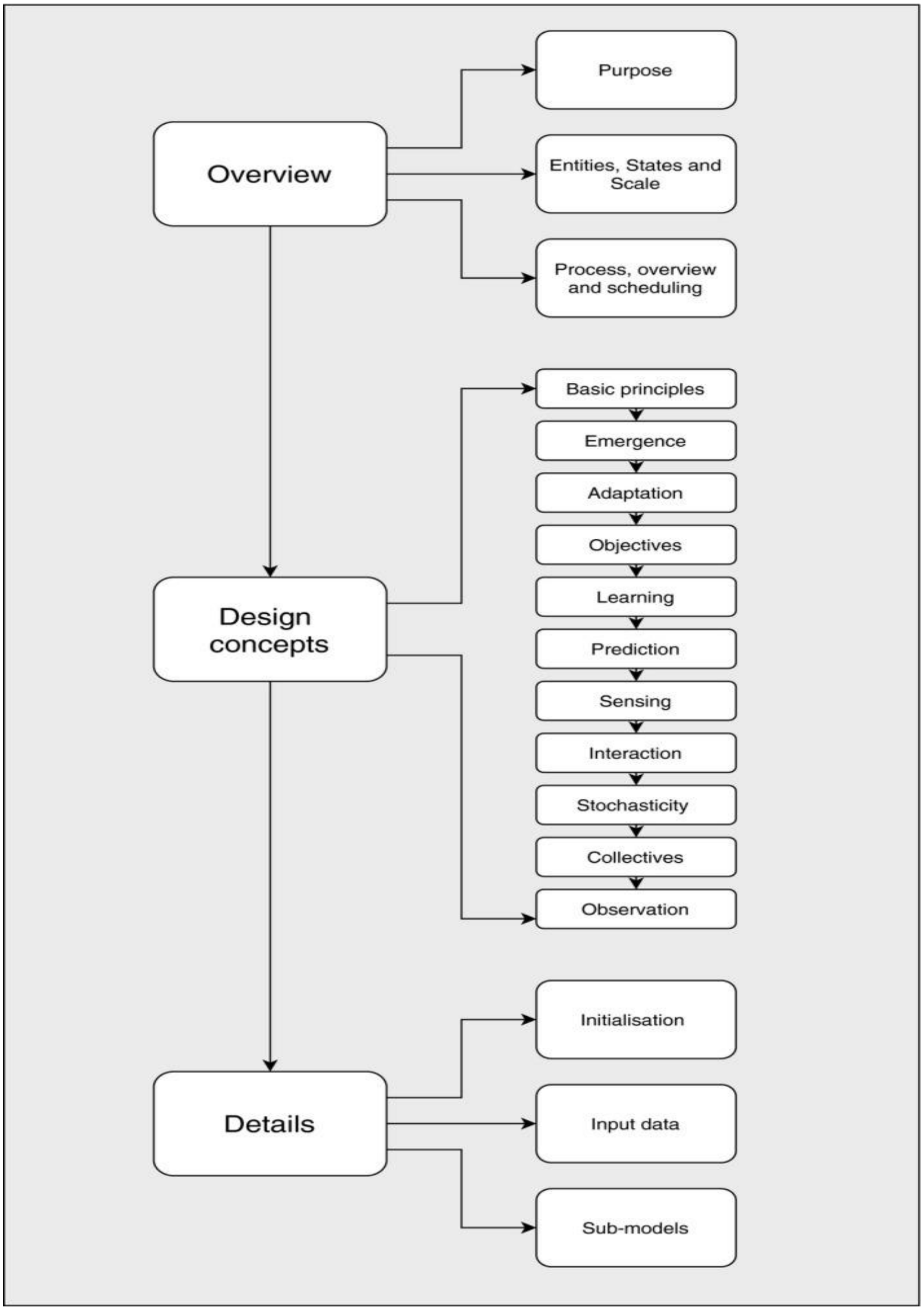

Figure 14 The main blocks of the ODD protocol and their subheadings, which may be omitted if not applicable.(Murphy et al., 2020)

4.1.1 Purpose

The purpose of the implemented model here is of significance of a better understanding of population dynamics of endangered whooping cranes in their nesting area, Wood Buffalo National Park, and to analyse which conditions are better for a self-sustaining population, particularly identifying the environmental factors, such as temperature and precipitation that are acting together on ups and downs in population size. The model aims to see the abundance of cranes under various demographic and environmental scenarios by creating stochastic agents that represent different age scales for this species and simulating them in NetLogo modelling environment.

4.1.2 Entities, State Variables (Attributes), and Scales

In this section, the ODD components elucidate the concepts portrayed within the model (Grimm et al., 2020a). The initial section reveals the entities within the model. An entity, which has similar roles in database management systems, denotes a distinct or separate object or actor that functions as a cohesive unit. ABMs typically encompass various types of entities, with one or more instances of each type.

The second part comprises a depiction of the state variables (Grimm et al., 2020a), which have similar functions of 'attribute' in DBMS, inherent to each entity type. Principally, state variables of an entity are variables that characterize its existing condition. A state variable either distinguishes an entity from others of the same type (i.e., diverse entities or agents possess differing values of the same variable) or traces how the entity evolves over time; meaning that the variable's value for an entity changes throughout simulated time.

In the model, WCs are divided into 4 age classes (see figure 19 for more detail). Because of their biological structure, chicks and juveniles are incapable of producing, while subadults and adults can give birth when they reach the age of 4 years of maturity. The nestling (fledging) period of chicks is 3 months, which is within the time that chicks spend in WBNP. During fledging, chicks are still confined to their nests, incapable of flight, and need their parents to provide nourishment. Incubation, nestling, and brooding are biological processes that occur during their breeding and later periods in WBNP. Considering data availability, the temporal scale of the model is selected at 55 years, beginning from 1966 to 2021, excepting 2020 due to COVID-19. A tick is a unit of time measurement in NetLogo models that modellers can replace these time scales with days, weeks, or months or whatever they want for their work, such as this model, which will have 55 iterations due to its yearly temporal scale. Survival rates of age classes are of different percentages for adults (0.91) and young (0.764), which shows adults can survive more likely than young because adult mortality is mostly caused by factors related to human activity, which are restricted by law in WBNP, and occurs during the migration process or when dwelling in the wintering grounds, which are not modelled here, and more importantly, young that are unable to fly are more vulnerable to various terrestrial predators and alterations in their surroundings. The initial population number at which the model starts running its first iteration is selected as 43, consisting of 38 adults and 5 young members, and 5 nests are available based on population data from 1966.

Table 4 contains all the parameters used in the model, along with a description of each of them as well as their references.

Parameters	Values/Units	Explanations	Sources
Age Structure	Youngs --> Chicks and Juveniles Mature Adults --> Subadults and Adults	Based on existing population data, the model essentially separated WCs into two main age classes: young and adults. These age classes are then segmented into four age stages: chick, juvenile, subadult, and adult.	(Whooping Crane (Grus Americana) Demography and Environmental Factors in a Population Growth Simulation Model, n.d.)
Young Fecundity	Juvenile and Chicks = 0	Due to limits imposed by biological processes, juveniles and chicks are unable to engage in reproductive activity.	(Songsasen, n.d.)
Adult Fecundity	Subadults and Adults = 0.245	The literature was combed through to determine the fecundity rates for each adult female in the WCs.	(Tischendorf & Lindsay, n.d.)

Parameters	Values/Units	Explanations	Sources
Young Survival	Juvenile = 0.764	Unprotected eggs and unable-to-fly young are more susceptible to a variety of terrestrial predators and environmental changes around them.	(Lewis et al., n.d.)
Adults Survival	Adults and Subadults = 0.91	The majority of adult mortality happens during the process of migrating or when residing in the wintering grounds and is mainly due to factors associated with human activities.	(Tischendorf & Lindsay, n.d.)
Annual growth rate	3.5 percent	Although this value fluctuates over time, data that has been averaged over the past sixty years has been observed.	(Canadian Wildlife Service and U.S. Fish and Wildlife Service. 2005. International Recovery Plan for the Whooping Crane. Ottawa: Recovery of Nationally Endangered Wildlife (RENEW), and U.S. Fish and Wildlife Service, 2007)

Parameters	Values/Units	Explanations	Sources
Initial number of populations	43	Assuming that there is enough habitat and that it can be easily accessed by 43 WCs. Initial population is chosen based on data.	Canada Wildlife Service (CWS) and United States Fish and Wildlife (USFWS)
Temporal scale	55	5 decades from 1966 to 2021 (except 2020 due to Covid-19)	Present Research
Time ticks represent	1 year	In NetLogo models, a tick is a unit of measurement (like seconds or minutes). Users can substitute ticks for days, weeks, or months.	(Wilensky, U. (1999). NetLogo. Http://Ccl.Northwestern.Edu/Netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL., n.d.)
Incubation time	1 month	The period from the laying of the last egg of the clutch until that egg hatches.	(Classen & McCracken, 2010)

Parameters	Values/Units	Explanations	Sources
Broods per year	1 chick	The female lays two eggs; however, it is typical for only one of the chicks to make it to maturity.	(Wilson, n.d.)
Maturity	4 years	WCs reach sexual maturity between the ages of four and five years, and subsequently breed once each year.	(Chavez-Ramirez, n.d.)
Breeding period	yearly, in May	When they get to WBNP in late April, they start nesting. The first clutch is usually completed by mid-May.	(White, 2001)
Clutch size	2 eggs	A clutch is the total eggs a bird lays per each nesting attempt.	(May, 1994)

Parameters	Values/Units	Explanations	Sources
Nestling period (Fledging)	3 months	A nestling is a bird developing in the nest and this bird is not yet ready to leave the comfort of the nest, cannot fly and needs to be fed by parents.	(Butler et al., 2017)
Temperature	11.35 Ave.Temp Celsius	Measured mean temperature data for the temporal scale of the model.	Environment and Climate Change Canada/ Birch Mountain Lo Station Historical Data
Max life span for an adult crane in the wild	25 years	The average life expectancy for adults varies up to 28 years in the wild.	(Stratton, n.d.)

Table 4 Overview of the parameters and default values of them in WCs population model

4.1.3 Process Overview and Scheduling

Process overview and scheduling are components that help describe how the simulation progresses and how agents interact over time. In this phase, a conceptual model can help readers to understand the questions of what entity (agent) does what, in what order and when in the model. Since the ticks represent 1 year, at each iteration, agents (turtles) get a +1-year age increment, and when adults cranes reach the age of 25 or the critical temperature level of -13 is exceeded, then they die.

```
  ask adult_cranes [                    ;;age increment for adult cranes
    set age age + 1
    set size 2.5
    set shape "bird"
    set color white
    if age = 25 [
      ask adult_cranes [
        die
      ]
    ]
  ]

  tick
end
```

For WCs in breeding ground, food availability is the resource of utmost importance during the mating season since an individual needs to maintain a positive energy balance to survive (Chavez-Ramirez, n.d.). Following figures explain the agents and their modelled behaviour in the model:

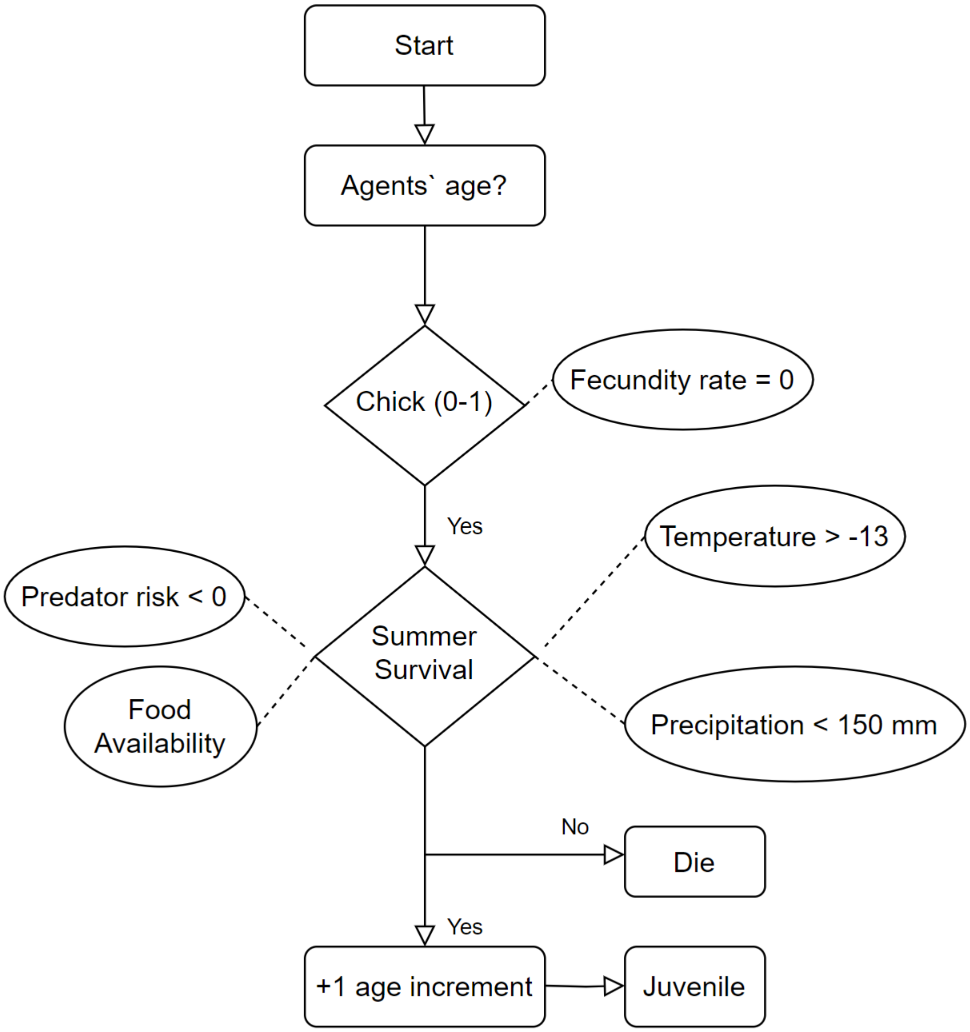

Figure 15 Conceptual model for chick agents

If the current circumstances are suitable for the growth of chicks;

```
  ask chicks [
    if precipitation >= 150 or
  temperature <= -13 or temperature >= 40
 or
  young-survival <= 0.763
  or
  predator-abundance >= 15
  or
  any? wolves in-radius 4 [   ;; radius is wider here because chicks and juveniles are unable to flee from a predator when they are approached
    die
  ]
]
```

then, they undergo a transition to the juvenile stage after a single time step, as depicted in the following figure:

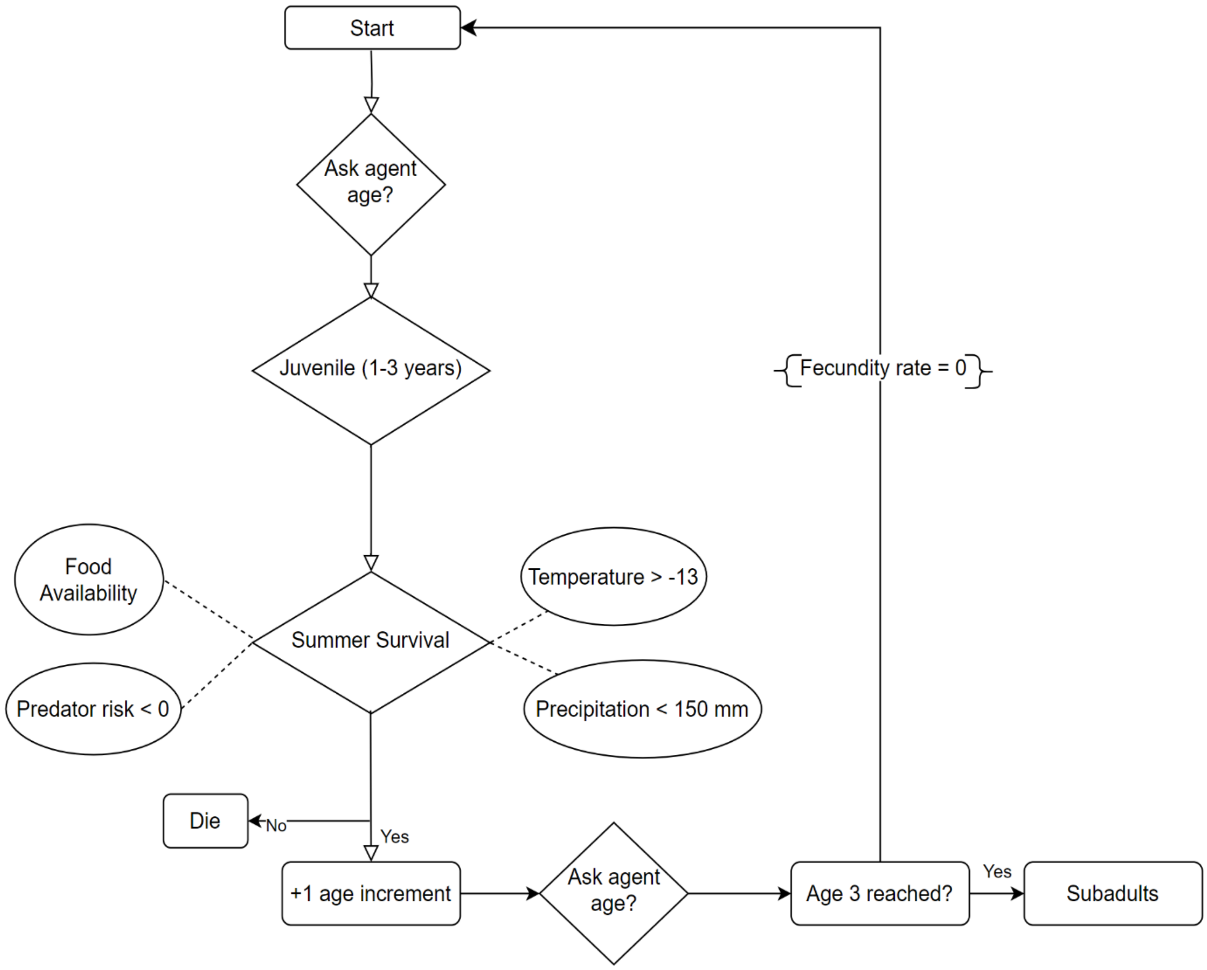

Figure 16 Conceptual model of juvenile agents

The lack of fecundity in juveniles can be attributed to their immaturity throughout this developmental stage. The above procedure is iterated until the juvenile agents attain the age of three or older, thus moving into the subadult stage, during which they achieve the ability to reproduce. The survival rates throughout the summer months are of greater significance for both fledglings and juvenile individuals.

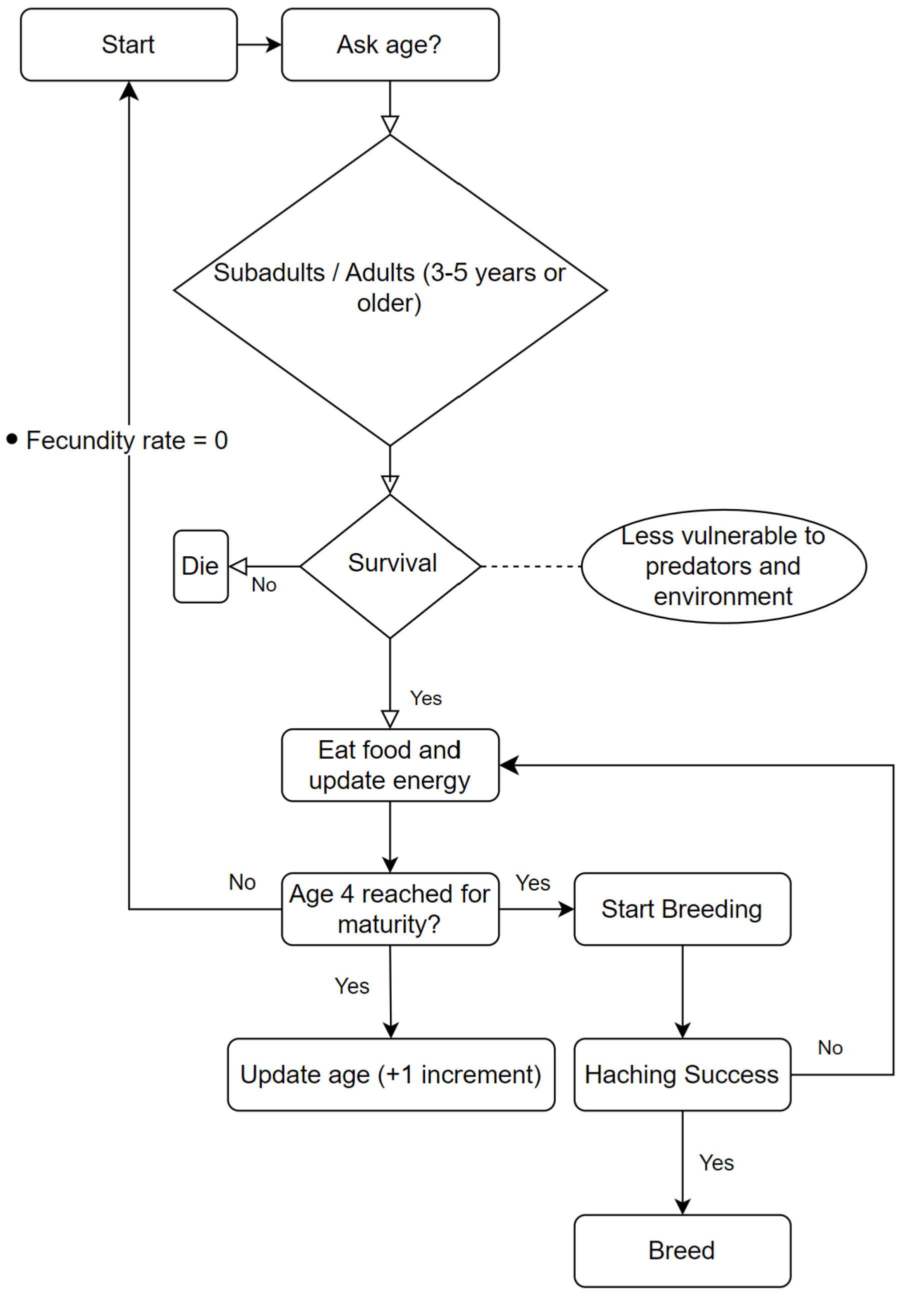

Figure 17 Subadults / Adults conceptual model

4.2 Desing Concepts

4.2.1 Emergence

Population dynamics stem from the behaviour of individuals within the simulated model and are represented by rules based on actual scientific findings gained from published papers and that describing, for example, life span, incubation period, clutch size, breeding period etc.

The ages of the cranes represented in the model are categorized into two main age classes, which are subsequently subdivided into even more specific categories, as illustrated in figure 6.

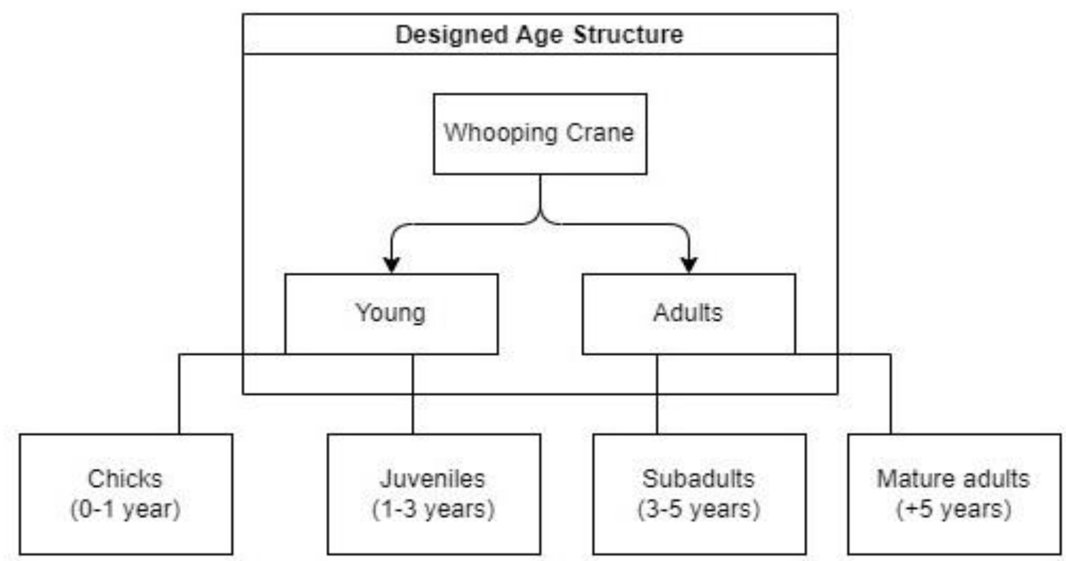

Figure 18 Modelled age stages for WCs.

```
breed [adult_cranes adult_crane]
adult_cranes-own [age]
breed [subadults subadult]
subadults-own [age]
breed [juveniles juvenile]
juveniles-own [ age]
breed [chicks chick]
chicks-own [age]
```

4.2.2 Sensing

Sensing is commonly represented by assuming that the agents have precise knowledge of specific variables they possess (Grimm et al., 2020b).

Agents are supposed to know their own features such as;

>> Chicks know their age, vulnerability against low-high level temperature; meaning that when lower critical temperature of -13 is exceeded, they die.

>> Juveniles know their age and age-related behaviours.

>> The prey senses the predator, and the predator senses the prey.

>> Subadults recognize their situation in population.

>> Only female adults can give birth to reproduction.

>> All agents are able to sense their internal and external situation.

>> Agents are able to decide when to move to another location if their current location has a low amount of food or predator risk for them.

>>Individuals recognize that there will be energy gain and loss with movement.

>> Agents` selection on where to move is depending on current energy state they hold, food availability at the intended patches and predation risk along with the movement.

4.2.3 Interactions

Interactions are fundamental concepts in agent-based modeling (ABM) as they form the basis for how agents in the model interact with each other and their environment. Next interactions have been modelled among the agents clearly;

>> WCs are both predators and prey, and they prey on blue crabs to gain energy,

>> When they reach certain age, they form pairs and only females start giving birth,

>> Both females and males incubate for eggs,

>> WCs are monogamous, meaning that they form pairs at the age of 2 or 3 years and mate for life,

>> WCs are omnivorous, meaning that they eat a variety of animals and plants,

>> Even though, there is ample knowledge on the food items that constitute the diet of WCs, there is a shortage of information regarding what their specific prey choices are, either plants or animals.

>> Paired cranes typically reach the same patches or locations for nesting after wintering,

>> New pairs often establish a territory near their parents.

>> Chicks live under parental control until they reach subadults age.

>> Predator starts from the smallest member of population to biggest in selection of their prey.

>> Agents` overall aim in any interaction is to maximize both growth and survival.

>> Both males and females have identical chances of survive and maturity age.

The design and implementation of interaction mechanisms in agent-based models are essential for capturing the desired real-world phenomena and studying how collective behaviors emerge from individual actions. It is important to carefully define and parameterize these interactions based on available data, domain knowledge, and research objectives. Sensitivity analysis and validation against real-world data can help ensure the validity and robustness of the modeled interactions.

4.2.4 Stochasticity

Assumptions play a crucial role in the construction and interpretation of agent-based models, as they define the characteristics and behaviors of the agents and the environment within which they operate. It's important to recognize that assumptions in agent-based modeling are necessary simplifications to make complex systems tractable for simulation.

Next assumptions have been made in the model;

>> All agents in the model are assumed to behave rationally, making decisions that maximize their utility or achieve their goals based on available information,

>> Young cranes are more vulnerable to high/low temperatures and expose to predator more than other adults,

>> The abiotic factors selected as main regulators for the cranes in WBNP are temperature and precipitation,

>>The temperature will be affecting the number of preys, which is blue crabs, but still all individuals needed to eat their prey can find blue crabs in their environment,

>> Blue crabs are assumed to be the primary and most important source of food and energy for WCs.

>> Grey wolves are intentionally chosen as the dominant predators for WCs in the area and will be operating in the model assuming that they remain unaffected by the fluctuations in temperature.

>> Preys and predators of WCs are considered adult species.

>> Since the model does not account for any form of human activity (e.g., shooting, chemical spills), the egg removal that was carried out by wildlife management was not accounted for in the model.

>> Overall life span is considered 25 for a senior adult,

>> Each adult female individual can reproduce 1 chick at each iteration, regardless of the population size,

>> Genetic algorithms (GA) of the population members remain constant over time,

>> There have been no fatal conflicts among cranes, e.g., sandhill cranes, within different the social hierarchy.

>> Most mortality among adult cranes occurs during migration/on the winter range.

>> In this scenario, there is no spread of the disease in the population.

>> Gender ratio for the model has been selected 50 percent between male and female.

>> Given that the sex ratio is widely acknowledged to be balanced, the female population serves as a reliable indicator for estimating the total number of breeding adult pairs.

>> The initial nest number is 5, hence it is presumed that survival rate * 5 nests have a successful chick production.

>> Because lower critical temperature (LCT) threshold is known as -13, and unknown for the chicks, it is assumed that LCT threshold is identical for all age groups.

>> Within the simulation, there will be a process of gaining and losing energy; however, given facts that WCs rarely never fly on the breeding area, and they store energy (fat) in the wintering ground; hence, it is presumed that when they arrive WBNP, there will be adequate energy (fat) reserves for breeding.

>> There is neither immigration nor emigration taking place since WCs only breeds in their unique habitat, WBNP.

>> WCs are targeted by predators both on land and in the air. Nevertheless, due to their infrequent flights in WBNP, the presence of air predators such as bald eagles are disregarded in the model. Air dangers predominantly occur during migration.

It is important to note that the model also includes some stochasticity in deciding where to go by combining probabilistic and logical rules, reflecting incomplete environmental knowledge and perceptual capacities.

4.3 Details

4.3.1 Initialization

The model starts with initial values of parameter for the year of 1966, and according to CWS population data, 5 nest are available at that time. Considered that the survival rate for young is 0.764, 3 of the 5 nests are counted as successful for hatching.

```
create-chicks 5 * 0.764 [                          ;;chicks turtle
  setxy random-xcor random-ycor                    ;; young survival rate is 0.764, and we have 5 nest at the beginning, therefore initially 3 chicks are created
  set shape "bird side"
  set color brown
set size 0.5
  set age 0
]
```

Above figure shows initial conditions of the model.

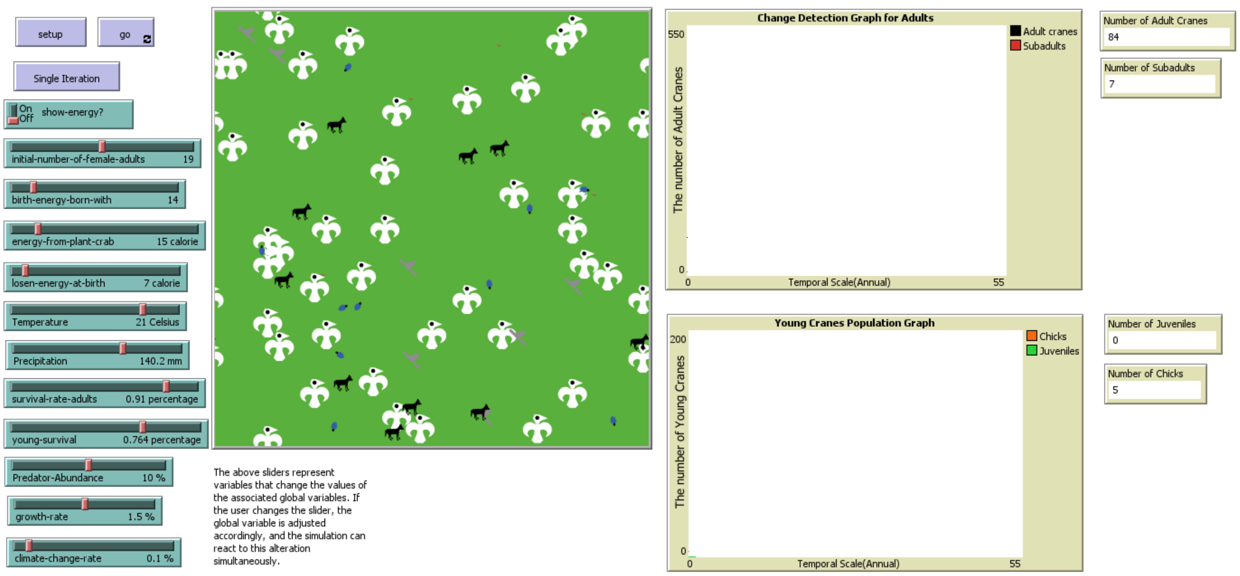

Figure 19 Initial Conditions of the Model

At the starting date of model, because there were 38 adults crane whose gender are unknown by the CWS staff, and only adult female cranes are able to breed, it is assumed that the population has a 50:50 gender rate meaning that; 19 female cranes are available in initial state, and turtles are distributed randomly in the landscape.

```
create-adult_cranes 19                ;; adults cranes(female) turtle
ask adult_cranes [
  move-to one-of patches
  set color white
  set shape "bird"
  set size 2.5
  set age 6
]
```

4.3.2 Submodels

The analysis of predator-prey ecosystems for WCs is examined in this submodel. A system is considered unstable if it tends to lead to the extinction of WCs. On the other hand, the model is considered stable if it looks to sustain itself during simulation, even when there are ups and downs in population sizes.

One of the key foods for the WCs during breeding season is the blue crabs, and it is believed that variables, specifically dry weathers, influencing the crab population could significantly affect the survival of the cranes (*Whooping Crane*, 2023). The ideal temperature range for the crabs is chosen between 3 – 30 °C degree (O'Connell et al., n.d.), meaning that when the temperature is lower than 3°C or higher than 30°C, they will move into deeper waters, which is interpreted in the model as meaning that they die. For this,

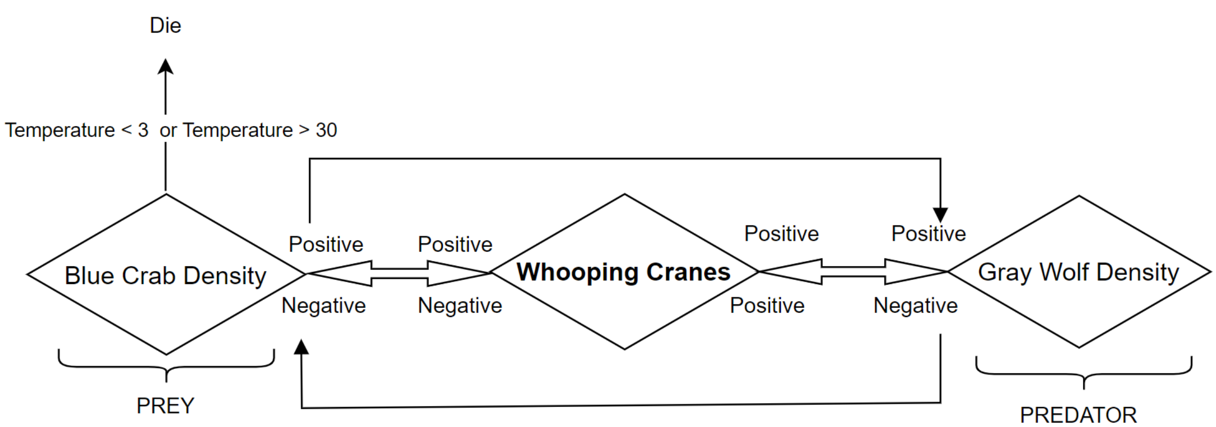

Figure 20 Whooping Crane Prey-Predator Relationship

(Chavez-Ramirez, n.d.) found that the available data on blue crab traps indicates that the availability of this significant food source for Whooping Cranes may be reduced during certain years in their wintering grounds. This limitation in food supply could potentially have mortality effects on WCs. The same study conveys that the observed decline in blue crab population from one season to the next took place in the months of August and September in the year 1993, and it can be interpreted as this decrease being directly related to a corresponding decline in the survival rate of young cranes at the same time.

CHAPTER 5: RESULTS AND DISCUSSION

The simulation model presented in this study aimed to replicate the ecological dynamics of WCs in WBNP considering internal and external factors that together influence the population.

The reproduction of adult cranes led to the emergence of chick populations, which matured into juveniles over time. The survival of chicks was contingent on various factors, including precipitation, temperature, and predator abundance by using summer-survival procedure. Chicks that survived to adulthood contributed to the overall population dynamics.

Subadult and juvenile turtle populations demonstrated growth and maturation processes. The age-based transitions from juveniles to subadults and subadults to adult cranes closely followed the specified age thresholds, resulting in a balanced population structure.

The adult crane population displayed fluctuating patterns over the course of the 55-year experiment. The reproductive procedure, driven by NetLogo *globals* like fertility rate of 0.245 and growth rate (λ), resulted in periodic increases in the number of young and consequent changes in the makeup of the adult crane population as shown in figure-22.

The model incorporated climate change scenarios, employing the temperature and precipitation values evolving over the 55-year simulation with a climate-change-rate of 0. 01, which can be changed by desired rate. These dynamic environmental factors acting together influenced WCs` reproduction, and overall population dynamics.

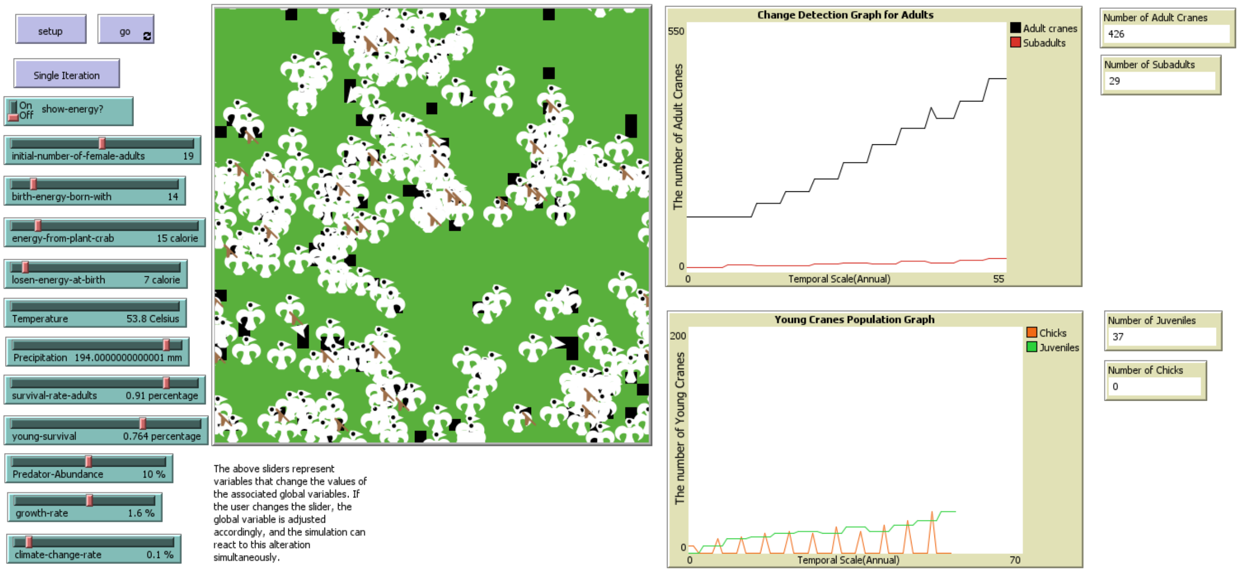

Figure 21 After 55 times running the model, it produces the population data to be evaluated

Since the adult cranes represent female adults only, and gender ratio is selected %50 between males and females, above adult crane number is multiplied by 2 to count correct adult numbers.

Color	Pen name	Pen update commands	
	Adult cranes	`plot count adult_cranes * 2`	
	Subadults	`plot count subadults`	

Same calculation is made for monitoring the number of adult cranes.

5.1 Model Evaluation

Simulations should accurately mimic the behaviour of their target system in order be effective and helpful as tools for exploring real-world phenomena. Even though evaluating model accuracy is a crucial step in the development of a model (Crooks et al., 2018) , it is often ignored or receives little attention by modellers.

Within the code section, a total of nine procedures are implemented to execute the model, excluding the set-up and go procedures, which are responsible for initializing and running the model depending on the defined rules, respectively. NetLogo utilizes procedures to establish a series of instructions that may be called and executed in a predetermined sequence. Procedures enhance the organization of code, enhance reusability, and foster adaptability.

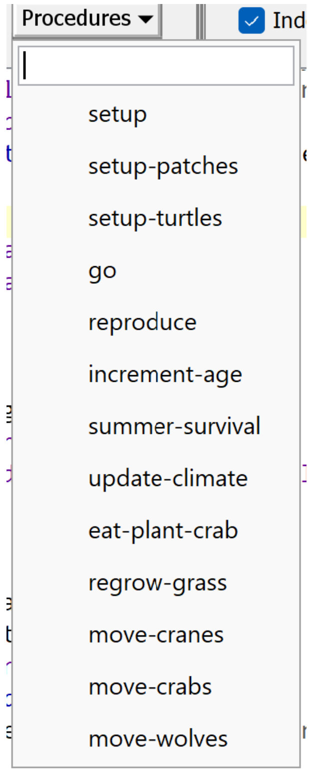

Figure 22 List of Procedures in the Model

Set up procedure initializes the model by creating patches, turtles of different breeds, and setting environmental parameters. The reproduce procedure handles the reproduction of different turtle breeds based on energy levels and random chances. The summer-survival procedure enforces survival rules based on age, environmental conditions, and predator presence. The update-climate procedure updates temperature and precipitation based on a climate change rate. The energy decrement for cranes during movement is considered, which adds a level of realism. The complete version of the code can be found within the appendix section.

Evaluation of ABMs requires a multidimensional approach and does not have a formal methodology, although many researchers have settled on an accepted approach that consists of three consecutive steps (Crooks et al., 2018): verification (internal validity), calibration, and validation.

5.1.1 Verification

There are numerous methods to validate that the model's execution aligns with the design (Crooks et al., 2018) :

** Manual model inspection, such as ensuring that agent variables change as expected

** Code testing, also known software testing, such as unit testing and pair programming, is performed to evaluate the functionality and quality of code.

** Docking refers to the process of implementing a model twice, utilizing distinct libraries or programming languages.

Out of these three options, code testing has been selected as the preferred method for verification. This is because even if the code may run correctly and produce acceptable outcomes based on the design of model, there is still a possibility of an error existing in the code, commonly known as a 'logical' or 'semantic' error. As shown in above figure 23; the rule is created in the right picture for turtles that if energy reserve is less than zero, they die. On the left picture, it says an adult crane is dead due to current energy level is -1.

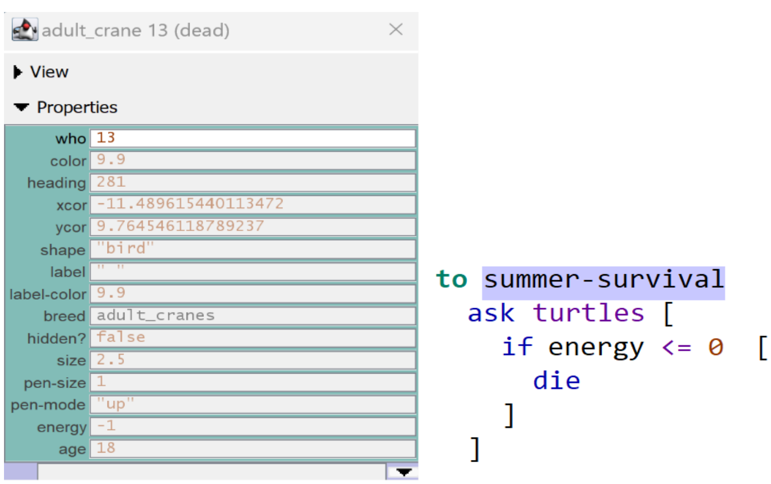

Figure 23 Unit Testing for verification.

5.1.2 Calibration

Model calibration refers to the process of adjusting a model's parameters to align with the actual outcomes or ground truth in a dataset. This can be accomplished by running the model with ranging parameter values and using statistics to compare the modelled outcomes with the observed data (Crooks et al., 2018).Two types of calibration are common for ABMs:

Qualitative Calibration: Without a thorough examination, the model undergoes modifications until it appears to be calibrated qualitatively. This method can be carried out by the modellers themselves using their own expertise and intuition, or with extra guidance from stakeholders, decision-makers, and outside specialists.(Crooks et al., 2018) This is also called face validation.

Quantitative Calibration: Quantitative calibration concentrates on selecting a set of parameter values (Crooks et al., 2018) from the model that most accurately capture the patterns of an interested system's behaviour in reality. (Railsback & Grimm, 2012) shows some considerations for calibration as follows:

1) The process of calibration ought to be restricted to a small number of parameters that are both unknown and of significant importance. Implementing a rigorous selection approach for test parameters results in a significantly simplified calibration procedure.
2) Perform a sequence of simulation experiments to investigate the configurations of parameter values through a process known as ‘parameter space search’ in NetLogo.
3) The calibration experiment findings are to be analyzed in order to determine the parameter value ranges that most accurately match the measured data.

The comparison of the adult crane population overall using data from the Canada Wildlife Service and the model is shown in Figure 24. The model's output closely resembles actual data, except for 2020 because of the COVID constraint. Since there is no actual data available for 2020, the model's population data from 1966 to 2019 is compared with CWS ones, and its R^2 score of 0.7866 is respectable. When 2020 is included, not only the R^2 value but also the m and c values have increased dramatically. The values are found by running the model under various parameter values to find the best matches to the real-world data. These data were found when the initial conditions were as follows: temperature is 10 °C, precipitation is 70 mm, growth rate (λ) is 1.12, climate change rate is 0.01, predator abundance is 10%, and the initial female number is 19.

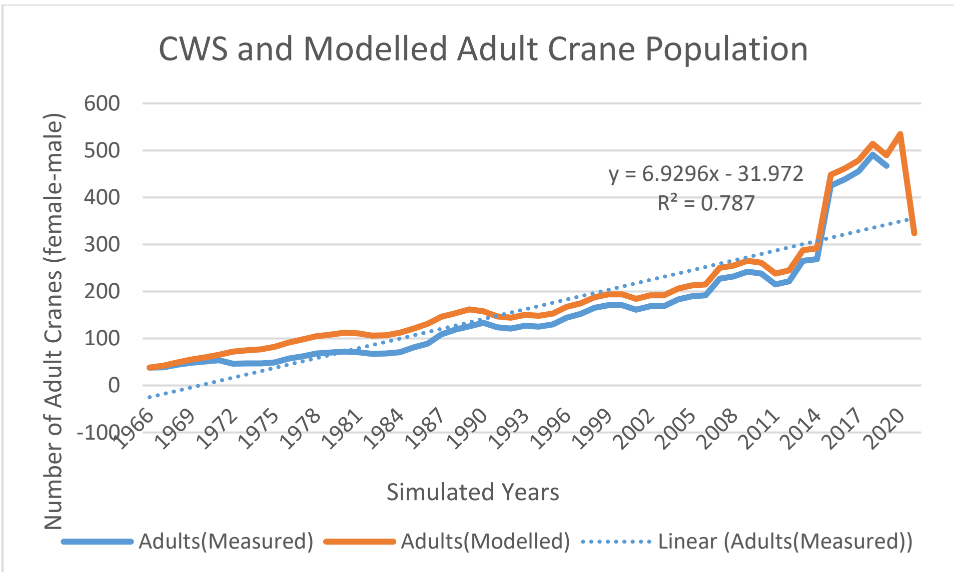

Figure 24 Comparison of modelled and CWS population data for adult cranes

5.1.2.1 Sensitivity Analysis

Sensitivity analysis (SA) is the prevailing technique employed to assess the calibration of a model`s parameter values. By employing this method, a measurable indicator is generated to determine the impact of minor or major changes in parameter values on the modelling outcome (Crooks et al., 2018).

In NetLogo, BehaviorSpace provides an easy-to-use tool for simulating the effect of different parameter values on model outcomes. BehaviorSpace runs a model many times, systematically varying the model's settings and recording the results of each model run. The toolset enables the setting of parameter values to specific ranges and increments, the execution of repeated runs, and specification of the outcome. The model has 12 sliders (parameters) that have different ranges on each of them influencing the population; meaning that hundreds of possibilities are available for population. When BehaviorSpace is launched, all the sliders and default values for them are seen in the variable section. Figure 25 shows an example of how to set up a BehaviorSpace for understanding how the model is sensitive to, in this case, a growth rate increase of 20%, while keeping other parameters constant over time to calculate adult crane numbers for female and male, which is also known as one factor at a time.

To simplify the calibration process, several parameters are combined based on their relative proximity in nature. For instance, it is assumed that environmental factors temperature and precipitation that are directly and importantly affected by climate change rate are considered together, while biotic factors such as fertility rate, energy gaining from the eating, and energy lose when moved or give birth are collectively evaluated for sensitivity analysis. Finally, the growth rate and female population ratio are grouped together. Paired parameter values are increased by 10%, 20%, and 30% simultaneously and respectively, and the simulation is run to analyze how the outcome evolves. The reason why these rates are preferred for SA is that in the initial population, 38 adult cranes are available, and 50% of them, 19, are considered female, which can be real in nature. Nevertheless, if the female ratio in the population is increased by 50%, 27 of the 38 first adult cranes, accounting for 72% of the population, would be classified as female, which deviates from the actual situation and reduces realism.

An example of this is from the growth rate and female ratio increment, where the initial values for these parameters are 1.12 and 19, respectively. These numbers are increased by 20% and changed in the simulation to 1.35 to 23, respectively. Repetition number 10 is constant over the entire sensitivity analysis process; meaning that the simulation will run ten times under new circumstances. For reporter section, since the adult crane population data is reliably available from CWS, comparisons of adult crane numbers have been selected and shown in figure-26.

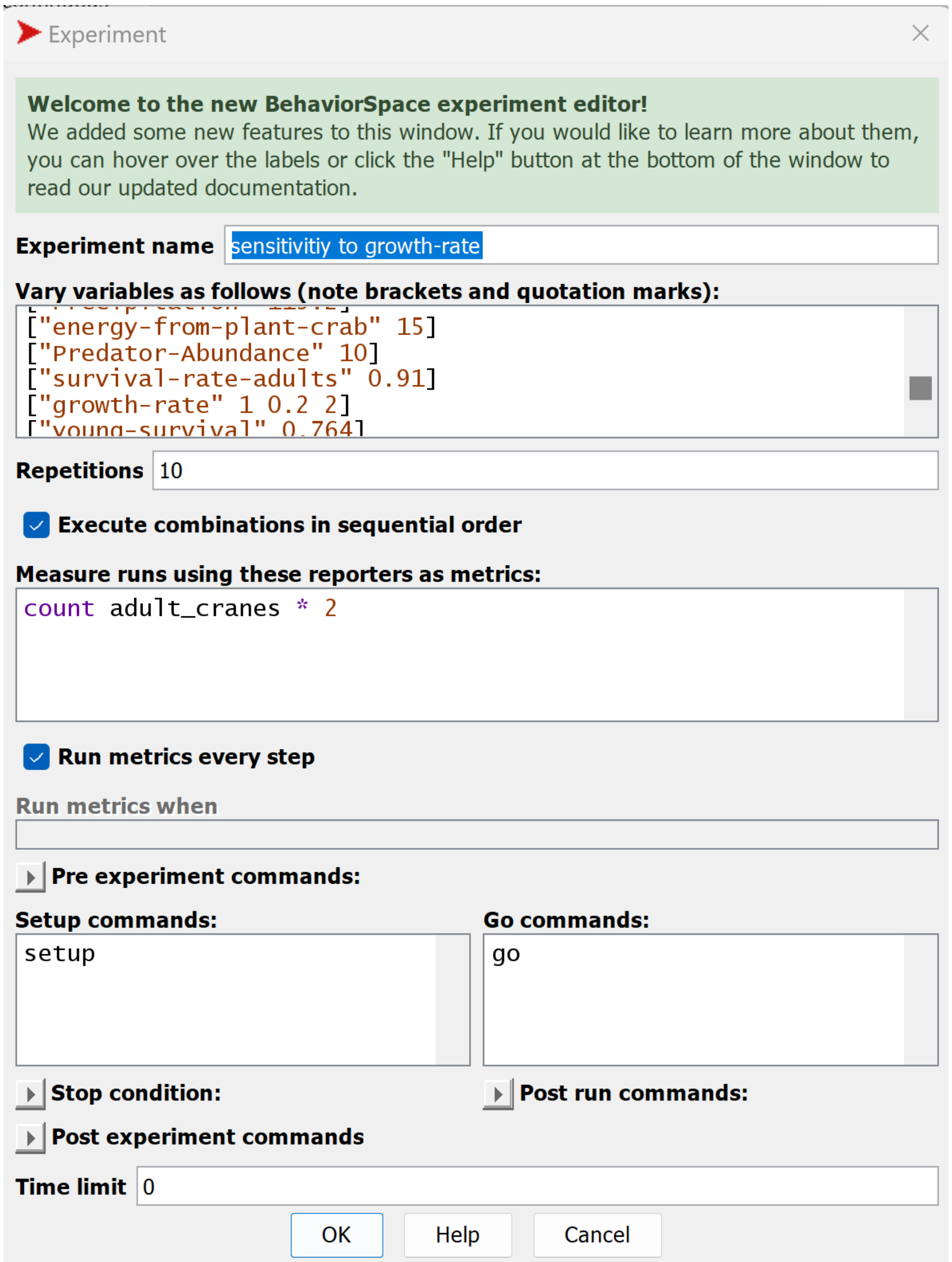

Figure 25 Behavior Space for conducting sensitivity analysis on the model parameters

The omnivorous nature of WCs has proven to be crucial for their energy intake and overall well-being, particularly in habitats like WBNP. The presence of blue crabs in the park has emerged as a significant contributor to the whooping cranes' dietary resources. Blue crabs, being a nutritious food source, play a vital role in ensuring the energy levels and reproductive readiness of the whooping crane population.

The gradual increase in prey availability, specifically ranging from 10% to 30%, has directly impacted the energy reserves of WCs. This heightened availability of prey resources has had a positive correlation with the reproductive success and population growth of WCs, visualized in figure 26. The improved energy intake resulting from a more abundant prey base has supported higher reproductive rates among the crane individuals. This, in turn, has contributed to an increase in the overall population of whooping cranes.

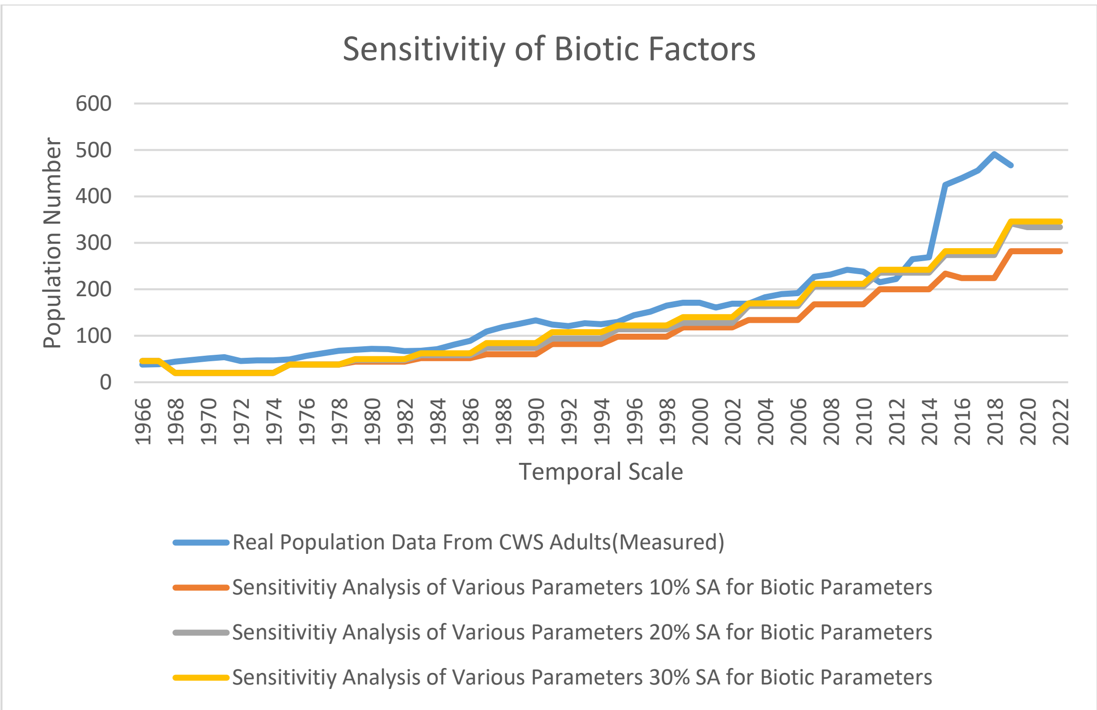

Figure 26 Population Sensitivity of Energy Gain from Prey

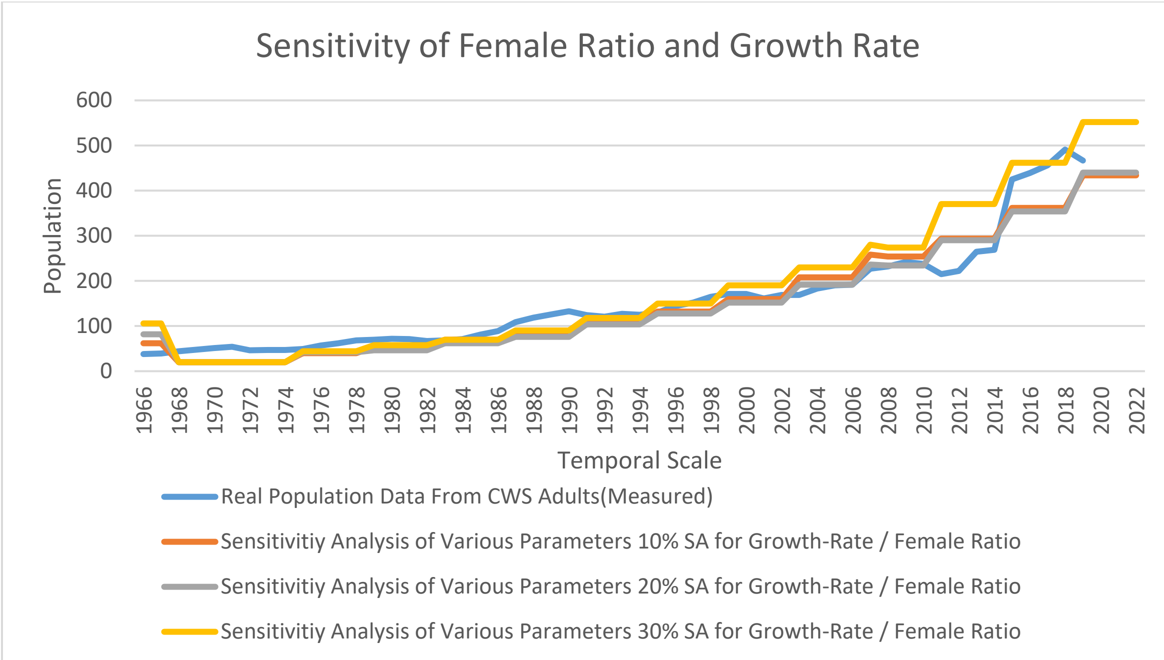

Figure 27 Population Sensitivity of Initial Female Ratio-Growth Rate in the Model

The female ratio is of great importance in population dynamics and recovery attempts for endangered species, both in general and specifically in this simulation, and it is a widely adopted conservation technique to reintroduce females into the wild. Ensuring a balanced gender ratio among released individuals helps establish more sustainable and viable populations. The growth rate of the WCs population is also another a critical aspect of conservation efforts for this endangered species. As of 1966, growth rate of WCs was 1.12 and this value is increased from 10% to %30. The reproductive success of WCs population is closely linked to the quantity of initial breeding females and growth rate. Inadequate female population might result in decreased fertility rates and thus, restricted population expansion that can result in extinction. The simulation has demonstrated population growth by increasing the initial female population and growth rate from 10% to 30% at a steady rate, which is visually represented in figure 27.

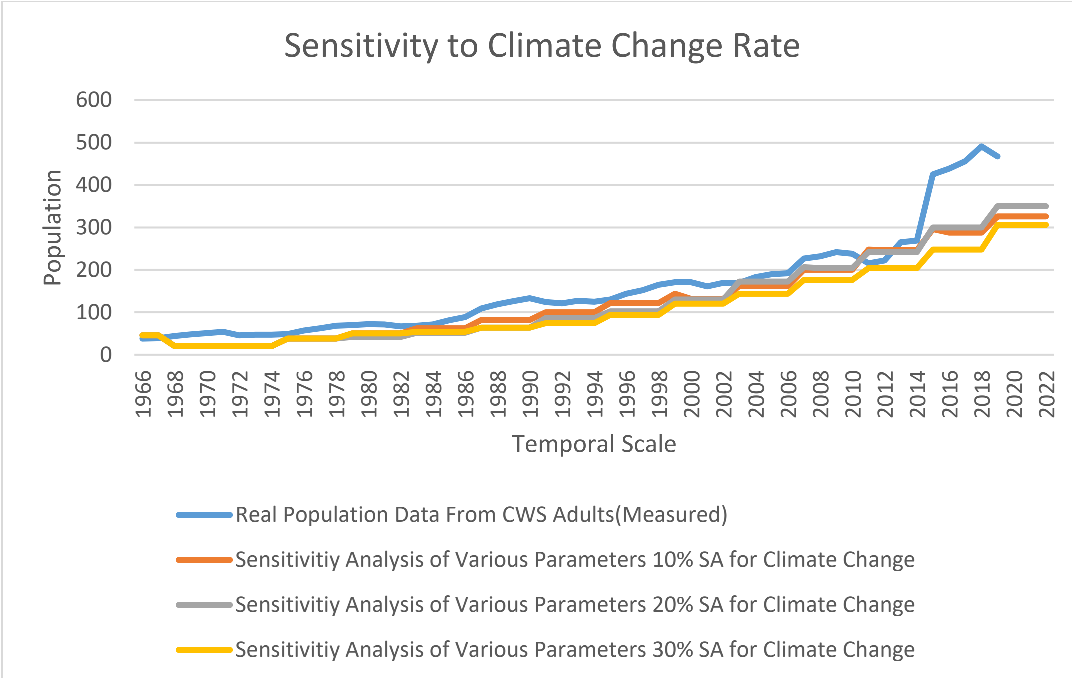

Figure 28 Population Sensitivity to Climate Change

WCs heavily depend on wetlands for breeding season, making them particularly sensitive to alterations in climate conditions. These wetlands serve as crucial breeding grounds where WCs raise their chicks and engage in other essential reproductive behaviors. However, climate change-induced shifts in temperature and precipitation patterns can disrupt the delicate ecological balance of these habitats, thereby impacting WCs population. Even seemingly small changes in climate variables, such as alterations in temperature and precipitation values, can have significant consequences for the crane population. For instance, if the climate change rate increases from 10% to 30%, it can result in substantial modifications to the wetland ecosystems that WCs rely on. Changes in temperature and precipitation patterns may disrupt critical life cycle events, such as nesting and chick-rearing, potentially resulting in a quantifiable decrease in chick survival rates and overall breeding success.

5.1.3 Validation

All models are simplification of reality and validation is a crucial step to understand how well the simulation corresponds to real world. Several approaches are available for validating agent-based models such as face validity, micro-macro validation, empirical validation, and construct validation, among which face validation is chosen for validation process.

Face validation involves reviewing the code based on its apparent logic and structure.

The simulation aims to model the population dynamics of WCs in a hypothetical environment represented in NetLogo. It includes different turtle breeds representing various life stages of cranes, as well as crabs and wolves as key components of the prey-predator ecosystem. The complete code in the appendix section defines several turtle breeds, each with unique characteristics such as age, size, color, and shape. The adult cranes (females only), subadults, juveniles, and chicks have different life stages, and their attributes are adjusted as they get aged. The simulation considers environmental factors such as temperature and precipitation. The update-climate procedure allows these parameters to change over time, providing a dynamic environment for the agents. The reproduce and increment-age procedures model the life cycle of the cranes. Reproduction is based on energy levels and a reproduction rate, while the age of turtles is incremented with 1-year corresponding tick number. The eat-plant-crab procedure models interactions between cranes and crabs. WCs eat crabs for energy, and the presence of wolves adds a predator-prey dynamic, with wolves potentially preying on all other turtles. The summer-survival procedure introduces survival conditions based on factors such as age, energy levels, environmental conditions (temperature, precipitation), and the abundance of predators (wolves). The model is set to run for 55 ticks, with each tick representing 1 year, after which the simulation halts after this duration.

CHAPTER 6: SUMMARY AND FUTURE WORK

6.1 Conclusion

In conclusion, this dissertation has undertaken a comprehensive investigation into the population dynamics of the endangered Whooping Cranes in the breeding grounds of Wood Buffalo National Park, utilizing an innovative agent-based modeling approach. The multifaceted analysis delved into reproductive success, predation dynamics, and the impact of climate variability on the intricate interactions that define the WCs population.

The findings of this study contribute to the field of wildlife conservation and management. ABM has provided a great understanding of the factors influencing the Whooping Crane population, offering a predictive tool for assessing the consequences of various scenarios and interventions. Throughout the simulated 55-year temporal scale, the model captures the life stages of Whooping Cranes, from chicks to adult cranes, considering the crucial roles of blue crabs as a primary food resource and wolves as dominant predators. The study has reflected the impact of climate change, introducing a global variable called climate-change-rate to mimic the real-world challenges faced by this species.

Sensitivity analysis has revealed that the climate change rate parameter emerges as the most sensitive factor influencing the Whooping Crane population dynamics by directly altering the blue crabs and chick survival, followed by growth rate - initial female number, and biotic parameters due to the energy reserves gained from the prey abundance. The rate at which climate varies, including temperature and precipitation, change over time has a profound impact on the overall environmental conditions crucial for sustainable population of WCs.

The implications of climate change on the breeding ground and foraging areas of Whooping Cranes are substantial. As the climate change rate increases, it directly affects the reproductive success, survival rates, and energy balance of the crane population. Shifts in climate conditions can alter the availability of suitable nesting sites, influence the abundance of prey (such as crabs), and introduce new challenges or opportunities for the cranes.

Reproductive dynamics, survival rates, and energy balance within different life stages have been explored, shedding light on the vulnerabilities and resilience of the WC population. The exploration of predation dynamics has revealed the delicate balance between natural predators and the different aged WCs population, suggesting the need for holistic approaches to breeding ground WCs.

The integration of climate variability into the model emphasizes the importance of adapting conservation strategies to the changing environmental conditions influencing the breeding habitat.

In the face of ongoing environmental changes, and the urgent need for conservation, the agent-based modeling approach employed in this study provides a dynamic tool for adaptive management and a foundation for future research in avian ecology and conservation biology.

6.2 Future Directions and Research Limitations

The future of ABM in ecology will depend on how well the modelling methods continue to get better and how much more data is needed to set up ABMs.

The below categorized considerations have been found useful for future researchers to be cared in the field.

<u>Animal-Human Interactions;</u> Human population is increasing, and, therefore, a promising area of research might include the examination of how human activities, such as disturbance from recreation or changes in land use, affect crane populations.

Animal-Plant Interactions: Considering WCs are omnivorous, this ABM can be employed to study mutualistic interactions between plants and animals (e.g., pollination, seed dispersal) and how disruptions in these interactions affect both plants and WCs.

Animal-Animal Interactions: To have a better understanding of the population's vulnerability, the modeller can take into account several potential scenarios, such as the spread of a disease. Since it is likely to encounter such a situation in the actual world, the susceptible-infected-recovered (SIR) model can play an important role in the process of understanding the reproduction rate of cranes in their breeding ground.

Taking Care of Climate Change; Another focus of future research can be on modelling the specific effects of a changing climate, taking into account the future predictions of the IPCC, on specific population members of WCs, such as chick survival, which has a central influence on reproduction, and identifying adaptive measures as the threat it poses grows every day.

Incorporation of Experts: The integration of experts from the CWS staff into the model has the potential to significantly improve the model's quality and credibility. Experts can bring domain-specific knowledge in wildlife and conservation that may not be readily available in standard data sources.

Integration with Additional Modelling Methods; The dynamics of the WCs population can be better understood by combining ABM with other modelling methods (hybrid modelling) like population viability analysis (PVA) and landscape modelling, but this time considering migration routine, and wintering ground activities and, importantly, incorporating the uncertainty into model is another thing to be considered for the future research.

Fuzzy Cognitive Maps (FCM) approach can provide rules of thumbs for individual. They are also being performed in evolving prey-predator systems.

In order to provide accurate projections about the WCs population's trajectory in the future, the modelling procedure may incorporate Monte Carlo simulations. Monte Carlo simulations involve running multiple random trials to model the probability distribution of possible outcomes. Additionally, novel approaches such as the Individual-Based Neural-Network Genetic Algorithm (ING) may be applied to enhance agents' decision-making comprehension. ING techniques are adaptable methods that apply the principles of neurobiology and natural selection to address optimization issues, leading to individuals making adaptive judgments as opposed to the set rules that dictate how an organism makes decisions (DeAngelis & Diaz, 2019).

Technologies and Data Sources in Development; Satellite and remote sensing developments can provide new avenues for more accurate data collecting and as a result, more reliable model improvement. For instance, given that WBNP is Canada's largest national park, and that climate data is derived from the Birch Mountain Lo weather station, which is approximately 12 km away from the study area, remote sensing-based climate data may be more accurate than the data gathered from the ground station.

ABM toolkits like NetLogo and Ecobeaker are being advanced in terms of model implementation. The abilities to develop complicated software will increase the model`s success in acquiring complexities of the world.

Improvements in GPS telemetry (and satellite telemetry in general) devices can make it possible to remotely watch a crane's movement, physiological state, and behaviour over long periods of time with relatively fine temporal resolutions. This is especially helpful when counting how hard it could be for field ecologists to study and watch animals in the wild during their wintering or nesting grounds. Basic movement parameters, such as dispersal from the nesting area, can be found in a time series of relocation data from GPS. Considering these, the factors that control how agents move inside an ABM can be defined more accurate.

An artificial neural network (ANN) might be benefitted to represent the decision-making of agents, mostly in movement in space for optimization of individual survival. A *trained* ANN can be applied to input data, spanning the species` survival, growth, life history, to determine the decisions and behaviours that satisfy the specific fitness measure because of the similarity between the movements of real-world individuals that are driven by neuronal responses and modelled ones.

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Appendix

```
turtles-own [energy]
breed [adult_cranes adult_crane]
adult_cranes-own [age]
breed [subadults subadult]
subadults-own [age]
breed [juveniles juvenile]
juveniles-own [ age]
breed [chicks chick]
chicks-own [age]
breed [crabs crab]            ;; WCs are omnivorous and the crabs are the most
important food resource
breed [wolves wolf ]          ;; Wolves are selected as predator since they are
dominant predator in the WBNP
wolves-own [ age ]
                              ;; All models in NetLogo basically have two main
command procedures; 1- to setup and 2- to go

;;to set the model up
to setup
  clear-all
  setup-patches
  setup-turtles
  set temperature 10           ;; This range is obtained from historical climate data
  set precipitation 70        ;; This range is obtained from historical climate data
  set initial-number-of-female-adults 19            ;; 1966 population data from CWS
  set survival-rate-adults 0.91                     ;; The reference is in the
document,  table-4
  set young-survival 0.764                          ;; The reference is in the
document, table- 4
  set predator-abundance 10
  set growth-rate 1.12
  reset-ticks
end

to setup-patches
  ask patches [                                  ;; During simulation time, research
area WBNP is plant-dominant
    set pcolor green
  ]
end

to setup-turtles

  create-adult_cranes initial-number-of-female-adults * growth-rate ^ 2          ;;
adults cranes (female) turtles. in 1966, there were 38 adult cranes, half of whom
were assumed to be female.
  ask adult_cranes [
    move-to one-of patches              ;; randomly distribution
    set color white
    set shape "bird"
    set size 2.5
    set age 5
```

```
  ]

  create-subadults 5 * growth-rate  [                              ;;subadults turtle
    setxy random-xcor random-ycor
    set shape "bird 2"
    set color gray
    set size 1.5
    set age 3]

  create-juveniles 0 * growth-rate [                              ;;juveniles turtle.
at the beginning no juvenile data is available.
    move-to one-of patches
    set shape "bird 3"
    set color gray
    set age 2
    set size 1]

  create-chicks 5 * 0.764 * growth-rate  [                              ;;chicks turtle
    setxy random-xcor random-ycor                         ;; young survival rate is 0.764,
and we have 5 nest at the beginning, therefore initially 3 chicks are created
    set shape "bird side"
    set color brown
    set size 0.5
    set age 1
  ]

  create-crabs 10 [                                      ;;blue crabs (prey) turtles
    setxy random-xcor random-ycor
    set shape "turtle 2"
    set size 1
    set color blue]

  create-wolves predator-abundance [                     ;;wolves (predator) turtles
  setxy random-xcor random-ycor
    set shape "wolf"
    set color black
    set size 1.75
    set age 5
  ]

end

;;to ensure the model run under these procedures;

to go
  if ticks >= 55 [         ;;the temporal scale of the study is 55 years, and 1 tick
represents 1 year. the simulation will halt after 55 times of running.
    stop
  ]                          ;;the condition after 'if' command should be written
within square bracket.
  reproduce
  increment-age
  eat-plant-crab
  summer-survival
  update-climate
```

```
  regrow-grass
  move-cranes
  move-crabs
  move-wolves
  tick                          ;;increase the tick counter by 1 each time
end


to reproduce
  let reproduction-rate 0.245 * growth-rate                         ; Adjust the
reproduction rate based on the growth rate

  ask adult_cranes [
    if energy > birth-energy-born-with and random-float 1.0 < reproduction-rate [
      set energy energy - losen-energy-at-birth
      hatch-chicks 1 [
        set energy birth-energy-born-with
        set size 0.5 * growth-rate                                 ; Adjust the size of
the offspring based on the growth rate
        set shape "bird side"
        set color brown
        set age 1
        right random 180
      ]
    ]
  ]

  ask subadults [
    if energy > birth-energy-born-with and random-float 1.0 < (0.5 * reproduction-
rate) [
      set energy energy - losen-energy-at-birth
      hatch-chicks 1 [
        set energy birth-energy-born-with
        set size 0.5 * growth-rate                                                  ;
Adjust the size of the offspring based on the growth rate
        set shape "bird side"
        set color brown
        set age 1
        right random 180
      ]
    ]
  ]

end

to increment-age

  ask chicks [                   ;;age increment for chicks
     set age age + 1
    if age >= 1 [
      set size 1
    set shape "bird 3"
    set color gray
    set breed juveniles
    ]
```

```
  ]

  ask juveniles [                ;;age increment for juveniles
      set age age + 1
      set size 1.2
    set color brown
    set shape "bird 3"
    if age > 3 [
        set shape "bird 2"
        set color white
        set size 1.5
      set breed subadults
    ]
  ]

  ask subadults [                        ;;age increment for subadults
      set age age + 1
      set size 1.75
    if age > 5 [
        set size 2.5
        set shape "bird"
      set color white
      set breed adult_cranes
    ]
      if age = 25 [
        ask subadults [ die
        ]
    ]
  ]

  ask adult_cranes [                 ;;age increment for adult cranes
    set age age + 1
    set size 2.5
    set shape "bird"
    set color white
    if age = 25 [
      ask adult_cranes [
        die
      ]
    ]
  ]

  tick
end

to summer-survival
  ask turtles [                ;; all turtles, including predator will die when they
run off energy
    if energy <= 0  [
      die
    ]
  ]
                                                              ;;apply rules based on life
stage and environmental factors
    ask adult_cranes [
```

```
      if age >= 25 or survival-rate-adults < 0.91 or any? wolves in-radius 1 [  ;;
risk from predator is less here because when a wolf approaches to an adult crane, the
crane can flee from its predator.
        die
      ]
  ]

  ask subadults [
      if survival-rate-adults < 0.91 or any? wolves in-radius 1 [
        die
      ]
  ]
    ask chicks [
      if precipitation >= 150 or
    temperature <= -13 or temperature >= 40
   or
    young-survival <= 0.763
    or
    predator-abundance >= 15
    or
    any? wolves in-radius 4 [   ;; radius is wider here because chicks and juveniles
are unable to flee from a predator when they are approached
      die
    ]
  ]

  ask juveniles [
      if precipitation >= 200 or temperature <= -13
   or young-survival <= 0.763 or predator-abundance >= 15 or any? wolves in-radius 4
[
      die
    ]
  ]

  ask crabs [
    if temperature <= 3 or temperature >= 30
   or predator-abundance >= 20 or any? wolves in-radius 4 [
      die
    ]
  ]

  tick
end

to update-climate                                        ;; Implement procedures to
update temperature and precipitation based on climate change scenarios

  set temperature (temperature + climate-change-rate * ticks)
  set precipitation (precipitation + climate-change-rate * ticks)

end

to eat-plant-crab

 ask adult_cranes [
```

```
    let prey one-of crabs
  if prey != nobody  [
    ask prey [ die ]
    set energy energy + energy-from-plant-crab
    if pcolor = green [
      set pcolor black
      set energy (energy + energy-from-plant-crab) ;; as the turtle eats grass, it
gets energy from the grass, which we put a slider to show energy from grass get a
space between math symbols
    ]
    ifelse show-energy?
    [set label energy]
    [set label " "]
  ]
  ]

ask chicks [
    let prey one-of crabs
    if prey != nobody  [
      ask prey [ die ]
    ]
      set energy energy + energy-from-plant-crab
    set size size + 0.5
    set shape "bird 3"
    set color brown
    set energy (energy + energy-from-plant-crab)
    set age 1
    set breed juveniles

    if size >= 1.4 [
    set shape "bird 2"
    set color white
    set size 1.5
    set age age + 1

  ]
    if size > 4.9 or age >= 5 [
     set color white
    set shape "bird"
    set size 2.5
    set age age + 1
      set breed adult_cranes
    ]
  ]

ask subadults [
    let prey one-of crabs
  if prey != nobody  [
    ask prey [ die ]
      ]
    set energy energy + energy-from-plant-crab
    if pcolor = green [                                ;; after if condition, what a
turtles`s task is written within square bracket
      set pcolor black
        set energy (energy + energy-from-plant-crab) ;; as the turtle eats grass, it
```

```
gets energy from the grass, which we put a slider to show energy from grass get a
space between math symbols
    ]
    ifelse show-energy?
    [set label energy]
    [set label " "]
  ]

ask juveniles [
    let prey one-of crabs
    if prey != nobody  [
      ask prey [ die ]
    ]
      set energy energy + energy-from-plant-crab
    if pcolor = green [ ;; after if condition, what turtle does is written within
square bracket
      set pcolor black
        set energy (energy + energy-from-plant-crab) ;; as the turtle eats grass, it
gets energy from the grass, which is why a slider is located in interface in order to
show energy from grass get a space between math symbols
    ]
    ifelse show-energy?
    [set label energy]
    [set label " "]
  ]
end

to regrow-grass
  ask patches [
    if random 100 < 10 [set pcolor green]
  ]
end

to move-cranes
  ask adult_cranes [
    right random 360
    forward 1
    set energy energy - 2 ;;when the turtle moves, its energy reduces by 2 unit (to
make the scenario more real )
  ]
end

to move-crabs
  ask crabs [
    right random 360
    forward 1
  ]
end

to move-wolves
  ask wolves [
    right random 360
    forward 1
    let prey one-of (turtles with [breed != wolves])   ; Excluding the wolves
themselves from potential prey
```

```
    if prey != nobody [
      if prey != nobody [
      ask prey [
          die ]
        ]
      ]
    ]
  tick
end
```