Simulating an Ecosystem

Investigating the Impact of Brown Bears' Omnivorous Behavior in a Simulated Ecosystem

Bachelor's thesis in Computer science and engineering

Tell Becker
Amar Bosnjak
Leo Johansson
Linn Lindgren
Elliot Lund

Department of Computer Science and Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
UNIVERSITY OF GOTHENBURG
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Supervisor (Handledare): Pauline Belford, Department of Computer Science and Engineering
Examiners: Patrik Jansson, Department of Computer Science and Engineering
Graded by teacher (Rättande lärare): Palle Dahlstedt, Department of Computer Science and Engineering

Bachelor's Thesis 2026
Department of Computer Science and Engineering
Chalmers University of Technology and University of Gothenburg
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: A screenshot from the simulation.

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Abstract

This bachelor thesis investigates the omnivorous impact of brown bears on ecosystem dynamics through an agent based computer simulation. A digital ecosystem set in a Swedish forest was developed using Unity. Within this ecosystem there are three species: brown bears which are omnivores, wolves which are carnivores and moose which are herbivores. The simulation uses state machines to model each respective animal behavior and interactions, states and attributes were tracked during runtime. Three main scenarios were evaluated: a scenario where no bears were present, a scenario where an average amount of bears were present and then a scenario where many bears were present. Each scenario was run 10 times over 900 seconds with the same amount of resources, moose and wolves. The impact of brown bears during hibernation was also checked by taking the final populations from the average bear scenario and using them as the start values for a winter scenario. Results demonstrated that in the simulation brown bears significantly influence ecosystem dynamics. Increased bear populations correlate to reduced moose and wolf populations, increased moose fleeing behavior and decreased wolf hunting success due to bear interference. Statistical analysis revealed that 53 out of 68 tracked metrics showed significant change between the scenarios, indicating that brown bears worked as a disruptor for both herbivore and carnivore species. These results should however not be taken as predictive due to the fact that the simulation implements simplified behavioral models and limited environmental complexity compared to real ecosystems. The results should therefore be seen as illustrative.

Keywords: Ecosystem simulation, Agent-based modeling, Brown bears, Predator-prey interactions, Behavior dynamics, Swedish forest, Digital ecosystem, Unity, Species competition

Abstrakt

Detta kandidatarbete undersöker den allätande brunbjörnens påverkan på ekosystemdynamik i ett agentbaserat simulerat ekosystem. Simuleringen är implementerad i Unity och modellerar en svensk skog bestående av tre arter: brunbjörn (allätare), varg (köttätare) och älg (växtätare). Simuleringen använder tillståndsmaskiner för att modellera djurens beteenden och interaktioner, där tillstånd och attribut loggas vid körning. Tre huvudsakliga scenarier utvärderades: utan björnar, med genomsnittligt antal björnar samt med en hög björnpopulation. Varje scenario kördes 10 gånger med en simuleringstid på 900 sekunder med identiskt antal av initiala resurser och populationsstorlekar för älg och varg. Brunbjörnars påverkan under ide kontrollerades också genom att ta de slutliga populationerna från det genomsnittliga björnscenariot och använda som startvärden för ett vinterscenario. Resultaten visade att brunbjörnar påverkar ekosystemets dynamik avsevärt. Ökad björnpopulation korrelerar med minskade älg- och vargpopulationer, ökad flyktbenägenhet hos älg samt minskad jaktframgång hos varg orsakad av konkurrens om resurser. Statistisk analys visade att 53 av 68 spårade mätvärden visade signifikanta skillnader mellan scenarierna, vilket indikerar att brunbjörnar fungerar som en störande faktor för både växtätande och köttätande arter. Dessa resultat bör dock inte tas som prediktiva på grund av att simuleringen implementerar förenklade beteendemodeller och har begränsad miljökomplexitet jämfört med verkliga ekosystem. Resultaten bör därför ses som illustrativa.

Nyckelord: Ekosystemsimulering, Agentbaserad modellering, Brunbjörnar, Rovdjurbytesdjursinteraktioner, Beteendedynamik, Svensk skog, Digitalt ekosystem, Unity, Artkonkurrens

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Glossary

Ecological and Biological Terms

Abiotic factors: Non-living physical components in an ecosystem, such as rocks, temperature and weather.

Aseprite: Tool for drawing pixel art, useful for creating UI elements.

Biotic factors: Living organisms, such as animals and plants.

Carnivore: An animal whose primary source of food is other animals.

Equilibrium: A state of balance between conflicting elements.

Habitat: An animal's, plant's or other organism's natural environment.

Figma: Tool for modelling UI, helpful when prototyping.

Herbivore: An animal whose primary source of food is plants.

Kanban Board: A board that shows the state of the product.

MVP: Minimum viable product.

Mutations: Random changes in DNA that may alter traits.

Omnivore: Consumes both animals and plants.

Proestrus: The preparatory phase before the reproductive cycle in female mammals.

Agile Methodology Terms

Product Backlog: A list of tasks that guides the working team what the next step is in their project.

Stakeholder: A stakeholder is a person or a group that can affect or be affected by the projects result.

Simulation Terms

States: Defines which part of an animal's behavior is active.

Traits: Attributes like speed, strength, and vision.

Trophic levels: Position in the food chain.

Metric: A measured value from a simulation run.

FinalPopulation: Number of living animals at the end of the simulation.

Starvation: Number of deaths caused by starvation.

AvgHunger/AvgThirst/AvgStamina: Mean values for these parameters over time.

Predation: Number of species killed by predators.

IdleTime: Time spent inactive/resting.

WanderTime: Time spent wandering/exploring.

SearchFoodTime: Time spent searching for food.

SearchWaterTime: Time spent searching for water.

EatTime: Time spent eating.

DrinkTime: Time spent drinking.

MatingTime: Time spent in mating behavior.

FleeingTime: Time spent fleeing from predators.

DefendTime: Time spent in defending behavior.

HuntingTime: Time spent actively hunting.

Statistical Terms

Significance (Sig): Statistical significance notation used in result tables:
- ns: Not significant ($p \geq 0.05$)
- *: $p < 0.05$
- **: $p < 0.01$
- ***: $p < 0.001$

Behavioral Metrics

Wolf Hunt Attempts: The number of times a wolf has started hunting a prey.

Wolf Hunt Failures: The number of times a wolf has failed to successfully kill its prey (e.g., losing sight or running out of stamina).

Wolf Successful Hunts: The number of times a wolf has successfully killed its prey.

Wolf Success Rate: The success rate of a wolf successfully killing prey.

Bear Interference: The number of times a bear has interfered with a wolf currently hunting.

Bear Hunt Attempts: The number of times a bear has initiated a hunt.

Bear Hunt Failures: The number of times a bear has failed to successfully kill its prey.

Bear Successful Hunts: The number of times a bear has successfully killed its prey.

Bear Success Rate: The success rate of a bear successfully killing prey.

Moose Successful Escapes: The number of times a moose has successfully fled from a predator or omnivore.

Packs Formed: Number of wolf packs formed.

Pack Hunt Attempts: Number of hunting attempts initiated by packs.

Pack Hunt Success: Number of successful pack hunts.

Scenarios

NoBear: Scenario with no bears present.

AverageBear: Scenario with 12 bears present.

ManyBear: Scenario with 25 bears present.

1

Introduction

Ecosystems are made up of living organisms that interact with their environment and each other. Within a specific area, biotic factors interact with surrounding abiotic factors. Understanding these interactions is important when it comes to the study of biodiversity and the impact of resources and environmental changes. Ecosystems are complex and include many factors that must be taken into account, both predictable and unpredictable.

Computer simulations of ecosystems allow them to be studied in a more controlled and repeatable way. By representing organisms and resources in a simplified way, it becomes possible to adjust specific parameters and study certain features of the ecosystems. This enables examination of how these particular features influence the behavior of other organisms.

1.1 Related Work

An earlier bachelor's thesis on ecosystem simulations investigated natural selection in a predator-prey environment. The goal was to observe how genetic changes could be evaluated in offspring and to see if natural selection contributes to keeping an ecosystem stable over time. Their aim was to "study what effect the number of resources, individual characteristics, and behaviors have on the natural selection of simulated animals" [1].

Another thesis aimed to "produce a software tool for simulating ecosystems with the use of Unity" [2]. The simulated ecosystem was designed to hold general concepts such as "carrying capacity, natural selection, and evolution" [2].

Apart from other bachelor's theses, *Equilinox* is a game in which users can create and manage an ecosystem. In *Equilinox*, numerous plants and animals interact through systems in which food chains, reproduction, and environmental conditions occur. Although this game has no research intention, it is rather more of a sandbox game for entertainment [3].

1.2 Background

Previous works mentioned in section 1.1 have been valuable sources of inspiration for this project, as it will also simulate an ecosystem in Unity. While earlier projects focused on natural selection and evolution, this project instead intends to only investigate the interactions between animals and how their own needs and behaviors influence other species.

This project focuses on developing a digital simulation of an ecosystem that is set in a Swedish forest. The simulation includes omnivores—represented by brown bears, herbivores—represented by moose, and carnivores—represented by wolves. These species were selected because they naturally occur in a Swedish forest, as well as having different behaviors and roles within the ecosystem. This distinction also enables comparison and evaluation of their behavioral patterns and interactions. This makes it possible to examine how the brown bear's omnivorous behavior influences the interactions of both carnivores and herbivores.

In this ecosystem simulation, each animal must gather essential resources, such as food and water, and as in real ecosystems, limited resources may lead to competition between species, as well as within species, which then affects their survival and interactions between each other. As the brown bear feeds on both animal- and plant-based resources, they affect resource availability for both moose and wolves, making it interesting to investigate further. Having species with different diets makes it possible to analyze a range of different dynamics such as predation, competition, and resource utilization. This approach is intended to enhance the comprehension of the brown bear's omnivorous influence in the ecosystem.

The brown bear was selected as the omnivorous species in the ecosystem based on findings from the Scandinavian Brown Bear Research Project [4], one of the longest active research programs on brown bears. The project examines how brown bears influence their environment and seeks to clarify their ecological role within the ecosystem. In other words, their overall goal is to gain a deeper understanding of the role of brown bears in the ecosystem, and therefore, knowledge about their behavior and ecology is relevant. A computer simulation would enable modeling of how they interact with other animals and how these interactions would influence their behavior and population.

1.3 Purpose

The overall purpose is to investigate behavioral dynamics in a digital simulated ecosystem that focuses on the impact of the omnivorous actions of brown bears. Specifically, the project evaluates behavioral patterns and interactions among herbivores, carnivores, and omnivores, using repeated simulations to collect data and identify trends and patterns. By modeling complex interactions between the species, it is possible to analyze how the presence of the omnivorous predator influences behavior among other species, resource availability, and ecosystem stability over time.

Additionally, the project aims to evaluate whether Unity can be used to create a viable ecosystem simulation by implementing a complex ecosystem model and observe whether it may exhibit complex dynamics.

1.4 Limitations

There are several limitations imposed on the project because simulating a real-world ecosystem with all of its complexity will not be feasible, as well as hardware constraints and other considerations that have to be taken into account.

1.4.1 Animal Limitations

The simulation only includes one species of omnivore, carnivore, and herbivore in the ecosystem. This approach allowed focus on the complexity of animal behavior instead of the quantity. Omitting other smaller animals obviously has an impact on the ecosystem dynamics between animals and reduces the overall realism of the simulation.

The implemented behavior of the animals is also not realistic due to varying timescales and specific design choices. Examples are that animals do not sleep, they exhibit fast gestation processes but move and attack at real-time speeds, and mutations of attributes are not present at birth, things that allow us to focus on implementing complex behavior but makes the simulation unrealistic.

1.4.2 Terrain Scale Limitations

The scale of the simulated terrain is limited, because it is only a square-shaped cutout of a forest, meaning it has edges where the animals cannot continue walking. In the real world, animals would be able to walk without encountering a physical stop, and they would also be further apart from each other, but for interactions to occur frequently for studying, the terrain is both smaller and limited. Having a smaller world is also a question of performance because a larger world requires better hardware.

1.4.3 Simulation Duration Limitations

As already mentioned in section 1.4.1, the time in the simulation is accelerated compared to the real-world time. However, the times remain proportional to each other. For example, wolves, in reality, have a gestation period of approximately two months, whereas bears can remain in gestation for up to nine months. To preserve this difference within the simulation, wolves were assigned a gestation period of 20 seconds, while bears were assigned a gestation period of 80 seconds.

Using a realistic timescale would render the simulation impractical, as would compressing the time to something like half a second per hour, since simulation behaviors over years would still take far too long and make observation difficult. Instead, by accelerating certain timescales, such as gestation and hunger rates, while keeping other processing running in closer to real time with appropriate proportions maintained between animals, it becomes possible to observe and analyze varied complex species interactions within a reasonable time frame. It should be noted that the results achieved under these conditions do not necessarily reflect what would occur in a real-world ecosystem.

1.4.4 Environmental Limitations

The simulation can only be in either summer or winter, where summer contains parts of spring and autumn, as there is mushroom growth and the animals both mate and give birth. This is due to the complexity and time to implement each of the four separate seasons, as well as summer and winter having the most drastic differences, meaning that summer and winter are the most relevant seasons for analysis.

Environmental modeling is also limited, as there are only two types of weather that can affect the surroundings, which are rainfall and snowfall. Other weather phenomena are not implemented. These limitations reduce realism but will allow for a clearer analysis of the core mechanics of the ecosystem within the set bounds of a certain type of environment.

1.4.5 Performance Limitations

Working with visual simulations requires different objects with different sprites and behaviors to be in the scene at the same time. If used with larger amounts of items, it will inherently lead to worse performance. The limit of the starting amount of every animal is set to 200 and can grow from that point but cannot start with thousands of animals due to performance issues, even if it would be more realistic in some cases to do so. The same starting limitations have also been set on food resources.

1.4.6 Physical Limitations

Regarding hardware limitations, the simulation was only made for PCs and is much smoother to run on desktops compared to laptops. The simulation has been optimized to not need the highest of specifications, but if run for longer durations at higher populations, there will be performance issues.

2

Theory and Background

This chapter presents both biological and technical theory, as they are relevant for understanding and building an ecosystem simulation. The biological theory part presents key ecological concepts and also provides information to understand the environment on which the simulation is based, whereas the technical theory part introduces concepts of modeling approaches.

2.1 Ecosystem

Ecosystems are physical environments containing biotic and abiotic components. Biotic components are living things that interact with each other, such as fauna, organisms, and plants, while abiotic components are non-living factors such as rocks and weather. Every part of an ecosystem is interconnected, as a temperature change can influence vegetation growth, which in turn affects animals depending on it [5].

2.1.1 Carrying Capacity

Abiotic components limit biotic components, resulting in an upper limit to population size called "carrying capacity." If a population exceeds the carrying capacity, it would start to decrease due to lack of resources, whereas a population lower than the carrying capacity has sufficient resources to grow [6, 7].

2.1.2 Equilibrium

When a population reaches and fluctuates around carrying capacity, it has achieved equilibrium, which is a state where population size and system conditions remain stable over time [7]. A predator-prey relationship is an example of this, where changes in one population affect another, creating relatively stable fluctuations in population, although external factors can disrupt the achieved balance.

2.1.3 Predator–Prey Dynamics

Predator-prey dynamics describe interactions between species where predators depend on prey for survival, making their populations interdependent. Changes in prey availability affect predator populations, while increased predators reduce prey populations, creating fluctuations in the animal populations [8].

The predator-prey dynamics can be modeled using the Lotka-Volterra equations. It describes predator-prey population changes over time, based on prey growth and predation rates, which can be seen in Figure 2.1 [9].

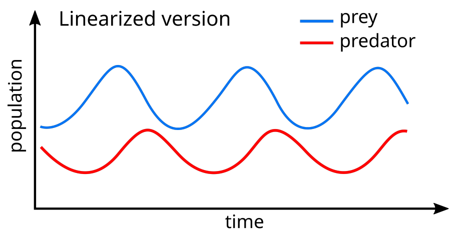


Figure 2.1: Illustration example for Lotka-Volterra model. By AspidistraK - Own work, CC BY-SA 4.0, `https://commons.wikimedia.org/w/index.php?curid=56484640`

The figure 2.1 is a linearized illustration of the Lotka-Volterra model, which presents how predators and prey cycle between behaviors over time. If the prey has an increase in population, predators will also increase in population due to the great availability of food. When the prey population becomes scarcer, the predator population will decrease due to less food availability. When the population of predators is declining, the population of prey will increase.

The Lotka-Volterra equations are not implemented in the ecosystem model, but they are essential to understand the underlying dynamics of predator-prey ecosystems.

2.1.4 Competition

Competition is an ecological interaction where species rely on the same resource, such as food, water, and space, causing them to compete over it. As resources become scarcer, the presence of one species will reduce resource availability for others, influencing general survival and reproduction. Competition may occur within species or between different species, depending on whether resources are shared [10].

2.2 Environment in Sweden

In Sweden, forests cover about 70 percent of the country's land area [11]. Coniferous forests, consisting mainly of spruce, are the most common. Deciduous trees such as aspen and birch may also occur. Central and northern parts of Sweden consist mainly of coniferous forests, while central-southern regions contain both coniferous and mixed forests [12].

Seasons

Sweden has four distinct seasons throughout the country. However, the same season does not necessarily occur at the same time across the country, as Sweden extends 1600 kilometers from north to south. Therefore, snow may still cover the very northern regions while leaves are returning in the south [13]. Although there are four seasons, only two seasons — summer and winter — were implemented in the simulation.

Each season is characterized by features such as weather patterns, plants blooming, and animal activity. Spring is characterized by rising temperatures that melt away snow and trigger flowers to bloom and leaves to return to trees. Stable warm temperatures are a sign of summer, where temperatures support the growth of fruits and berries [14]. Decreasing temperatures is a sign of autumn and is when some vegetation starts dying. Some plants might still be in bloom, and mushrooms may also be visible on the surface [14, 15]. Winter is a season where the temperature persistently reaches zero degrees Celsius. Snowfall occurs in the northern regions of Sweden but may fail to appear in the south [16].

2.3 Animal Biology

The simulation focuses on three species found in Swedish forests: brown bears, wolves, and moose. Understanding their behavior and interactions is crucial for the implementation of complex ecosystem dynamics. While a thorough understanding of the behavior is important, not all aspects of it are implemented in the simulation.

2.3.1 Brown Bears

The brown bear is the largest predator in Sweden, weighing between 60 and 250 kilograms, with males being heavier. They are also very fast, as they can reach speeds of up to 65 to 70 kilometers per hour [17]. Their approximate lifespan is 30 years, but it is not unusual for some to die earlier due to diseases or accidents [18].

The diet of brown bears varies throughout the year. As omnivores, they consume both plant-based food sources and other animals. The diet also varies with seasonal changes; for example, in spring when resources are limited, they eat whatever is available, typically ants and accessible plants [17]. As spring transitions into summer, food sources such as elk or reindeer calves become more important, while in summer and especially autumn, berries become an important intake [17, 18]. The brown bear has to eat a lot before going into hibernation.

During winter, when food sources are scarce, brown bears enter hibernation, a state in which their bodies slow down and they no longer need to eat and drink as they normally would [4]. Brown bears “normally hibernate from the end of October until the end of April” [17], though the duration is not fixed and can vary, as a bear that has cubs might stay a bit longer in the den.

Brown bears have a polygamous mating system where males mate with multiple females and females with multiple males throughout their lives. [4] Around May to July, both genders travel far searching for mates, and after a successful mating, two or three cubs are born in January or February [17]. Cubs typically become independent at one and a half years of age, and females become sexually mature around three to four years old [4, 17].

2.3.2 Wolves

Wolves are large canids with males weighing between 30 and 35 kilograms, whereas females are slightly lighter [19]. Wolves can also live up to 12 years of age, but they usually die younger due to causes such as hunting and traffic [19].

Wolves are carnivores, meaning they feed on other animals, mostly deer, moose, and wild boar. They occasionally hunt smaller prey such as beavers and hares [19]. When hunting, wolves reach speeds of 60 to 70 kilometers per hour for short periods and then maintain speeds between 40 and 45 kilometers per hour for several kilometers [20].

Occasionally, wolves and bears prey on one another, but they are not each other's main prey. Bears and wolves compete over shared prey such as moose calves [21, 22]. Bears may also steal carcasses from wolves [22]. This can influence wolf kill rates by either making wolves hunt new prey or making them defend or reclaim the carcass.

In cases when bears kill wolves, it is often due to the bear perceiving the wolf as a threat to its resources or cubs. Wolves, on the other hand, avoid attacking healthy bears due to risk of injury. Wolves instead target vulnerable individuals such as bear cubs that are less capable of defending themselves, especially when they are alone, separated from the protection of their mother [21].

The wolf mating season generally lasts from late winter to spring, with females entering estrus around March and April. If the mating was successful, gestation lasts about 63 days, and then two to eight pups are normally born around May or June. After five weeks the pups start to eat meat, and by 10 weeks the pups have stopped nursing from their mother. Wolves then become sexually mature around 20 weeks after birth [20].

2.3.3 Moose

The moose is the largest land mammal in Sweden. Cows weigh about 200 to 300 kilograms, whereas bulls weigh about 380 to 800 kilograms [23] and their maximum speed which only lasts for shorter periods is around 60 kilometers per hour [24]. They can also live up to 25 years but often have a shorter lifespan of approximately 10 years due to both hunting and traffic accidents [23, 25].

Moose are herbivores, meaning they feed exclusively on grass, leaves, twigs, and bark. Winter food scarcity results in their diet becoming less nutritious, as it mostly consists of trees and juniper, leading to about a 20 % loss in weight during winter [25].

Reproduction occurs between September and October with around an eight-month gestation period that produces around one or two calves. The calf remains dependent on its mother and stays close for about a year [23, 25].

2.4 Unity Game Engine

The simulation was implemented using Unity, a real-time development platform that supports both 2D and 3D environments. It offers a scalable structure, which makes it ideal for developing complex simulations with interacting entities. It is also a scene-based system, where each of the scenes has a group of objects that represent the components of the simulation [26].

GameObjects and the Component System

The Unity architecture is mostly built around GameObjects and components. GameObjects are objects that act as holders for different types of functionalities [27]. By attaching components to GameObjects, behavior and interactions can be defined to build an ecosystem such as positioning, appearance, and physics. Unity has built-in components that most GameObjects use, for instance, Transform, Renderer, Rigidbody, and Collider, but developers can also create their own components using scripts [28].

Terrain Tool

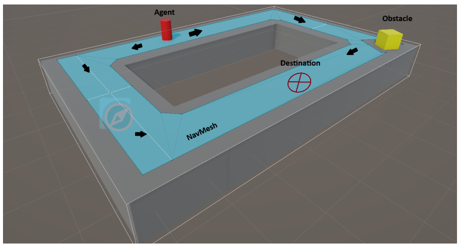
The unity terrain tool allows the creation and modification of landscapes through paint tools. With this feature, it is possible to sculpt the terrain to create small hills, flat areas, and depressions for lake creation. It also allows for the application of visual textures such as grass or sand and the placement of vegetation such as grass and trees. The placement of environment objects, such as trees, contributes to a realistic environment and can also serve a functional purpose, for example, by acting as obstacles for agents [29].

Colliders

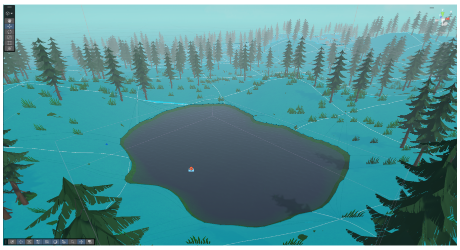
Colliders are components that define a GameObject's boundaries, allowing collision detection between GameObjects. Handling interactions between different entities in the simulation is essential to make agents react to their environment. These colliders can either act as solid objects or as triggers to detect whenever an object enters a defined area [30].

NavMesh Navigation and Agents

The NavMesh is a built-in Unity package that can be added through Unity's package manager, which allows the creation of a walkable surface for agents. The generation of a NavMesh is based on the geometry of the scene and allows for pathfinding. The package provides different types of functionalities that support navigation. A NavMesh Surface is used to generate a walkable area of the environment for the agents, which can be seen in figure 2.2. It can also determine which parts are included or excluded in the NavMesh and how it is generated [31].



(a) NavMesh, agent, and an obstacle



(b) Turquoise walkable area (NavMesh)

Figure 2.2: Visual NavMesh examples

NavMesh Agents are components that allow GameObjects to move around on the NavMesh surface. The agents automatically calculate paths to their destinations, avoiding obstacles and adjusting their movement based on the environment. The algorithm for calculating the shortest path in a NavMesh is the A* algorithm [32]. Unity forms the walkable area using a set of connected polygons; the A* algorithm uses the connected polygon nodes to reach its destination.

Additionally, NavMesh Modifier Volume allows the NavMesh to be altered to make certain areas walkable or non-walkable. For example, a NavMesh Modifier Volume can be set to non-walkable to define a NavMesh boundary around a lake (See Fig. 2.2b).

Creating Custom Scripts

The main programming language in Unity for creating custom scripts is C#, and scripts are components that can be attached to GameObjects [33]. With these scripts, developers can define the behavior of GameObjects within the simulation.

Unity has a built-in class called *MonoBehaviour* that custom scripts inherit [34]. The class allows scripts to interact with the game engine and also provides built-in methods that are automatically called during the execution of the program. The *Start()* method allows initialization logic to be defined at startup, and the *Update()* method continuously updates each frame during runtime.

2.5 Ecosystem Modeling in Unity

2.5.1 State Machines

A state machine, or finite-state machine (FSM), is a technique that allows the modeling of behavioral states for non-player characters, also known as NPCs [35]. With the FSM, it is possible to manage different states as well as handle transitions between a finite amount of available states. Each state has a behavior, and transitions between states in response to certain predefined events or rules. Thus, FSM was implemented to model each animal's behavior in the simulation.

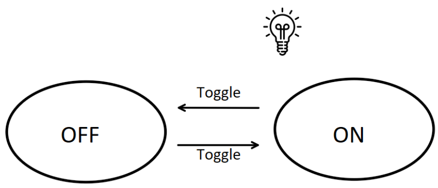


Figure 2.3: FSM example: a light switch that can toggle on and off

An example is shown in figure 2.3, illustrating an FSM that has two states: *On* and *Off*. At any given time, the FSM can be in exactly one of these two states and will transition between the states through an event; in this case, it is a *Toggle*. When the FSM is in the *Off* state and receives a *Toggle* event, it transitions to the *On* state. Similarly, when it is in the *On* state and receives the same input, it transitions back to the *Off* state.

State machines allow for a structured and modular way of developing behaviors, making it easier to design, test, and extend. Each state can be implemented individually, and transitions define how behaviors are connected.

2.5.2 Agent-based Modeling

Agent-based modeling, also known as ABM, is where a system has a collection of autonomous entities, which are also referred to as agents [36]. Agents interact with their environment and with each other. Each of the agents follows a set of rules and makes decisions based on their internal states and external factors (see section 2.5.1). The outcome of an ABM model is complex behaviors and changes in decision-making without these being explicitly programmed.

Instead of representing population dynamics using aggregate mathematical equations, ABM focuses on how individual agents are simulated. This makes it suitable for systems that simulate agents individually, where variation and interactions play an important role in behavioral systems.

2.5.3 Boid Algorithm

Boids is a way to simulate flocking behavior using agents known as boids that follow a set of rules, which is used in the simulation to model the behavior of wolf packs. The three fundamental rules are separation, alignment, and cohesion, but more principles can be introduced to enhance the complexity even further [37, 38, 39].

The separation rule adjusts the boids to avoid colliding into adjacent flock mates, meaning that they steer away from each other if they get too close. The alignment rule ensures that each agent aligns with the average direction of its local flock mates, and the cohesion rule ensures that each boid moves towards the center of mass defined by neighboring flock mates [38, 39].

2.6 Kruskal-Wallis H-test

The Kruskal-Wallis test is a statistical test used to detect significant differences between three or more independent groups. It is a nonparametric test, making it a suitable alternative for data that are not assumed to be normally distributed. The test is based on the rank of the observations. The Kruskal-Wallis test compares the mean ranks in different sample groups and identifies whether there are differences between them [40]. The Kruskal-Wallis test can identify significant differences in behavioral metrics across different scenarios in the simulation in order to validate and support the analysis.

The test produces an H-statistic, which represents the degree of difference in ranks between groups. A higher H-value indicates a stronger difference between groups. The p-value indicates the probability of obtaining the H-value under the assumption that the null hypothesis is true. Therefore, a smaller p-value implies that the observed differences are unlikely to be caused by random variation [40, 41].

The null hypothesis states that all samples come from the same distribution and that there is no significant difference between groups. The alternative hypothesis states that there is a significant difference between at least two of the groups. The significance level represents the acceptable risk of rejecting the null hypothesis when it is actually true. In practice, this is the threshold for determining whether the observed differences are statistically significant or not[42]. If the p-value goes under the significance level, the null hypothesis is rejected. The test determines whether groups differ from each other but does not indicate which groups differ [40].

2.7 Agile Methodology

Agile is an approach within project management that is based on values such as "continuous improvement, flexibility, efficiency, and the ability for teams to adapt quickly to evolving end-user feedback" [43]. To put the agile methodology into practice, Scrum is a well-known framework that makes the approach actionable [43, 44].

Scrum Framework

Working agile is about dividing the development process into iterations, meaning it allows building a project incrementally by completing or recreating smaller sections of the project. Unlike linear approaches that have distinct rigid phases, agile workflow is instead a cyclical process [44, 45]. The short iterations in this cyclical process are called sprints, and a sprint typically contains a set of phases that are repeated each time [45].

The first phase is in the beginning of each sprint where the team discusses and decides what needs to be done within the current sprint. Tasks are often visible in the product backlog [45, 46]. During the sprint, each member of the team works on tasks that were previously selected in the planning phase [45], which means that by adding new functionalities and refining earlier implementations, the product should improve after each completed sprint [47]. As the sprint then concludes, the team presents the product, including its new or updated features, to stakeholders to obtain proper feedback [45]. When the sprint ends, a reflection phase is conducted where the team evaluates successes, identifies areas of improvement, and creates a plan for the next iteration [45]. This helps the team adopt better approaches and discard ineffective practices for further improvement [48].

Kanban Framework

Kanban is another framework to put agile methodology into action. Kanban has a visual workflow and is popular within software development. With the help of a board containing tasks visually, called a kanban board, kanban shows the steps of an iterative process as distinct stages. Whenever a person looks at the board, they are able to see the status of every task, and if a task changes status, its card on the board can be moved to another stage [49].

3

Method

This chapter presents the tools and methodologies used during the design, development, testing, and evaluation of the ecosystem simulation. It also includes information about how the program is structured and the simulation environment, as well as behaviors and interactions of animals.

3.1 Development Tools

Unity and GitHub were selected and used as primary development tools throughout the whole project.

Unity

The primary tool for development was the game engine Unity, which is described in section 2.4. It was chosen because of its support for real-time agent-based modeling, built-in physics motor, animation manager, and environment-building tools. Within Unity, the main programming language that is used is C# due to its simplicity and usability. Overall, Unity is a suitable platform for building a visual ecosystem because it is used for game development and has most necessary functionality and features built into the engine. It also has loads of online resources regarding how to use the engine, helpful in the development process.

Github

The developer platform GitHub was used for code collaboration and version control, as it offers a shared hub with multiple tools [50, 51]. A shared repository stored the development project, which made it possible for each member to track active changes to the project as well as work in parallel as different features were progressing in different branches. To keep the development organized, GitHub milestones were used because it made it easier to organize tasks and divide the workload within the group.

3.2 Design Tools

Methods and tools used for prototyping and creating the final design will be described in the sections below, as they have been used mostly at the beginning of the project but also at the end after test sessions where feedback suggested necessary redesigns.

Paper Prototypes

At the initiation phase of the project, paper prototyping and sketches were used to visually set an initial design for the simulation. At this stage, some very basic and necessary functionality was shown, but specific features and details, like font, colors, and most animal interactions, were avoided (see figures in section A.6).

Figma

Figma was used for UI design, as it is a popular tool for developers when designing websites and game UI [52]. It allows for collaboration and has multiple tools available, such as color pickers and auto layout, which is suitable for a responsive design, and interactive features to visually show changes on the screen [53, 54, 55] (See figure in section A.6).

3.3 Workflow

Agile practices, described in section 2.7, were used throughout the development process to support a flexible workflow. The project combined Scrum and Kanban, where tasks were managed on a Kanban board with stages such as "Assignments", "to-do during sprint", "In progress", "To be reviewed", and "Completed". Each week was considered a sprint, in which each team member selected a task from the Kanban board to work on, and by the end of the sprint, most tasks were usually successfully completed.

There were, in total, two meetings each week. The first meeting was dedicated to concluding the previous sprint as well as initiating the upcoming one. Therefore, during this meeting, earlier tasks and overall progress were reviewed, and upcoming tasks were discussed and put in priority order and then distributed in the group. The second meeting conducted later in the sprint was more flexible and provided an opportunity to regroup, address questions that may have arisen, review issues or potential problems, and even assign new tasks if needed.

3.4 Testing

When a new function became complete, its feature branch was merged into a development branch named "Dev". Once sprint implementations were completed and merged into the development branch, the team members tested the new features. Testing the simulation each iteration became a critical part in the progress, as it was decided that new code had to be tested before being merged into the main branch because it is intended to contain the final version of the project.

When the minimal viable product was achieved, more extensive testing could be conducted through external testing. Test participants were asked to run the simulation with different start parameters and then fill in a form to gather user feedback. The form contained questions about UI clarity, existence of bugs, and overall opinions on animal behavior.

The external test sessions were conducted two times in total; the first tested the minimal viable product and the second time a version improved from earlier feedback. The overall goal of the test sessions was to obtain essential information regarding visible bugs and if animal behavior seemed reasonable.

3.5 Assets

All resources used in the project come from the Unity Asset Store, as it contains a variety of assets fit for use within Unity [56]. Assets that have been used during the development of the project;

Lowpoly Environment Assets, **Lowpoly Forest Animal Assets**, **Simple Water Shader Asset**.

3.6 Implementation

The implementation of the simulation is based on three parts. Firstly, there is a setup menu where start parameters for runs can be adjusted. Secondly, the simulation itself where animals interact with each other and resources. Thirdly, a result screen that displays data collected during the simulation run.

3.6.1 Animals

The ecosystem simulation includes three kinds of animals: moose, wolves, and bears. The choice of these animals was because they naturally occur in Swedish forests and represent different types of consumers within an ecosystem. The moose represents herbivores, the wolves carnivores, and the brown bears omnivores. By having the distinction of different consumers, this allows studying interactions between different trophic levels and investigating how consumers affect ecosystem dynamics. In addition, having three different species supports the main objective, which is to study the impact of the omnivorous brown bear on an ecosystem. It becomes possible to observe how feeding behaviors affect predation, competition, and distribution of resources.

Each animal is assigned food sources. Brown bears can eat most foods, including animals, mushrooms, and berries. Moose eat berries, mushrooms, and nutritious trees. Wolves can only prey on other animals. The feeding behavior is determined by a type of decision mechanism that prioritizes food sources based on different parameters, such as availability, distance, and memory.

3.6.2 Behavioral Implementation Using State Machines

Animal behavior is implemented using state machines, explained earlier in section 2.5.1. An animal superclass defines the states, but the individual animal subclasses override with animal-specific behavior for each state, and the respective state triggers (Refer to figures A.1 - A.3 for diagrams).

Animal → State ↓	Moose	Wolf	Bear
Idle	✓	✓	✓
Wander	✓	✓	✓
SearchFood	✓	✓	✓
SearchWater	✓	✓	✓
SearchMate	✓	✓	✓
Eat	✓	✓	✓
Drink	✓	✓	✓
Hunt		✓	✓
Fleeing	✓	✓	✓
Hibernate			✓
Defend	✓	✓	✓

Table 3.1: Animal States

***Idle*:** The animal stands still for two to five seconds to avoid constant wandering before transitioning to any of the available states.

***Wander*:** Animal walks to random point on radius at a randomized range of max ten units from animal; can be interrupted by any higher priority state.

***SearchFood*:** Triggered when the animal is hungry. The animal searches for food using nearby detection or memory.

***SearchWater*:** Triggered when an animal is thirsty. The animal searches for water using nearby detection or memory.

***SearchMate*:** Triggered when an animal is not thirsty, hungry, fertile, pregnant, recently mated, or threatened. The animal searches for suitable mates based on species, age, gender, and reproduction conditions.

***Mating*:** Two animals of the same species reproduce for 1 second; the female enters gestation, and mating cooldowns are applied.

***Eat*:** The animal is actively consuming food for 2 seconds, and the hunger bar fills up given the specific nutrition score the food has.

***Drink*:** The animal is actively drinking water for 2 seconds, and the water bar fills up completely.

***Hunt*:** A predator chases prey until prey escapes, is killed, has its stamina depleted, or is interrupted by another animal.

***Fleeing*:** The animal flees in the opposite direction from the predator, ignoring lower priority needs. An animal can transition into defending itself if it takes damage.

***Hibernate*:** Bears enter hibernation during winter, and resource hunger and thirst depletion get lowered to a tenth.

***Defend*:** The animal attacks the current predator that is hunting it instead of fleeing.

3.6.3 Agent-Based Model Implementation

The ecosystem simulation is implemented using an agent-based model combined with a state machine, where each animal is represented as an autonomous individual agent. This approach allows for investigation and study of behavioral dynamics by examining varying behaviors and individual decision-making among the simulated animals.

As mentioned in the previous section 3.6.2, the behaviors of each agent in the simulation are implemented using state machines. State machines define how an agent reacts at a given moment, while agent-based modeling describes how many agents are interacting with the environment. By combining these two approaches, it can capture both individual decision-making and system dynamics.

3.6.4 Attributes and Traits

Each herbivore, carnivore, and omnivore has attributes that impact their survivability in the ecosystem:

Gender: Animals spawning have a 50% change of being either female or male. Gender has impacts on available partners but also impacts strength, size, speed, and health.

Animal ↓	Female
Strength	80%
Size	80%
Speed	90%
Health	80%

Table 3.2: Female attributes compared to a male

Size: A scaling factor on the animal assets that impacts how large they are. Larger animals have increased strength and health but burn food quicker.

Speed: Attribute that determines how fast an animal is moving. The top speed of each animal in the real world, as described in section 2.3, has been taken into account when deciding their running speeds. An animal that moves faster will burn through more stamina compared to slower animals when running.

Speed → Animal ↓	Base Walking Speed	Base Running Speed
Moose	2.5	Walking Speed * 1.75
Wolf	2.2	Walking Speed * 1.75
Bear	2.5	Walking Speed * 1.75

Table 3.3: Values for base speeds

Strength: Amount of damage an animal does per attack to an animal's health. Affects some of the risk the animal is willing to take.

Strength → Animal ↓	Base Strength Amount ("Attack Damage")
Moose	14.0
Wolf	10.0
Bear	24.0

Table 3.4: Values for base strengths

Health: Amount of damage an animal can take before it dies. The amount of health an animal currently has affects the amount of risk it is willing to take.

Health → Animal ↓	Base Maximum Health Amount
Moose	90.0
Wolf	30.0
Bear	110.0

Table 3.5: Values for base health

Hunger: Indicates how hungry an animal is, starting at 100 and reaching starvation at zero, where it starts taking one tick of damage each second. When hunger goes below a threshold of 65%, it gets hungry. After an animal has been starving and then goes to eat, it will start regenerating 1 health each second if all other needs are met. An animal that is hungrier is willing to take more risk to get food. On certain occasions when bears go below a hunger threshold of 25%, they get more aggressive and might, for example, attack dangerous wolf packs for possible food.

Thirst → Animal ↓	Hunger
Moose	0.6 *units/second*
Wolf	0.8 *units/second*
Bear	0.8 *units/second*

Table 3.6: Values for hunger decrease

Thirst: Indicates how thirsty an animal is, starting at 100 and reaching dehydration at zero, where the animal starts taking one tick of damage per second. If the thirst is below a certain threshold, the animal will be considered thirsty. An animal that is thirstier is willing to take certain risks to get to water.

Thirst → Animal ↓	Thirst
Moose	0.5 *units/second*
Wolf	1.0 *units/second*
Bear	1.0 *units/second*

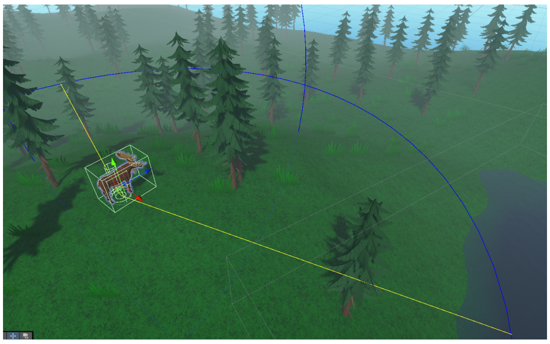
Table 3.7: Values for thirst decrease

Vision and Hearing: Each animal has a unique field of vision, represented by the yellow lines in figure 3.1a, as well as a maximum viewing distance illustrated by the blue curved line in the same figure. The field of vision is implemented in such a way that it corresponds to a section of a circle defined by a specific angle α. If a threat in the form of a predator or a food source is detected, the animal will register it within its memory, which is explained in more detail in Section 3.6.6, and then the animal will avoid the threat by moving in the opposite direction.

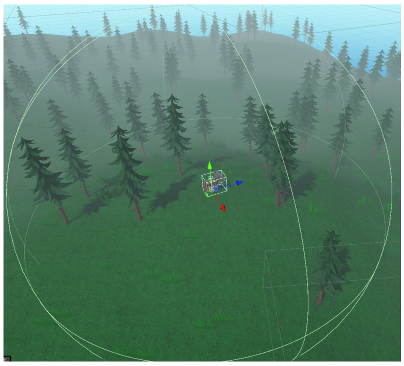
In addition to vision, each animal has a specified hearing radius that allows it to detect nearby animals. In figure 3.1b, the green sphere represents the hearing radius, which is somewhat larger than that of vision. If an animal hears the other animal running towards them, they will identify it as a threat and start fleeing until they can no longer hear the other animal.

Senses → Animal ↓	Base Degree of Vision / Base Vision Distance	Base Hearing Radius
Moose	150°/ 25	30
Wolf	150°/ 25	45
Bear	120°/ 25	40

Table 3.8: Base values for senses



(a) The moose's vision



(b) The moose's hearing

Figure 3.1: Vision and hearing

Stamina: Indicates how much energy an animal has starting at 100. Running depletes stamina, and when it reaches zero, the animal is exhausted and will need to be in the idle state to regain it. Stamina drain depends on species but also depends on the speed or size of the specific animal.

Stamina Usage → Animal ↓	stamina usage for running
Moose	5.0 $units/s$
Wolf	4.0 $units/s$
Bear	8.0 $units/s$

Table 3.9: Values for stamina usage

Gestation: Is a boolean that indicates if a female is pregnant or not. The boolean is active during a gestation period whose length is dependent on species. During this period, the animal loses stamina, hunger, and thirst at an increased rate, as well as becoming somewhat slower in speed.

Gestation → Animal ↓	Gestation Period
Moose	80 seconds
Wolf	20 seconds
Bear	80 seconds

Table 3.10: Values for gestation periods

The starting animals of each run get a multiplier between 0.85 and 1.15 for these attributes, to vary attributes between animals.

3.6.5 Newborn Animals

Newborn animals are born with the averaged stats from both their parents, such as speed, size, sight range, and hearing range, multiplied with a randomized factor between 0.9 and 1.1. The strength, health, and speed of newborn animals are, however, significantly lower than those of adults but scale with age until adulthood. Their needs and mating components are disabled at birth to prevent premature starvation or reproduction. Newborns are compelled to follow their mother until they become adults, or if their mother dies, they are forced into premature adulthood. If the mother enters states such as hunting or fleeing, the cub will, however, speed up to be able to keep up with the mother and stay in the following range. Once the cub reaches adulthood, cub behavior will be removed from the animal, which re-enables its needs and reproduction capabilities.

3.6.6 Memory Mechanism

The implementation of the memory system included both a storage mechanism and a scoring mechanism that used previous knowledge to evaluate the most appropriate decision.

To implement the storage mechanism, the terrain was divided into equal-sized chunks where each animal's coordinates correspond to a specific chunk. Whenever an animal consumes food resources, drinks water, or detects a threat, a point is added to the corresponding chunk in one of four matrices, each for food, water, prey, and threat. The accumulated points within a chunk represent the availability of resources.

To prevent the memory from remaining static, a memory decay mechanism was implemented. Over time, stored information gradually fades, which means that the animal will eventually no longer have memory of danger or resource availability within a chunk. This was primarily implemented to introduce variation in the animal behavior, which also prevents them from appearing too deterministic.

When searching for resources, the animal will check its memory, but to avoid appearing too deterministic and static, there is a 20% probability that the animal will ignore its memory mechanism and instead just continue searching for resources in the nearby area. However, if the memory system is used, it will then compare its current needs with its stored knowledge of food, water locations, and dangerous zones. These parameters will be evaluated in a scoring function that will consider both the animal's needs and the associated threat level before selecting a suitable chunk to travel to. If an animal is desperately hungry, the memory of danger will not matter as much, meaning it is willing to take more risks.

A random parameter is also included in the scoring function to prevent it from appearing too static, though the more desperate an animal is, the less impact this parameter will have. This means that when the animal is not desperate, it is more likely to explore new areas, but if the situation is critical, it will instead target a chunk that it remembers to contain desired resources.

3.6.7 Pack Behavior

Wolves form a pack if two solitary wolves are nearby, with the strongest becoming the leader, and the other one a follower. The follower keeps a certain distance and follows the leader, joining in hunts. If a lone wolf approaches a pack that is not full, it joins. A simple boids algorithm (described earlier in section 2.5.3) ensures that wolves keep distance for complex movement, maintaining alignment, separation, and cohesion within the pack. If a wolf has a hunger level below a 10% threshold, it becomes very hungry and decides to leave the pack to search for food alone. If the leader dies, the next strongest wolf in the pack takes over.

3.7 Environment

The simulation visual environment is based on a combination of coniferous and mixed forests. Since Sweden consists mainly of spruce and pine, with deciduous trees occurring more frequently in the southern regions, this environment was chosen to resemble a reasonable habitat for the included animals, referenced in 2.3. To create a more realistic environment, environmental factors such as precipitation and seasons have been included.

3.7.1 Precipitation

There is a 3% chance of rainfall during summer and snowfall during winter, occurring at each time step in the simulation. In Sweden, snow may occur during winter as described in section 2.2. In the simulation when rain or snow has been activated, the duration is randomized from 40 to 60 seconds.

3.7.2 Seasons

Summer and winter have been implemented into the simulation by toggles in the start menu. Although, as described in section 2.2, in reality Sweden has four seasons in total, but due to the complexity of implementing each season, it was decided to keep two seasons that illustrated the biggest behavior difference in the brown bears as they go into hibernation during winter. Summer includes spring, summer, and autumn altogether, as the animals can mate and give birth during this season.

Summer

This is the simulation's baseline season. Animals behave according to their default behaviors without amplifications, and food sources spawn at a standard rate without any modifiers. Rain makes animals less thirsty over time but mostly affects the growth of mushrooms, as they have a higher probability of reproduction when raining.

Winter

During winter, resource availability and animal behavior are affected due to the colder environment. Bears are also not active as they enter hibernation.

All animals during winter have a 50 % larger hunger decrease rate, take double starvation damage, and avoid remembered endangered areas when searching for food and water. When snow falls, the stamina drains 50 % faster than normal. The wolf hunting cooldown timer is also halved, so wolves can return to hunting faster because they need more food. Additionally, the wolf pack spacing is halved to make them stay closer together for warmth.

In addition to animals, mushrooms and berry bushes are also affected by winter. Mushrooms will not reproduce during winter and cannot spawn at the start of the simulation. Berry bushes also have a 7 times longer growth period compared to during summer.

3.7.3 Plant-based Food

Edible plants represent an important resource in the ecosystem, serving as food for omnivores and herbivores. In order to make a realistic and simplified version of a Swedish forest ecosystem, there are several plant resources implemented.

These resources consist of berry bushes, mushrooms, and tree-related food, such as sticks and bark. To make the ecosystem as realistic as possible, each plant differs in nutrition and availability. For example, berry bushes provide less nutrition, compared to bark that provides more nutrition. Animals eat the plant-based food that is nearest.

3.8 User Interface

This section covers the graphical user interfaces in the simulation, which display ecosystem setup, animal information, and also statistics.

3.8.1 Setup Scene

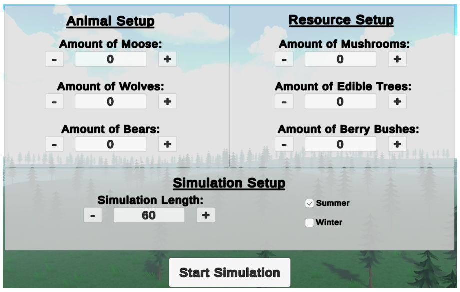


Figure 3.2: Simulation startup menu

See the setup menu in figure 3.2. The simulation setup contains input fields as well as buttons that increment and decrement the value in the field for each respective animal and every food type: mushrooms, berry bushes, and edible trees. Using these fields, the user can specify the number of animals and resources for controlled experimentation.

The setup also contains the same setup for the simulation length so that the user can decide how long to run the simulation before getting all the data visualized. This is to prevent having to manually stop the simulation during runtime, which might lead to variability between runs. Season and precipitation can also be toggled to test animals during different weather conditions.

3.8.2 Animal Information UI

In figure 3.3 below, an animal has an outline when hovering over it to indicate that it can be pressed. When clicking on the animal, it will show an interface at the top of the screen for the specified animal. This interface is shown in figure 3.4. The interface displays, for example, hunger, thirst, stamina, gender, current health, and active state. The male and female interfaces are separated to show that a female can have a pregnancy status while a male cannot. The interface is helpful when observing individual animal behavior.

Figure 3.3: Outline on hover

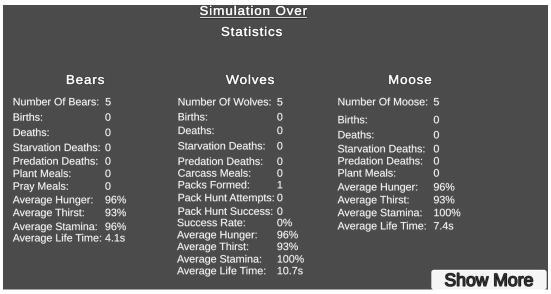
(a) Male UI

(b) Female UI

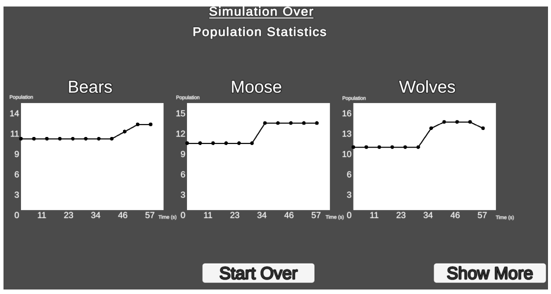
Figure 3.4: Animal Interface showing hunger, thirst, stamina, health, gender, pregnancy, and state.

3.8.3 Statistics Scene

After running the simulation, four types of statistics scenes are accessible. The first scene, figure 3.5a, shows general information, such as the amount of moose at the end of the simulation, specific deaths, and average physiological needs. The second scene, figure 3.5b, shows how the population of the different animals has changed during the simulation runtime. The third scene, figure 3.5c, displays how long the animals have been in each of the respective states. Lastly, the fourth scene, figure 3.5d, a table containing probabilistic statistics, is related to how different animals behaved during the simulation.

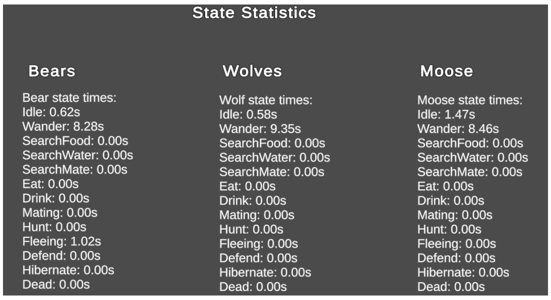


(a) First scene displaying general animal information

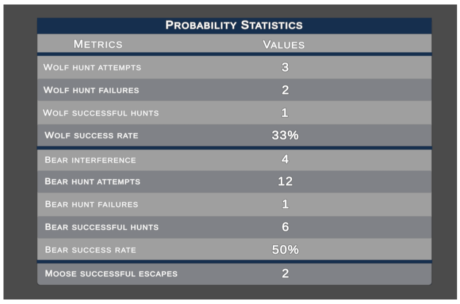


(b) Second scene displaying population changes

Figure 3.5: Statistics scenes



(c) Third scene displaying time in state for animals



(d) The fourth scene displaying behavioral statistics

Figure 3.5: Statistics scenes

3.9 Evaluation

To conduct a proper evaluation of the impact of the omnivorous behavior of brown bears, three simulation scenarios were executed to obtain statistical data for analysis: (I) *NoBear*, (II) *AverageBear*, (III) *ManyBear*.

For each scenario, ten simulations were run with the same starting values for animals and resources for 900 seconds. The simulations are run in a medium world (500x500 meters) for more reasonable animal populations and resources. Every run starts with summer as a season; when the simulation has ended, every value of animal population and resources is taken as input. After getting final populations for animals from the AverageBear bear run, 10 runs with the final population as starting values set during winter are run to see how animals behave and recuperate when bears are hibernating.

3.9.1 Start Values

All values chosen here have been tested through multiple runs to decide which seems to be the most stable. A more realistic population distribution would be more moose, around 200, but when running with a higher moose population, the growth exploded very quickly and became unreasonably high. To be able to see the impact of bears on lower moose populations during the 900-second runs, a lower value of 125 was ultimately chosen. With this population, the moose population sometimes became very high, but other times it decreased. In addition, the number of bears and wolves is chosen in relation to moose because they are much smaller in population than moose in the real world.

Animals → Scenarios ↓	Bears	Moose	Wolves
NoBear	0	125	25
AverageBear	12	125	25
ManyBear	25	125	25

Table 3.11: Animal distribution in scenarios

Resources → Scenarios ↓	Mushrooms	Food Trees	Berry Bushes
All Scenarios	50	100	100

Table 3.12: Resource distribution in scenarios

3.9.2 Data Collection

Data is collected during runtime using dictionaries that track population every five seconds and state durations. When an animal changes state, a timer records the time spent in each state. Deaths are measured by cause, in this case predation or starvation through specific method calls. Food consumption is measured as a total per species, and average animal needs were tracked every five seconds. Other statistics like fleeing, packs formed, successful hunts, and births are calculated per animal, then averaged out of all the animals. When animals die, their stake times and lifespan are saved to ensure that both dead and alive individuals are included in the statistics.

3.10 Play-testing

During the two phases of play-testing, user feedback from external play-testers was gathered.

Alpha Play-testing

During our first round of play tests, the external play testers found the sliders difficult to use (see figure A.6a), and simulation interface text was hard to read (see figure A.6b). Collision issues also caused some animals to stop eating or moving.

In response, the sliders in the setup menu were replaced with input fields featuring minus/plus buttons for easier control (see figure A.7a). The simulation interface (see figure A.7b) was updated with white text on a semi-transparent black background, improving readability.

Regarding collision issues, instead of making animals eat when they are in the range of the collision box, animals use method calls when entering the collision box. This reduced the number of problems caused by unreliable collider interactions and prevented animals from freezing or not eating.

Beta Play-testing

During the second round of play tests, the users found that the animals walk very freely without acting upon nearby threats. For example, a moose that sees a wolf hunting another moose should act upon it and run away in another direction. To prevent this, an avoidance system was implemented to make animals recognize threats and avoid other animals that endanger themselves.

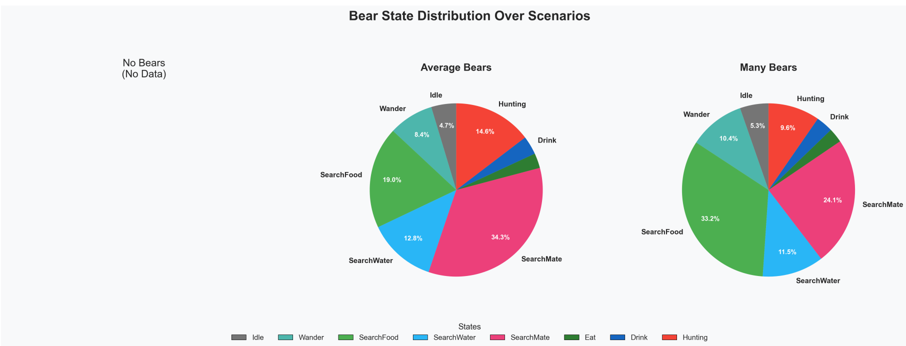
4

Results

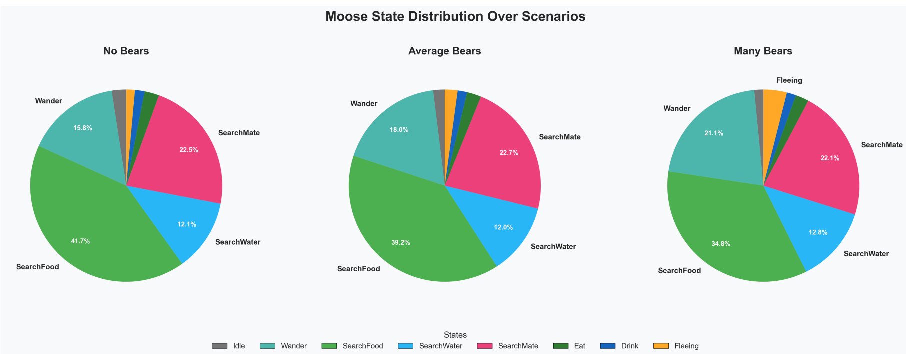
This chapter presents the results collected during simulation runs. The simulation was run in three differing scenarios: *NoBear*, *AverageBear*, and *ManyBear*. Statistical results have been provided to analyze the impact of the omnivorous behavior of brown bears.

4.1 Animal States

Figures 4.1 - 4.2 show the percentage of time each species spent in different behavioral states. These figures show that Wander, SearchFood, and SearchMate were the most common states across all species. As the number of bears increased, both moose and wolves spent less time searching for food and instead spent more time fleeing. The moose fleeing time increased noticeably across the different scenarios ($p<0.001$, Appendix 1, Table A.1). Wolf fleeing also showed a statistically significant increase across scenarios ($p<0.001$, Table A.2). Idle time for both wolves and moose decreased as the presence of bears increased (Appendix 1, Table A.1). The other states remained stable to some extent.



(a) State distribution for bears in all scenarios



(b) State distribution for moose in all scenarios

Figure 4.1: State distribution for bears and moose in all scenarios

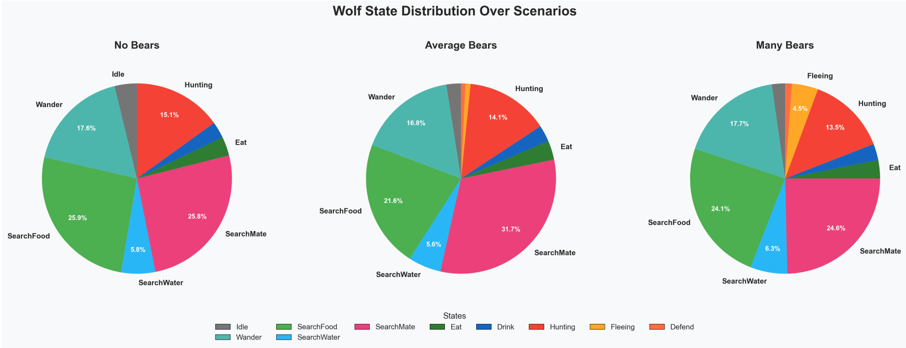
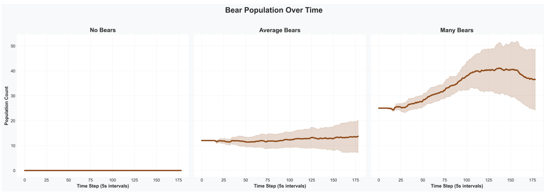


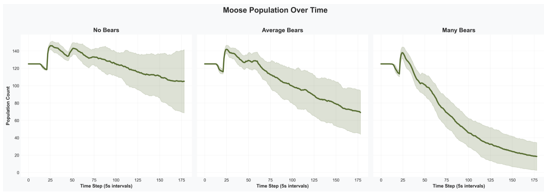
Figure 4.2: State distribution for wolves in all scenarios

4.2 Animal Populations

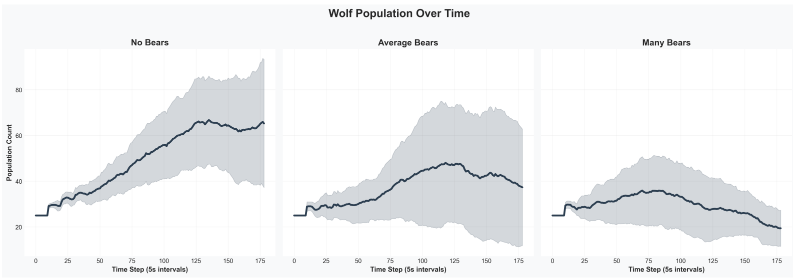
Figure 4.3 shows the average animal population for each animal type in all scenarios. The strong line represents the average, while the shaded area represents the range between the minimum and maximum observed population across runs. Population was measured at five-second intervals, resulting in 180 recorded time points over each 900-second simulation.



(a) Bear population



(b) Moose population



(c) Wolf population

Figure 4.3: Animal population over 900 seconds, in order: *NoBear*, *AverageBear*, *ManyBear*

Figure 4.3b shows that moose populations declined across all scenarios. The decline in moose population was steepest in *ManyBear*. The final moose population showed a statistically significant difference between the scenarios ($p < 0.001$, Appendix 1, Table A.1) with the lowest average observed in *ManyBear*, which was 18.2. However, the wolf populations showed growth in *NoBear*, shown in Figure 4.3c, but growth weakened as the presence of bears increased. Bear population increased until reaching a threshold in *ManyBear*, see figure 4.3a.

4.3 General Statistics

This section presents general attributes and behaviors that were collected, for example, average hunger, death statistics, and feedings. For all graphs in this section, the black error bar that goes through each individual bar represents the 95 percent confidence interval for each measurement.

4.3.1 Death Statistics

The figures below show the average death statistics for bears, wolves, and moose in the three scenarios.

Figure 4.5a shows that the total number of moose deaths remained relatively constant across the different scenarios (*NoBear*: 197,6, *AverageBear*: 206,1, *ManyBear*: 194,2) with no statistically significant difference between scenarios ($p = 0.306$, Appendix 1, Table A.1). In the same way, wolf deaths did not differ significantly across scenarios ($p = 0.132$). However, the causes of death differed substantially across scenarios. Figure 4.5b shows that moose starvation decreased as bear presence increased (*NoBear*: 67,4, *ManyBear*: 22.1,$p = 0.005$). Wolf starvation showed a similar decrease with increasing bear presence (*NoBear*:96.0, *ManyBear*: 50,7, $P = 0.003$). Wolf predation deaths increased with more bears ($p<0.001$,Table 4.1)

Figure 4.5b shows that starvation deaths were most common among wolves in *NoBear*, and they declined as the bears became more common. Bear starvation deaths was, as expected, absent in *NoBear*, but increased Significantly in *ManyBear* ($p < 0.001$, Table A.2)

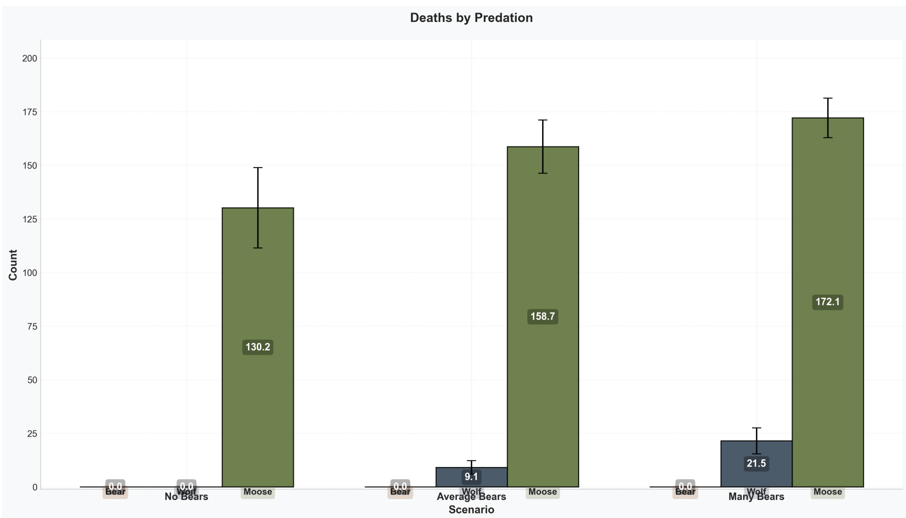
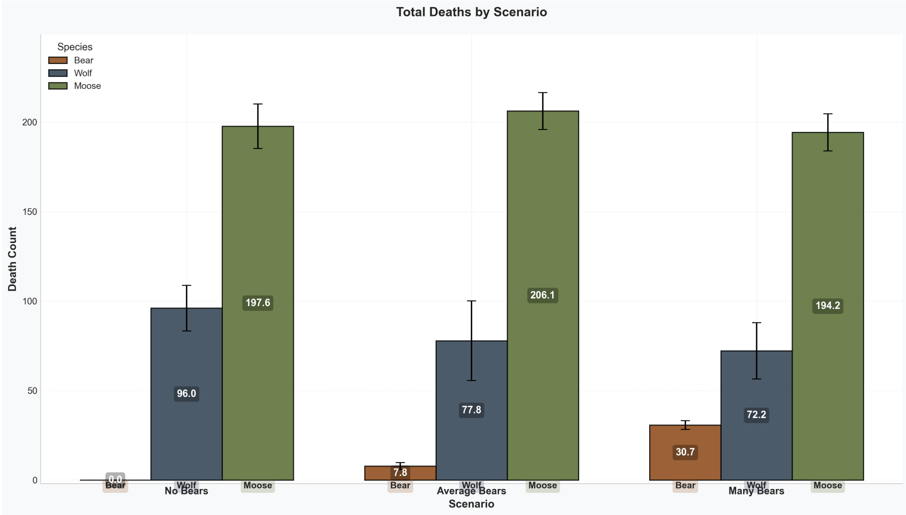
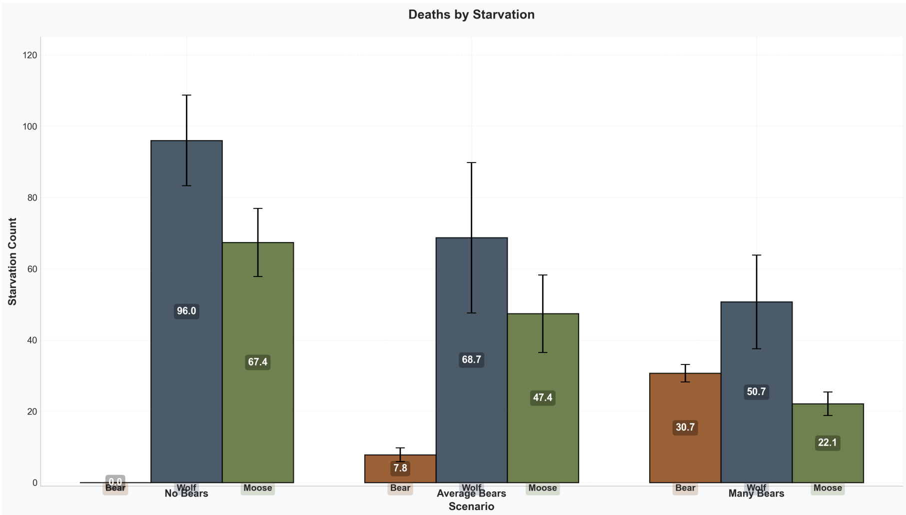


Figure 4.4: Deaths caused by other animal species for each animal in every scenario



(a) Total Deaths of each animal species in every scenario



(b) Deaths due to starvation for each animal in every scenario

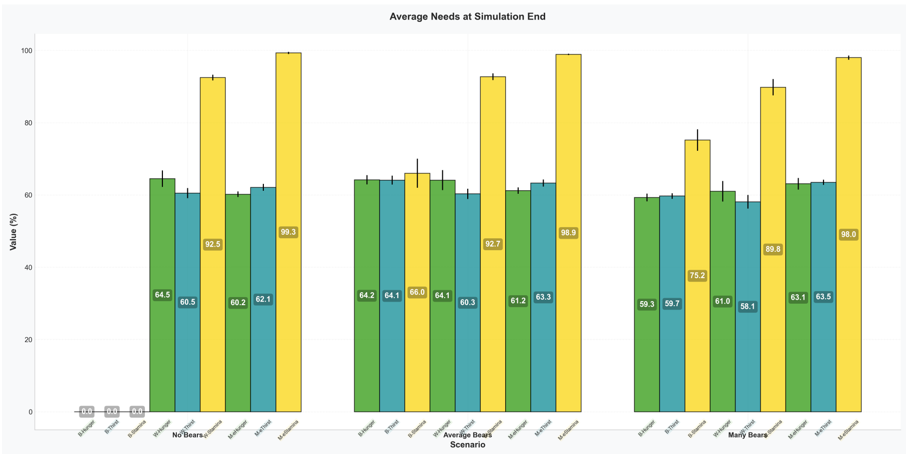
Figure 4.5: Death Statistics

4.3.2 Resource and Hunger Statistics

The figures below show food consumption and the average animal needs statistics for each scenario. Needs were sampled every 5 seconds during each run and then averaged.

Figure 4.6a shows a shift in resource consumption across scenarios. Bear plant consumption increased dramatically with more bear presence. Moose plant consumption decreased as the bear populations increased (*NoBear*: 1015,4, *ManyBear*: 505,8; $p < 0.001$, Table 4.1)

(a) Feeding habits by different animal types for each scenario. Yellow: plant, pink: bear eating carcass, green: moose eating plant, red: wolf eating carcass



(b) Animal average needs during all scenarios for each animal. Hunger: green, Thirst: blue, Yellow: Stamina

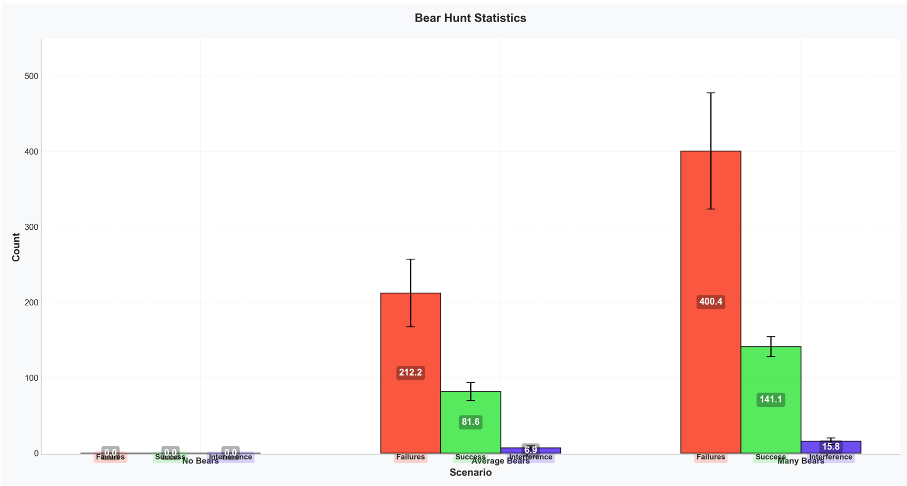
Figure 4.6: Resources and Needs

Figure 4.6b shows that average hunger and thirst levels remained stable across the different scenarios for most of the species. The average moose hunger was significantly higher in *ManyBear* ($p = 0.006$, Appendix 1), although the differences were small (*NoBear*: 60,2, *ManyBear*: 63,1). Average hunger level for wolves did not differ significantly between the scenarios ($p = 0.142$), and the same for average thirst level for wolves and moose ($p > 0.05$). Moose stamina remained high across all scenarios with $p < 0.001$, Appendix 1, but the practical differences were small.

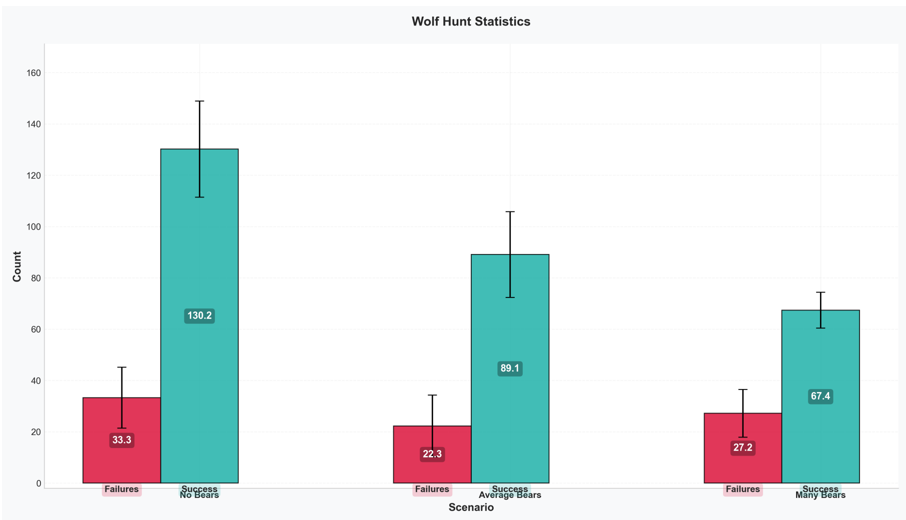
4.3.3 Predator Hunting Performance

The figures below show the hunting behavior of bears and wolves for the different scenarios.

Figure 4.7 shows that predator hunting performance differed between scenarios. Bear hunting statistics increased with more bear presence. In contrast, wolf hunting performance decreased with an increased number of bears. Successful hunts decreased from 130,2 to 67,4 ($p < 0.001$, Appendix 1). Figure 4.8 shows that pack hunt success declined in a similar way, going from 102.1 to 54.0 ($p < 0.001$, Appendix 1). However, total wolf hunting time did not change significantly between scenarios ($p = 0.303$), showing that wolves spent a similar amount of time hunting but were less successful. The number of packs created had a small decrease with more bears (*NoBear*: 12.6, *ManyBear*: 10.3; $p = 0.046$, Appendix 1).



(a) Bear hunting statistics over all scenarios. Interference is when a bear interrupts a wolf's hunt by hunting that wolf



(b) Individual wolf hunting statistics over all scenarios

Figure 4.7: Hunting Statistics for bears and wolves over all scenarios

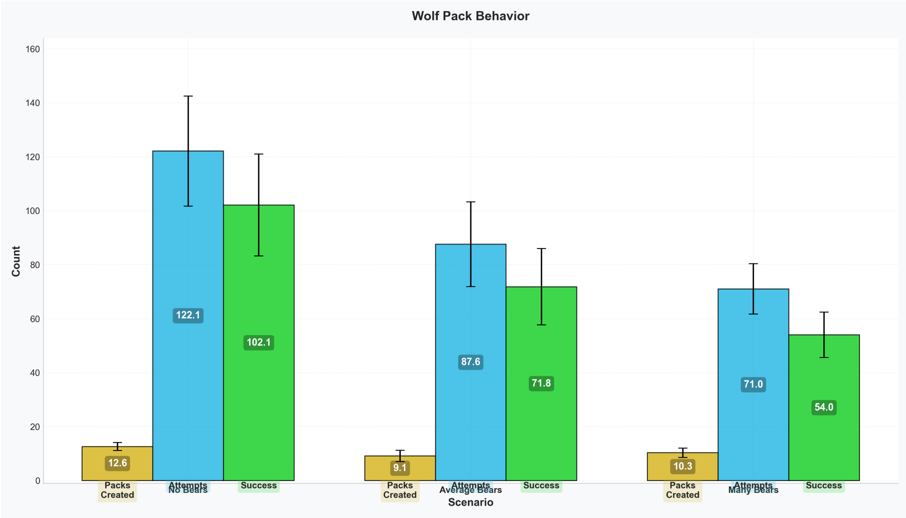


Figure 4.8: Packs formed and pack hunting statistics over all scenarios

4.3.4 Animal Survival Success

The figures below show lifespan for animals, the number of births, and moose escape success during predation attempts for all scenarios.

Graphs 4.9 - 4.10 show differences in survival-related parameters across different scenarios. Moose's successful escapes increased across scenarios, from 192.8 in *NoBear* to 307.3 in *ManyBear*. Moose average lifespan decreased across scenarios (39.2, 36.1, 30.0). Wolf average lifespan showed smaller variation and was not statistically significant ($p = 0.494$). The number of births decreased for both moose and wolves with increasing bear presence.

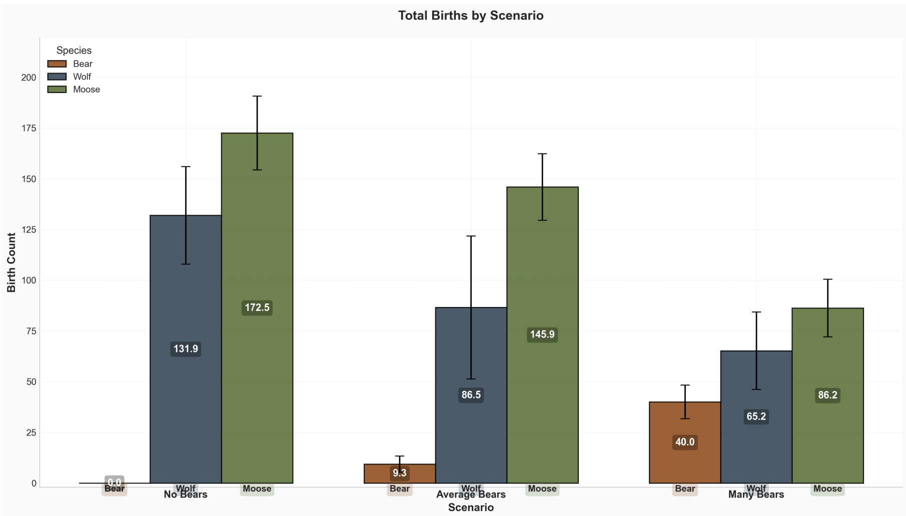
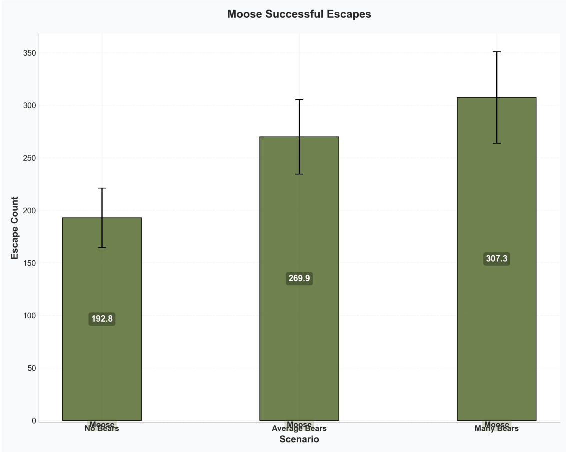
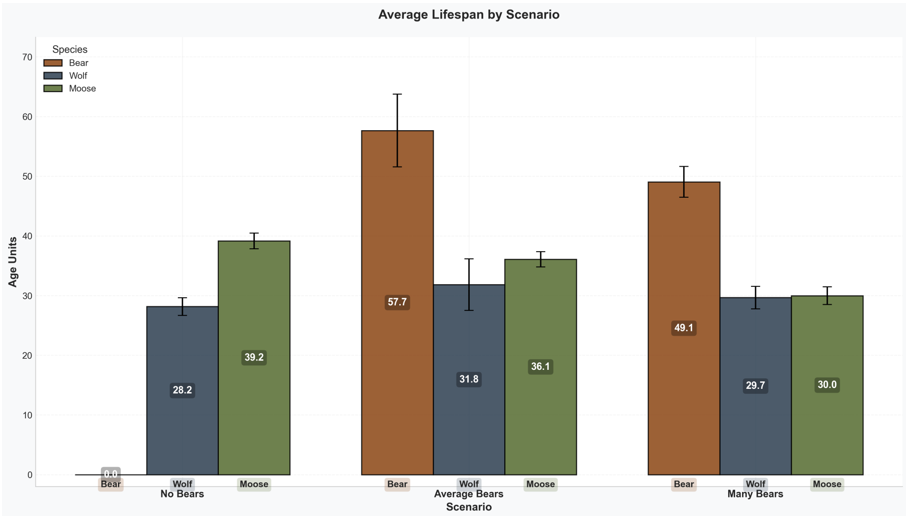


Figure 4.9: Average births for each animal in every scenario



(a) Total moose escape attempts in scenarios



(b) Average lifespan for each animal in every scenario

Figure 4.10: Moose escape and average lifespan

4.4 Statistical Analysis

The Kruskal-Wallis H-test was performed to identify significant differences between scenarios. Out of the 68 analyzed metrics, 53 showed statistical significance at $p < 0.05$.

Table A.2 presents the 10 most significant metrics overall. Bear-related metrics dominated this list, which is expected given that the starting bear population was the manipulated parameter for the experiment with different starting values (*NoBear*: 0, *AverageBear*: 12, *ManyBear*: 25). To understand the indirect effects of the ecosystem, Table 4.1 shows the 10 most significant non-bear metrics.

The complete list of all metrics is provided in Appendix 1, Table A.1, along with a visualization of the results in Figure A.4.

Table 4.1: Top 10 most significant non-bear metrics from Kruskal-Wallis H-test.

Metric	**H-statistic**	**p-value**	**Sig**	**NoBear**	**Avg Bears**	**ManyBear**
WolfFleeingTime	25.2789	< 0.001	***	0.0	2.6	12.0
WolfPredation	23.8873	< 0.001	***	0.0	9.1	21.5
MooseSearchFoodTime	22.8877	< 0.001	***	147.6	126.1	87.6
MooseAvgLifespan	22.3430	< 0.001	***	39.2	36.1	30.0
WolfDefendTime	22.0454	< 0.001	***	0.0	2.2	3.1
MooseEatTime	22.0462	< 0.001	***	8.7	7.7	5.7
MoosePlantMeals	22.0023	< 0.001	***	1015.4	861.7	505.8
MooseStarvation	21.0778	< 0.001	***	67.4	47.4	22.1
MooseIdleTime	20.9987	< 0.001	***	8.6	6.3	3.9
WolfIdleTime	20.6523	< 0.001	***	10.1	7.4	6.0

4.5 Environmental Impact

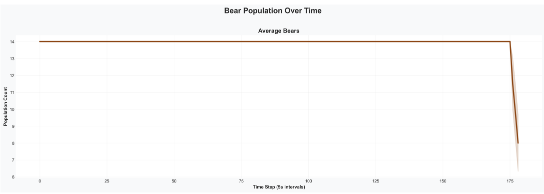
The figures below show the impact of hibernation and environmental factors on animals during winter. The simulation was run with the averaged final populations as the starting population from the *AverageBear*.

Species	Starting Population
Moose	69
Wolves	37
Bears	14

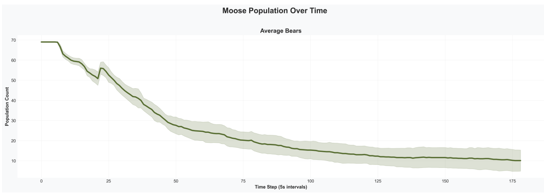
Table 4.2: Starting populations in winter scenario

4.5.1 Animal Population

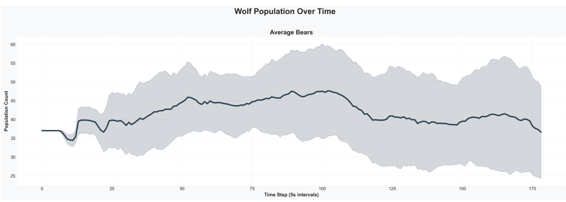
The figures below show average animal populations during the winter scenario.



(a) Bear population averaged



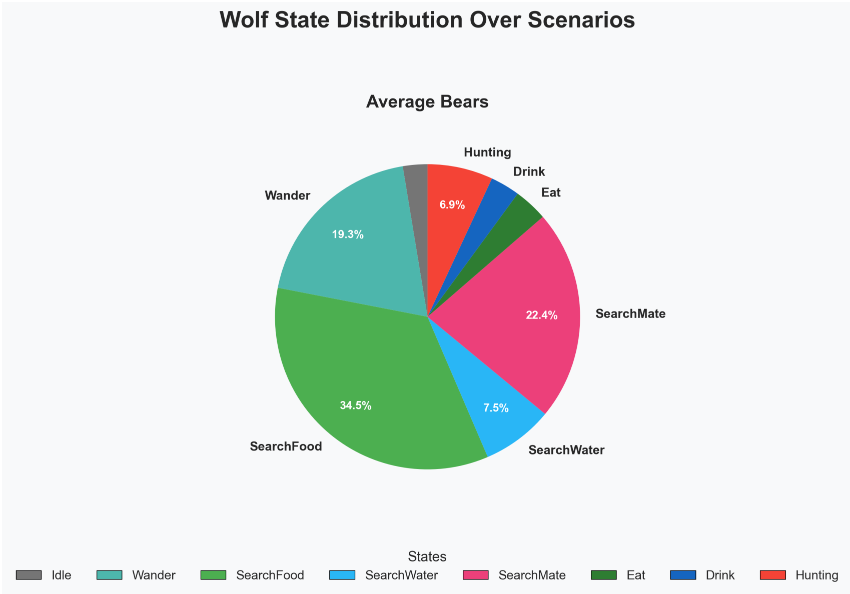
(b) Moose population averaged



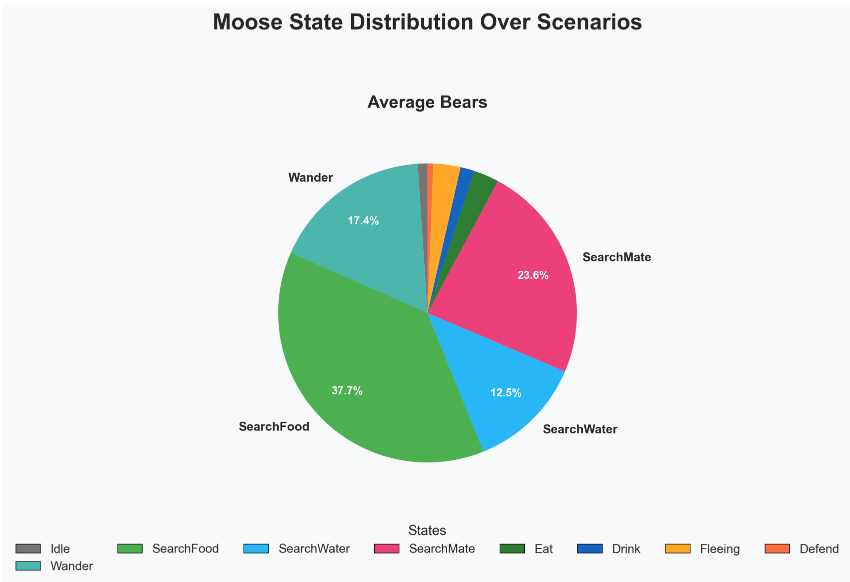
(c) Wolf population averaged

Figure 4.11: Winter impact on animal populations

Observing figure 4.11, during winter, the bear population is stable until the end of winter, where some bears have died of starvation during their hibernation. Moose population consistently regresses during winter while the wolf population increases at the beginning of winter but declines when the moose population gets too low.



(a) Wolf state distribution during winter



(b) Moose state distribution during winter

Figure 4.12: State distribution during winter

Figure 4.12 shows that animal states during winter show that bears are hibernating and that the biggest change from summer is wolves spending more time searching for food: 21.8 –> 34.8 % and less time hunting 14.1 –> 6.9 %.

5

Discussion

This chapter evaluates and discusses the current state of the project, the results, and possible improvements.

5.1 Ecological Impact of Brown Bears

The results indicate that brown bears have a significant impact on ecosystem dynamics. However, this must be interpreted in relation to the limitations discussed later in section 5.3.

5.1.1 Impact on Wolf Populations and Behavior

As shown in 4.3, larger bear populations lead to a reduced increase in the wolf population, likely because bears function as both competitors and occasional predators of wolves.

When bears are absent, wolves do not face competition in hunting moose, which allows population growth. Successful wolf hunts decreased significantly as the presence of bears increased. This decline in hunting success, despite stable hunting time across scenarios, suggests that bears interfere with wolf predation through competition and direct hunting interference, reducing the probability of wolves securing kills. This indicates that wolf hunting behavior remained similar, while hunting success was significantly affected by the presence of bears.

In addition to individual hunting outcomes, pack-level dynamics was also negatively affected by increased bear presence. Both pack hunt attempts and successful pack hunts decreased, while the number of packs formed showed a smaller variation. This suggests that although wolves continued to form packs, bear competition reduced the effectiveness of pack hunting. Together with fewer wolf births, these changes help explain the observed decline in wolf populations across scenarios.

5.1.2 Impact on Moose Survival and Resource Competition

Brown bears influence moose through direct predation and resource competition. Figure 4.1b indicates that, in *ManyBear*, moose spend significantly more time fleeing. The moose population also suffers a steeper decline when bears are present compared to when only wolves are present.

The total deaths of moose remain relatively similar between runs, but bears cause the number of predation deaths in moose to increase and starvation deaths to decrease. Indicating that bears change the cause of death for moose, but not the total mortality.

However, the overall lifespan of moose and their total feeding change as a result of resource competition and predation. In Figure 4.6, it can be seen that moose plant consumption decreases from around 1015 to 506 meals between the *NoBear* and *ManyBear*, indicating that the bears' omnivorous diet creates direct resource competition between the two species.

5.1.3 Impact on Other Bears

In *ManyBear*, it initially shows a steady increase in the number of bears, while the populations of both moose and wolves decline. However, once their populations become scarce, the bear population also starts to decrease. This may be explained by the scarcity of non-plant-based food resources combined with an excessive bear population competing for the remaining vegan food sources. This is likely the cause of the decrease in the bear population, as it causes some individuals to starve, as can be seen in Figure 4.5b.

5.2 Interpretation of Results

Many of the results achieved do not always align well with the expectations of the real-world ecosystem. This section examines whether discrepancies reflect genuine ecosystem properties or are the result of simplified ecosystem design and unrealistic time frames.

5.2.1 Population Decline and Carrying Capacity

The moose population continuously decreases across all three scenarios and during winter, which can be seen in Figure 4.3. Such a steady decline seems unlikely in a realistic ecosystem, but due to the choice of having a lower distribution of moose to avoid the moose population exploding, this result is not completely unexpected. Animal populations are also expected to fluctuate, which cannot be seen in the average moose population but was the case in individual runs.

A part of the decreasing moose population is due to starvation deaths, where a reasonable explanation would be that limited resources cause these deaths. However, this is not the case, as a majority of resources remain unconsumed in large areas of the map that animals rarely visit. Animals clustering around water sources is the leading reason behind this, so a large part of the animals' starvation and not being able to mate is driven by behavioral dispersal limitations and not resource scarcity.

5.2.2 Predator-Prey Balance and Species Strength

Another possible reason behind the declining moose populations is that certain parameter and trait values may have been configured either too high or too low. Bears and wolves seem to be quite dominant, as wolves seem to have a high hunting success rate both individually and in packs, as illustrated in figures 4.7b and 4.8. Furthermore, Figure 4.4 shows that bears never died as a result of attacks by other animals. This may indicate either that wolf packs rarely attempted to hunt bears when desperate or that bears consistently succeeded in defending themselves by eliminating the attackers. In either case, the bears survive and are therefore able to increase in population, along with wolves, whose high hunting success contributes to their own growth. As both species prey on moose and seem to be strong and successful, they cause the moose population to decline. Over time, the reduced moose population can lead to a decrease in food availability for both predators, causing bears and wolves to suffer higher rates of starvation.

Moose might also have been implemented too weakly, since they primarily die from attacks by other animals, not starvation, as seen in Figures 4.4 and 4.5b. In addition, moose appear to experience a disadvantage as they, in comparison, spend the most time searching for food and the least time searching for a mate. This may suggest that moose are forced to devote more time to survival-related behavior, while other species are able to reproduce more often.

5.2.3 Within Species Animal Avoidance

Due to the clustering pattern disclosed in Section 5.2.1 and further discussed in 5.3.2, many animals within the same species appear close to each other, which makes the lack of implementation for interspecies animal avoidance clear. Male moose and bears that protect cubs should avoid other animals of the same species, but this was not implemented. This behavior could have divided groups of animals more naturally between different areas of the map. As a consequence of this, predator-prey dynamics are compressed to certain sections of the map instead of being distributed across varied territories.

5.2.4 Seasonal Survival and Winter Dynamics

Winter simulations (Figure 4.11) reveal the response of different species to food scarcity and lack of competition from bears due to hibernation. The moose population declines before it stabilizes at a lower moose population, while the bear population is completely stable until the end of winter, when some bears have died of starvation, while the wolf population fluctuates from growing at the beginning of winter until later decreasing.

Hibernating for bears was seen as a successful strategy that led the majority of the bear population to survive, but also allowed wolves to hunt without competition and increase their population until the moose population got too low and wolves started dying of starvation. Moose also had a hard time foraging during winter due to food resources becoming scarcer, as mushrooms perish and berries grow more slowly, leading to a steady decline in moose population over time.

Figure 4.12 shows that wolves search for food for much longer periods and spend less time hunting, indicating that there is a shortage of available food. This pattern aligns well with the dynamics of the real ecosystem during winter due to the colder weather impacting both herbivores and carnivores.

5.2.5 Statistical Analysis and Interpretation

Statistical analysis performed using the Kruskal-Wallis H-test led to strong support for the differences between the scenarios that were observed. Of the 68 metrics tested, 53 showed statistically significant differences between scenarios ($p < 0.05$), showing that changes in behavior between scenarios are not random, but influenced by differences in the bear population. This test was chosen because the simulation data consisted of multiple independent groups and a normal distribution could not be assumed due to random parameters and varying population dynamics between runs.

It became clear that the majority of the most significant metrics were directly related to bear behavior, which was expected since the initial bear population was the experimental variable. However, there were several non-bear metrics that showed strong significance, such as *MooseSearchFoodTime*, *MooseStarvation* and *WolfIdleTime*. This indicates that introducing more bears has indirect effects on ecosystem dynamics, affecting both predator and prey dynamics.

At the same time, it is important to understand that the Kruskal-Wallis test only confirms that there are differences between scenarios. The test does not explain why the difference occurred or how realistic the result is. Therefore, it is important to interpret the differences in the correct way, combining statistics with assumptions and the fact that the simulation was a simplified version of an ecosystem.

5.3 Limitations Impact on Result

There have been limitations in design choices and data collection, which have had an impact on the result.

5.3.1 Design Choice Limitations

This subsection presents the design choices made during the development of the project and how they may have affected the results.

Low Moose Starting Population

As stated in Section 3.9.1, the simulation starts with a very low moose population of 125, compared to the predator population, which is 25 wolves and between 12 and 25 bears in scenarios. This choice was made due to higher populations of moose resulting in exponential increases in the moose population numbers, while lower predator populations lead to almost zero total bear and wolf births. This choice was necessary to observe the varied predator behavior and ecosystem dynamics within the set 900-second time frame and to ensure the simulation performance was adequate. However, it also introduces caveats when interpreting the results.

The ecosystem has to be seen as a low-density prey environment, so findings cannot be seen as predictive of most ecosystems with more realistic predator-prey distributions.

Inconsistent Time Frames

The time frames between different behaviors are unrealistic. There are many inconsistencies that create a skewed scaling for behaviors, affecting the simulation in several ways, such as how fast the animals move around the map and how often they display certain behaviors. For example, the gestation period for wolves is 20 seconds in simulation, which was made to correspond to 2 real-world months, while they can also go without food for 20 seconds in simulation, which in itself is not supposed to represent 2 real-world months, but rather a shorter period. This time frame was designed with the intention of making it possible to observe all of the behavior in a shorter time span. However, this design choice severely affects the realism of the simulation, which in turn has a significant effect on the results and the way they should be interpreted.

5.3.2 Behavioral Limitations

This section discusses how specific animal behavior may have influenced the simulation result.

Reproduction

The reproduction system also has an important limitation, in which it favors species with shorter gestation periods. In the simulation, wolves gestate for 20 seconds, while bears and moose gestate for 80 seconds. This is a realistic relation of time between the species, but the implementation allows wolves to produce offspring four times more rapidly when, in reality, most species reproduce approximately once annually, as described in section 2.3. This implementation makes it so that the gestation period time alone is much more important than the number of offspring and their survival rate.

As a result, this leads to increased growth of the wolf population in *NoBear* seen in Figure 4.3c. This may explain why steady population declines were seen instead of predator-prey oscillations, as the reproductive dynamics are unbalanced and favorable towards wolf populations.

Animal Movement

During visual observation of multiple simulation runs, a recurring behavioral pattern was identified. Most of the animals remained close to water sources. As a result, predators and prey frequently occupied the same or neighboring chunks containing water, increasing the likelihood of predation events. Although it is not necessarily unrealistic for animals to gather around water sources, the limited scale of the simulated terrain may have amplified this behavior of predators and preys being in close proximity to each other. The representation of water sources in the simulation is considerably smaller than in the real world, which may be one reason why predators and prey are often concentrated in the same areas. In the real world, water sources typically cover much larger areas, allowing predators and prey to utilize the same water resource while maintaining greater separation.

A possible explanation for why animals remain within the same chunk containing water, rather than exploring new areas or moving farther away from water sources, may be the design of the memory system. The memory scoring function strongly favors chunks that contain both water and food when the animal is hungry and thirsty, which it often is. Additionally, animals can continue to occupy the same chunk as spending more time in an area provides greater opportunities to discover food resources. Since finding food increases the chunk food score, locations that have already been explored tend to become increasingly attractive over time. This creates a greater possibility that the animals will return repeatedly to familiar areas.

Although the memory system includes a 20% probability of exploring new chunks and ignoring its memory, animals may not travel far before using their memory again, which has a high probability of redirecting them back to a familiar area. The memory system can be adjusted by modifying the values and parameters. In this case, it may have been a better option to increase the exploration rate and only narrow it down when the animal is desperately hungry or thirsty.

A consequence of this behavior is that predators can more easily find and hunt moose, as many are gathered around the same water source. That is, there is an increased possibility that predators find prey. During observation, it was also obvious that most resources were completely unconsumed when located in areas further away from water sources. The competition for food resources between moose also increased an unrealistic amount due to the number of moose searching for food within the same areas and not in more distant locations on the map.

5.3.3 Data Collection Limitations

There have been limitations to the amount and type of data collected due to time constraints. The following sections show how additional data could have strengthened the analysis of behavioral dynamics.

Movement Heatmap

Saving animal positions during the simulation at regular time intervals would have allowed for visualization of where animals spend time, directly validating the clustering at water source observation. It would also show the difference in movement patterns between species.

Individual Resource Consumption

Figure 4.6a shows the total consumption but does not show the average food consumed per individual animal. So, only overall feeding habits for populations can be observed, but not how individual feeding habits vary between scenarios.

Extended Temporal Data

Multiple simulations of longer duration would make predator-prey dynamics clearer over time. For example, if populations trend towards equilibrium or die out. The current simulation length of 900 seconds might not capture trends that occur at certain points in animal populations.

5.3.4 Alternative Modeling Framework

Unity has been very effective for visualizing and implementing agent behavior, but it might not be the best tool for large-scale ecosystem simulations. This would include simulations encapsulating several years or even longer and all seasons continuously, rather than just a couple, as it does in this simulation. If studying population dynamics became a larger focus, alternative simulation frameworks that are specialized for large-scale modeling would definitely be better. This is because it would provide better scalability and lead to better precision in the analytics.

5.4 Random Parameters Impact

When starting a simulation, all animals begin with randomized traits within certain ranges that depend on the individual species. Examples of traits include strength, speed, and stamina. Additionally, the gender distribution and initial spawn points were randomized.

This randomization introduced variance between runs. For instance, a simulation where the majority of animals were of the same gender or animals of the same gender spawning near each other would lead to the animals exhibiting different mating patterns and affect the reproduction rate between runs.

The impact on this variance is clear in Figure 4.3, where the population varies a large amount between different runs. Here, animal populations in some runs showed clear growth at the start, while other runs showed a clear decrease in population. This is also clear in Figure 4.9, where total births vary massively for different animals, especially for wolves between runs.

Precipitation is also something that is random. There is a 3% chance of rain, and the rain supports mushroom reproduction, which means that if a simulation had more rainy periods that have a longer duration, there would be a slight increase in available plant-based food. This would benefit the moose and the bear, but the beneficial impact would probably be quite low.

5.5 Further Development

Given more time, several improvements could be made in different areas of the modeling process and data collection, which would strengthen the simulation and analysis.

5.5.1 Amount of Runs and Individual Run Duration

Additional runs would allow for more reliable averages and reduce variance from the random variables discussed above. Extended simulation duration, for example 2000-3000 seconds, would eventually allow for observations of predator-prey oscillations and equilibrium points, if they in fact exist in the simulation.

5.5.2 Terrain Size

A larger map implemented with within-species avoidance would allow for clearer animal territories and decreased clustering. It would also allow for more realistic species populations and animal distribution relative to the size of the ecosystem.

5.5.3 Realistic Reproduction

If correct seasonal changes were implemented, reproduction could be limited to specified seasons only and also allow animals only to mate once a year. This would also require a more precise timeline, which was never really implemented.

5.5.4 Expanded Species Diversity

Expanding the number of species by introducing smaller animals such as rabbits or deer would make the predator-prey dynamics more complex. These species are more plentiful and reproduce at higher rates than moose, and this would increase the variety of predation options for both wolves and bears. This could be incorporated alongside a priority system in which predators would prioritize the hunting of smaller animals before pursuing moose.

5.5.5 Expanding Data Collection

Expanding data collection to encompass everything in section 5.3.3, such as movement heatmap and individual resource consumption, would have led to a stronger analysis of ecosystem dynamics.

5.6 Societal and Ethical Aspects

This project involves the simulation of an ecosystem that does not involve real animals or human participants. Therefore, no direct physical harm will be caused to any living entity during the development and the execution of the simulation.

However, the simulation represents a simplified simulation of a real ecosystem with simplified ecological aspects such as natural selection, competition, and the impact of omnivores. As a result, there is a risk of misinterpreting the findings, and the results get generalized to real-world ecosystems. Therefore, it is important to interpret the result of this study as illustrative rather than predictive.

6

Conclusion

This thesis developed a digital agent-based ecosystem simulation, set in a Swedish forest to investigate the impact of omnivorous brown bears on ecosystem dynamics. The simulation was examined in three scenarios, one without bears, one with an average amount of bears and one with many bears. Each scenario was run 10 times, where each run was 900 seconds long where behavioral patterns and population changes were tracked and observed.

Key findings demonstrate that brown bears significantly disrupt the balance of the digital ecosystem. Increased bear population correlated with reduced moose population and decreased wolf population growth. The bears omnivorous diet lead to competitiveness between species which for example led to interrupted wolf hunts, reduced prey consumption and decreased overall feeding efficiency. Statistical analysis revealed that 53 of 68 metrics showed a significant difference between the scenarios, confirming that in our ecosystem brown bears function as disruptor for both herbivorous and carnivorous species.

The simulation demonstrated that agent-based modeling in Unity was viable for exploration of animal behavioral dynamics. The results should however not be taken as predictive and instead as illustrative. This is because the simulation used simplified models for animal behavior and resources. Simulation timescales varied across different ecosystem processes, unrealistic interactions between animals were present, environmental complexity was limited, and data tracking could have been more extensive.

Future work could fix many of the problems that were present, for example extending data collection by adding a movement heatmap for each animal species, extended simulation duration, and more accurate timescales. To observe how behavior accurately fluctuates over longer periods of time, more complex and realistic behavioral models are needed. Greater animal and resource diversity, as well as longer runs, would also be required.

If simulation were to ever be taken as somewhat predictive, simulation timescales would need to be fully consistent, and a rework of the scope and focus would need to be done. For example, not focusing on longer processes, such as hunger and gestation, but instead on behaviors that can happen over shorter periods of time, such as hunting mechanics and realistic movement patterns.

The project established a foundation for exploring how omnivores, specifically brown bears, can influence ecosystem dynamics in an agent-based simulation. It also demonstrates how simulation tools can be used to investigate interactions between species and generate hypotheses for future research.

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A

Appendix 1

A.1 Github Repo

Link to our Github repository: `https://github.com/DeRo9/Simulating-an-ecosystem---Kandidatarbete-2026`

A.2 State Machine Diagrams

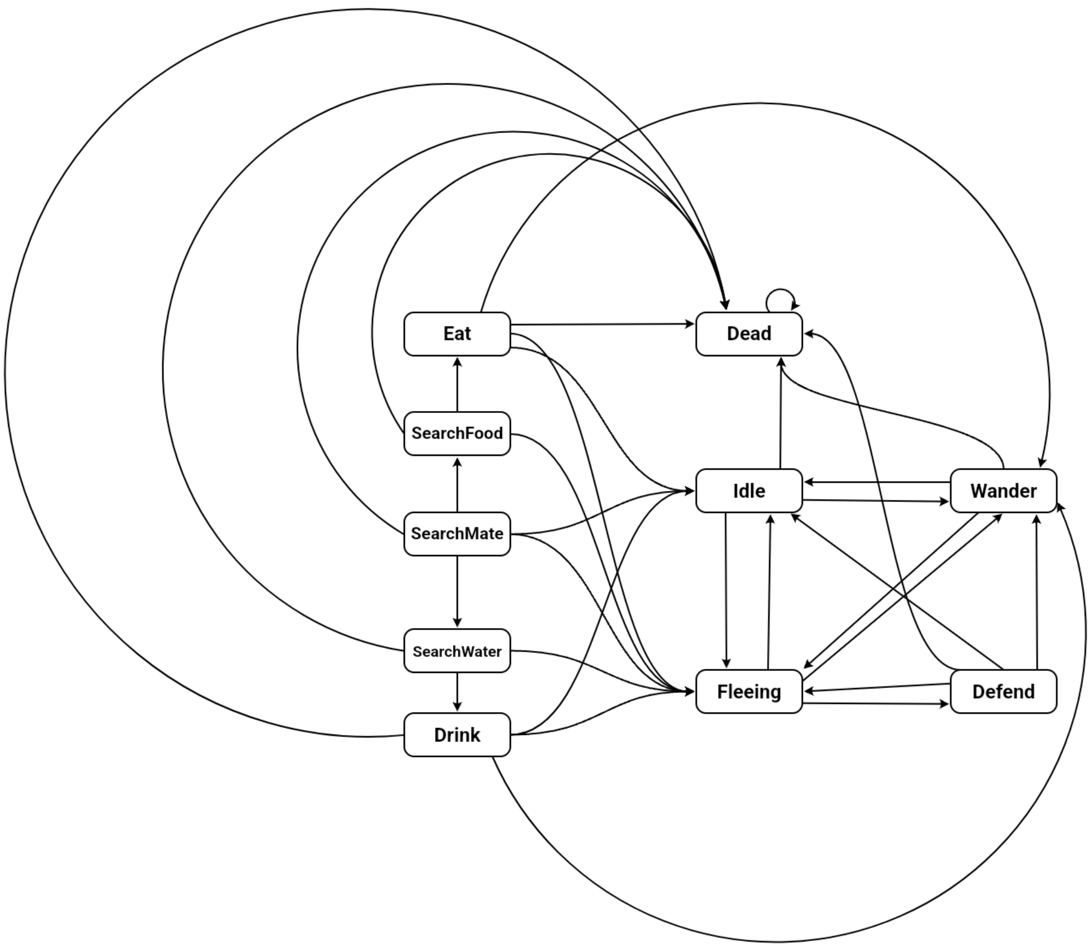


Figure A.1: State Machine: A moose's State Machine Diagram

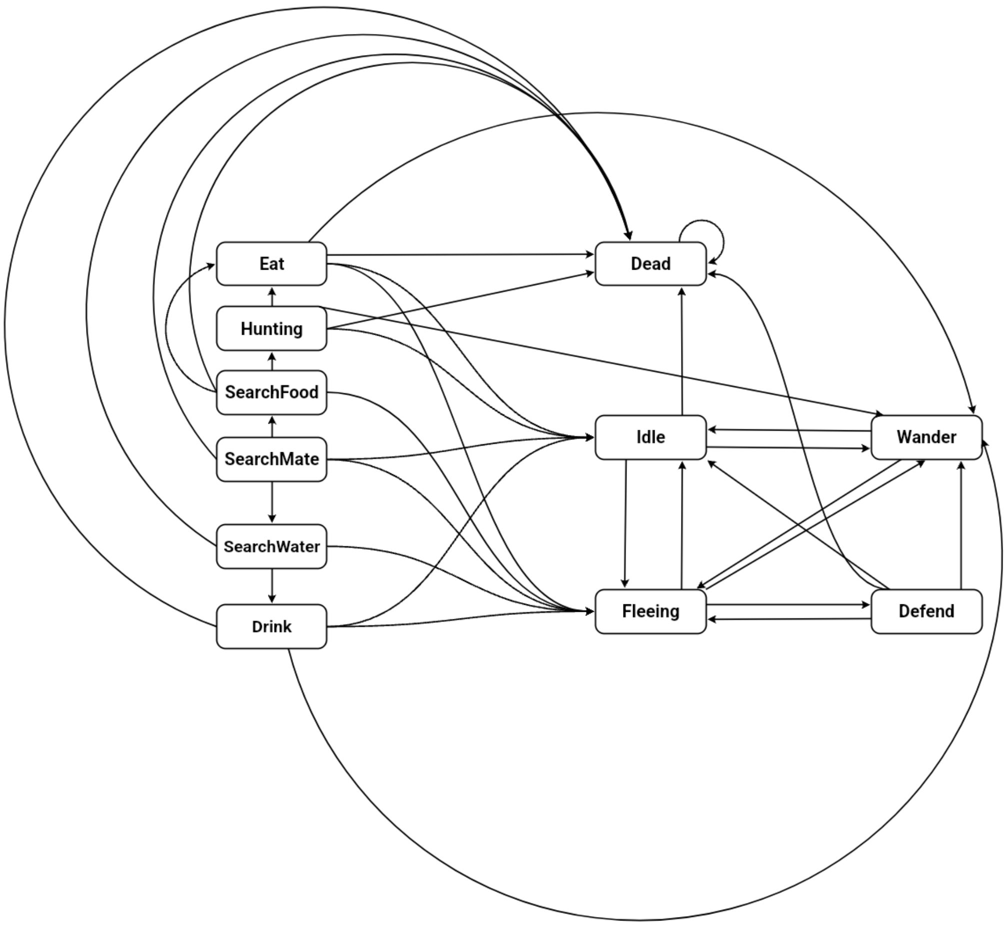


Figure A.2: State Machine: A wolf's State Machine Diagram

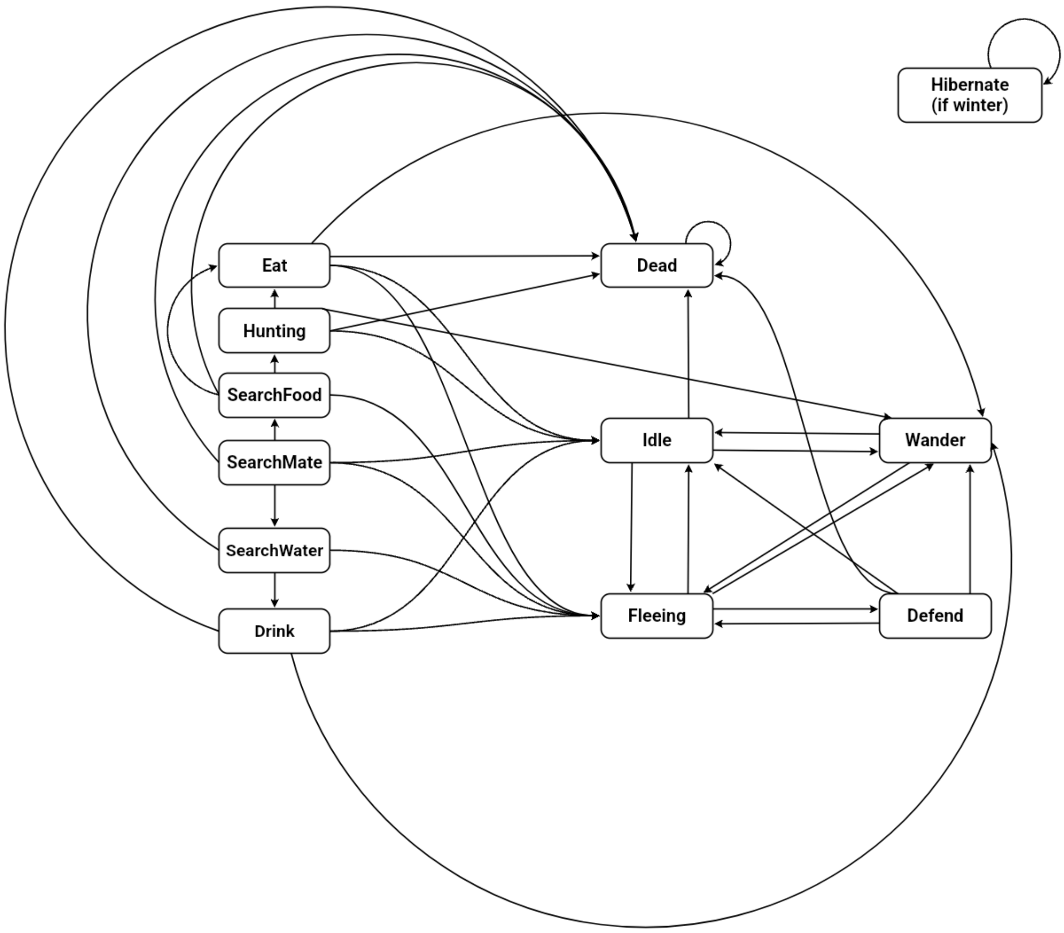


Figure A.3: State Machine: A bear's State Machine Diagram

A.3 Kruskal-Wallis H-test Results

The following table presents the complete results of the Kruskal-Wallis H-test for all 71 metrics. Metrics are ranked by p-value (lowest first). Statistical significance at $\alpha = 0.05$ is indicated with asterisks (*** p < 0.001, ** p < 0.01, * p < 0.05).

Table A.1: Complete Kruskal-Wallis H-test results for all metrics.

Metric	H-stat	p-value	Sig	NoBear	AvgerageBear	ManyBear
BearFinalPopulation	25.9389	< 0.001	***	0.0	13.6	36.6
BearBirths	25.8517	< 0.001	***	0.0	9.3	40.0
BearDeaths	26.8146	< 0.001	***	0.0	7.8	30.7
BearStarvation	26.8146	< 0.001	***	0.0	7.8	30.7
BearCarcassCount	26.0163	< 0.001	***	0.0	84.7	144.5
BearPlantMeals	26.7898	< 0.001	***	0.0	62.9	227.0
BearAvgHunger	26.3131	< 0.001	***	0.0	64.2	59.3
BearHuntAttempts	26.0103	< 0.001	***	0.0	299.4	558.1
BearSuccessfulHunts	26.5307	< 0.001	***	0.0	81.6	141.1
WolfFleeingTime	25.2789	< 0.001	***	0.0	2.6	12.0
BearHuntingTime	25.2789	< 0.001	***	0.0	77.1	43.7
BearAvgThirst	25.7423	< 0.001	***	0.0	64.1	59.7
BearSearchFoodTime	25.0458	< 0.001	***	0.0	100.1	150.4
BearHuntFailures	24.7120	< 0.001	***	0.0	212.2	400.4
BearAvgStamina	24.1190	< 0.001	***	0.0	66.0	75.2
BearDrinkTime	23.7599	< 0.001	***	0.0	18.3	14.3
BearInterference	23.6943	< 0.001	***	0.0	6.9	15.8
WolfPredation	23.8873	< 0.001	***	0.0	9.1	21.5
BearEatTime	23.3741	< 0.001	***	0.0	14.6	12.3
BearSearchWaterTime	23.1893	< 0.001	***	0.0	67.2	52.1
BearAvgLifespan	23.0098	< 0.001	***	0.0	57.7	49.1
MooseSearchFoodTime	22.8877	< 0.001	***	147.6	126.1	87.6
MooseAvgLifespan	22.3430	< 0.001	***	39.2	36.1	30.0
WolfDefendTime	22.0454	< 0.001	***	0.0	2.2	3.1
MooseEatTime	22.0462	< 0.001	***	8.7	7.7	5.7
MoosePlantMeals	22.0023	< 0.001	***	1015.4	861.7	505.8
MooseStarvation	21.0778	< 0.001	***	67.4	47.4	22.1
MooseIdleTime	20.9987	< 0.001	***	8.6	6.3	3.9
WolfIdleTime	20.6523	< 0.001	***	10.1	7.4	6.0
BearMatingTime	20.5419	< 0.001	***	0.0	0.0	0.0
MooseDrinkTime	20.4510	< 0.001	***	5.7	5.1	3.9
BearIdleTime	20.3094	< 0.001	***	0.0	24.6	24.2
BearWanderTime	20.2638	< 0.001	***	0.0	44.2	47.3
MooseBirths	20.2013	< 0.001	***	172.5	145.9	86.2
MooseFinalPopulation	19.6721	< 0.001	***	105.0	68.5	18.2
MooseFleeingTime	18.5777	< 0.001	***	5.1	6.9	9.9

Continued on next page

Table A.1 continued

Metric	H-stat	p-value	Sig	NoBear	AvgerageBear	ManyBear
MooseSearchWaterTime	16.3417	< 0.001	***	42.8	38.8	32.2
WolfSuccessfulHunts	16.2672	< 0.001	***	130.2	89.1	67.4
WolfFinalPopulation	15.0533	< 0.001	***	65.7	36.7	19.2
MooseAvgStamina	14.8507	< 0.001	***	99.3	98.9	98.0
PackHuntSuccess	13.1458	0.0014	**	102.1	71.8	54.0
MooseSuccessfulEscape	12.3202	0.0021	**	192.8	269.9	307.3
WolfStarvation	11.8582	0.0027	**	96.0	68.7	50.7
PackHuntAttempts	11.3773	0.0034	**	122.1	87.6	71.0
WolfCarcassCount	11.0818	0.0039	**	647.0	487.9	350.8
MooseMatingTime	10.8372	0.0044	**	0.0	0.0	0.0
MoosePredation	10.5744	0.0051	**	130.2	158.7	172.1
WolfBirths	10.3947	0.0055	**	131.9	86.5	65.2
MooseAvgHunger	10.3013	0.0058	**	60.2	61.2	63.1
WolfHuntAttempts	9.8516	0.0073	**	127.3	85.4	69.4
WolfMatingTime	9.0941	0.0106	*	0.1	0.1	0.0
MooseWanderTime	8.1832	0.0167	*	55.9	58.0	53.2
PacksFormed	6.1693	0.0457	*	12.6	9.1	10.3
WolfAvgStamina	5.5530	0.0623	ns	92.5	92.7	89.8
MooseAvgThirst	4.6601	0.0973	ns	62.1	63.3	63.5
WolfAvgThirst	4.3644	0.1130	ns	60.5	60.3	58.1
WolfDeaths	4.0476	0.1320	ns	96.0	77.8	72.2
WolfWanderTime	3.9200	0.1410	ns	46.9	49.7	47.5
WolfAvgHunger	3.9011	0.1420	ns	64.5	64.1	61.0
MooseDefendTime	3.4412	0.1790	ns	1.2	0.9	0.9
WolfHuntingTime	2.3871	0.3030	ns	40.1	41.8	36.2
MooseDeaths	2.3679	0.3060	ns	197.6	206.1	194.2
WolfEatTime	1.8707	0.3920	ns	8.6	9.7	8.4
WolfHuntFailures	1.8212	0.4020	ns	33.3	22.3	27.2
WolfAvgLifespan	1.4116	0.4940	ns	28.2	31.8	29.7
WolfSearchWaterTime	0.7974	0.6710	ns	15.5	16.6	16.9
WolfSearchFoodTime	0.3329	0.8470	ns	69.0	64.1	64.8

A.3.1 Top 10 Most Significant Metrics Overall

Table A.2 presents the 10 most statistically significant metrics across all scenarios, ranked by p-value.

Table A.2: Top 10 most significant metrics (overall) from Kruskal-Wallis H-test.

Metric	H-statistic	p-value	Sig	NoBear	AvgerageBear	ManyBear
BearFinalPopulation	25.9389	< 0.001	***	0.0	13.6	36.6
BearBirths	25.8517	< 0.001	***	0.0	9.3	40.0
BearDeaths	26.8146	< 0.001	***	0.0	7.8	30.7
BearStarvation	26.8146	< 0.001	***	0.0	7.8	30.7
BearCarcassCount	26.0163	< 0.001	***	0.0	84.7	144.5
BearPlantMeals	26.7898	< 0.001	***	0.0	62.9	227.0
BearAvgHunger	26.3131	< 0.001	***	0.0	64.2	59.3
BearHuntAttempts	26.0103	< 0.001	***	0.0	299.4	558.1
BearSuccessfulHunts	26.5307	< 0.001	***	0.0	81.6	141.1
WolfFleeingTime	25.2789	< 0.001	***	0.0	2.6	12.0

A.3.2 Full Significance Visualization

Figure A.4 shows the statistical significance (-log10(p-value)) for all analyzed metrics.

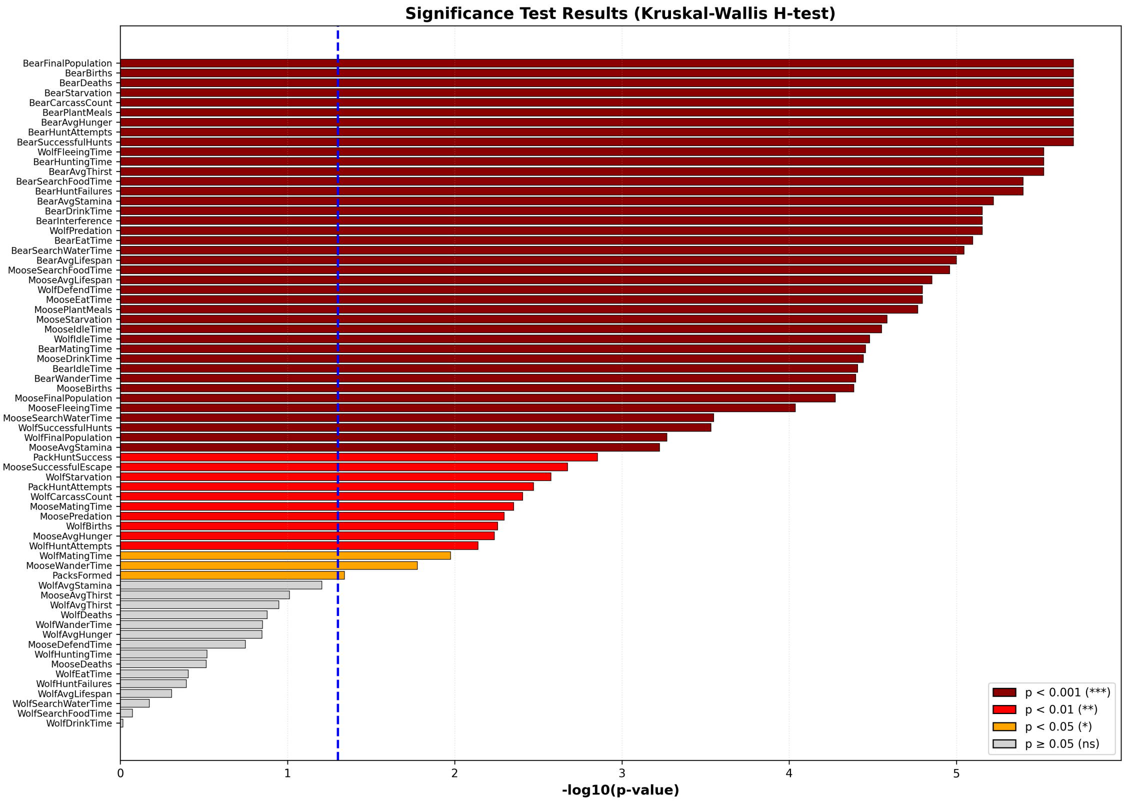


Figure A.4: Statistical significance for all analyzed metrics (Kruskal-Wallis H-test). Higher values indicate stronger differences between scenarios.

A.3.3 Complete Statistical Dataset

The complete compiled dataset, including mean values, standard deviations, Kruskal-Wallis H-statistics, and p-values for all scenarios and metrics, is provided in the supplementary Excel file:

`https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fraw.githubusercontent.com%2FDeRo9%2FSimulating-an-ecosystem---Kandidatarbete-2026%2Frefs%2Fheads%2Fmain%2FAnalysis%2Foutput%2FSimulation_Data_Summary.xlsx&wdOrigin=BROWSELINK`

A.4 State diagrams

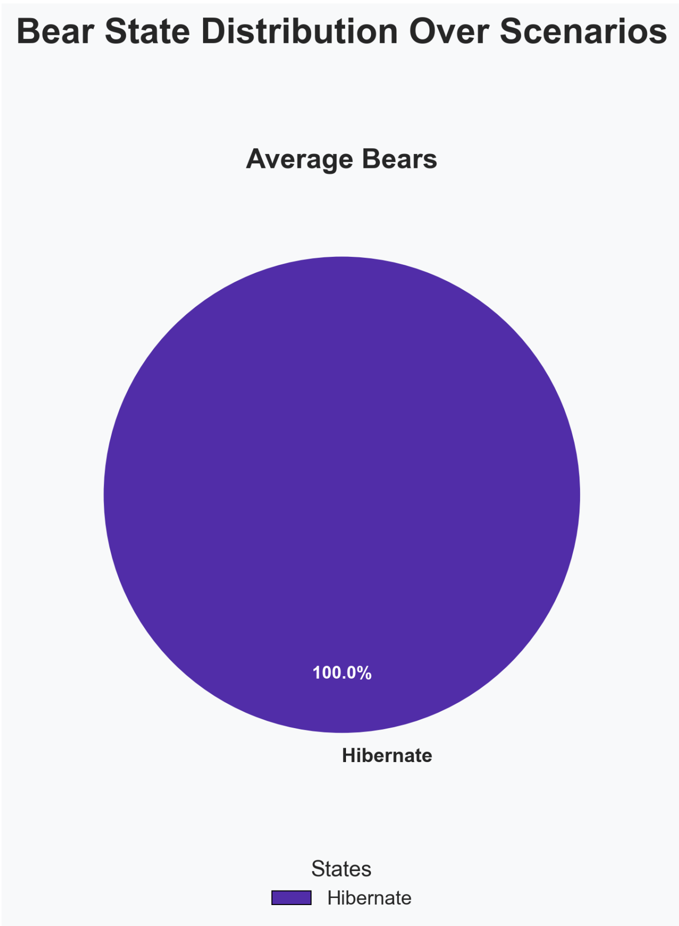
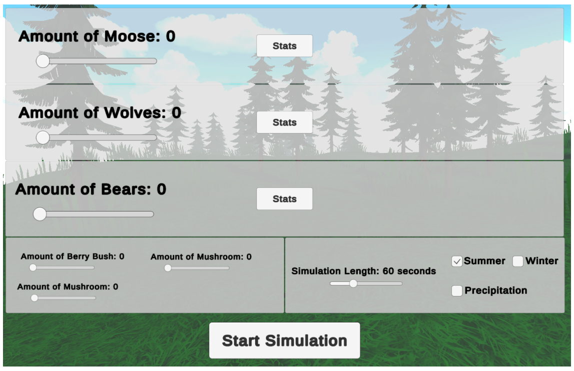


Figure A.5: Bear state distribution during winter

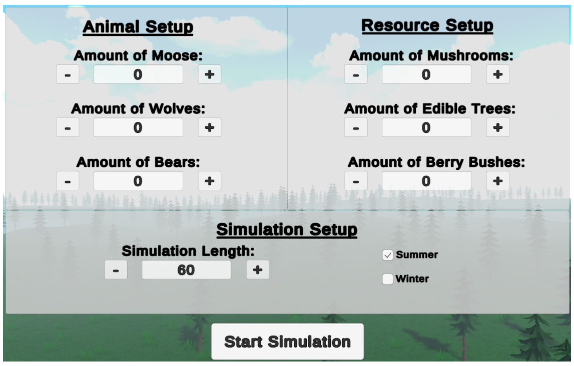
A.5 UI Overview



(a) Animal Setup

(b) Simulation UI

Figure A.6: UI before the first round play-testing



(a) Animal Setup

(b) Simulation UI

Figure A.7: UI after the first round play-testing

A.6 Figma & Paper Prototypes

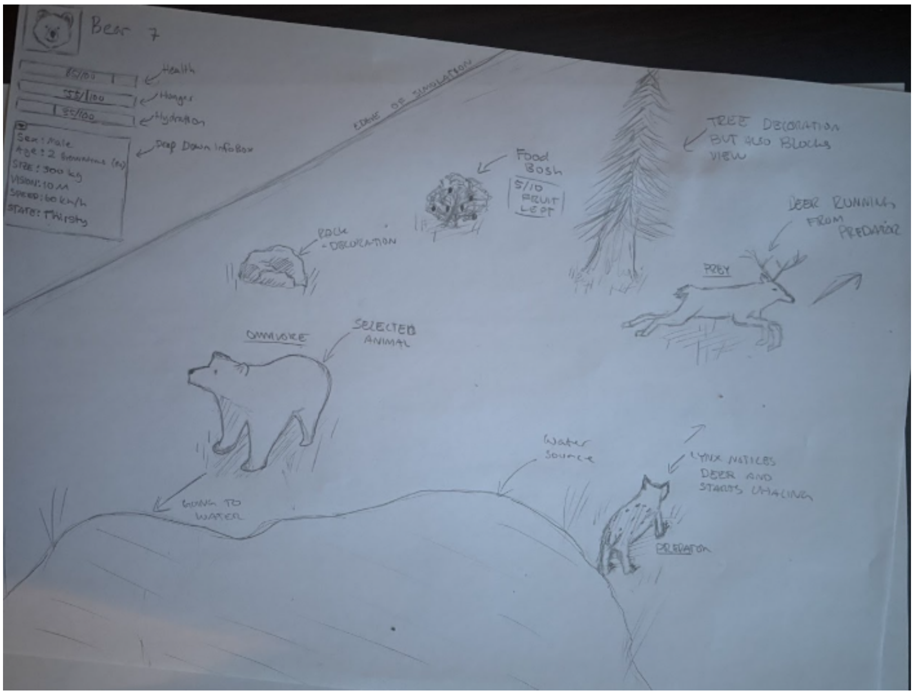


Figure A.8: Simulation Prototype

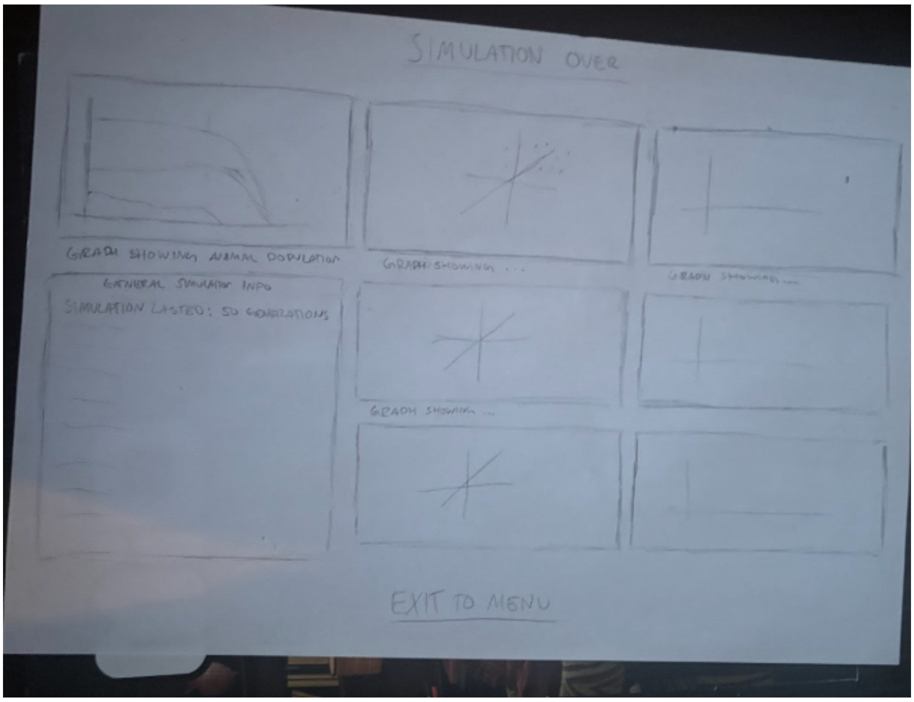


Figure A.9: Statistics Prototype

Figure A.10: Menu Prototype