COMPUTATIONAL MODELING FOR THE SOCIAL SCIENCES Project

Project Name:

The use of ABM in identifying the effect of invasive species in Egypt.

Project Number: **1**

Under Supervision of:

Dr. Rasha Hassan

Student Name	E-mail	ID
Ezz Eldin Ahmed Mohamed (Leader)	ezzeldine.ahmed2022@feps.edu.eg	5220532
Abdulrahman Mostafa Kamel Hassan	abdulrahman.mostafa2022@feps.edu.eg	5220323
Mohamed Amir Mohamed	mohamed.amir2022@feps.edu.eg	5220644
Nada Mohamed Abbas	nada.mohamed2022@feps.edu.eg	5220276
Sondos Yehia Ahmed	sondos.yehia2021@feps.edu.eg	5210616
Yasmeen Mohamed Ahmed	yasmin.mohamed2021@feps.edu.eg	5210802

Task	Ezz Eldin	Abdulrahman	Mohamed	Nada	Sondos	Yasmeen
Introduction	✓	✓				
CAS	✓	✓				
Why ABM	✓	✓				
Agents	✓	✓	✓			
Agents' properties	✓	✓	✓			
Environment	✓	✓	✓			
Relations	✓	✓	✓			
Time step	✓	✓	✓			
Flowchart				✓		
Model coding			✓			
Behavior space				✓		
Results					✓	
Verification and validation					✓	✓
3 scenarios					✓	✓
General ideas						✓
Conclusion						✓

- **Introduction:**

Invasive species are an outsider, introduced and non-native organisms (diseases, parasites, plants, animals) from an ecosystem that spread in new environments, disrupting ecological balance. Causing serious threats to harm the environment, the economy and human health.

They are competing native species on limited natural resources, also it endangers human use of these resources. Since they are outside their original ecosystem, they are not threatened by their natural predators in the new environments, so they massively and uncontrollably reproduce which endanger the native biological systems and reduce biodiversity. A remarkable example of this phenomena is water hyacinth in Egypt also known as Nile lily or (ward el-nil) in Arabic. It has remarkable characteristics such as: Free-floating plant with fibrous roots and thick, glossy leaves. It has beautiful violet flowers with a yellow spot. It mainly spreads by runners and can also produce a huge number of seeds which sustain viability for 28 years. It is a naturalized hydrophite in water bodies (irrigation and drainage) in the Nile Valley, oases, and saline lakes on the Mediterranean Coast. Originally from Brazil in South America introduced to Africa in the nineteenth century, through Egypt during the rule of Khedive Tawfiq (1879 - 1892) as a fancy ornamental plant for gardens. After that in (1932) it was reported that water hyacinth was widely spread in freshwater canals of the Nile Delta, near Cairo and Alexandria. It blocks waterways, messes up fishing and swimming as well as limits boat traffic, and stops light and oxygen from reaching submerged plants underwater, endangering fish and algae by consuming the nutrients. To sum up, it is causing great water loss nationally in Egypt; mechanical elimination costs 150 million LE/year.

- **Study Question:**

How does the introduction of an invasive aquatic plant species like water hyacinth (Eichhornia crassipes) affect the ecological balance, dissolved oxygen levels, and aquatic biodiversity in a simulated ecosystem?

- **Invasive Water Hyacinth as a complex adaptive System (CAS) and the Role of Agent-Based Modeling (ABM)**

1. Micro and Macro-Level

The interactions between individual agents (Micro-level):

- **Water hyacinth:** grows rapidly under warm temperatures, high nutrient availability, and low plant density. It reproduces vegetatively once energy or biomass thresholds are met, and plants may drift with water currents. As it forms dense mats, it blocks sunlight and absorbs large amounts of nutrients, suppressing algae growth and altering aquatic ecosystem balance.

- **Weevils (neochetina eichhorniae):** develop through three distinct stages: egg, larva, and adult. Larvae feed directly on water hyacinth tissue, damaging the plant from within. Adult weevils locate dense hyacinth mats to lay eggs, reinforcing targeted plant infestation. larvae feed directly on water hyacinth tissues.
- **Fish:** fall into three functional groups, each playing a distinct ecological role. Herbivores consume hyacinths and algae, planktivores feed primarily on algae, and predators prey on smaller fish. All types exhibit adaptive movement, migrating in response to changes in oxygen levels and food availability.
- **Algae:** Competing with water hyacinth for light and nutrients. They tend to bloom under high nutrient conditions but decline when shaded by dense hyacinth mats. Despite this competition, algae serve as a primary food source for planktivorous fish, making them a key component of the aquatic food web.
- **Environmental Factors:** Seasonal fluctuations in temperature, flow rate, and nutrient runoff directly influence agent behaviors and interactions—altering growth rates, movement patterns, and species dynamics across the ecosystem

Emergent properties, behaviors and patterns (Macro-level)

- **Ecological Imbalance:** Excessive water hyacinth growth blocks sunlight, reduces dissolved oxygen (DO) levels, and may lead to widespread fish suffocation.
- **Biodiversity Loss:** Hyacinth dominance displaces native plant species and disrupts fish populations, leading to significant biodiversity decline.
- **Biological Control and Risks:** Introducing weevils can reduce hyacinth biomass and improve DO levels. However, overgrazing may cause hyacinth collapse, potentially disrupting fish habitats reliant on moderate plant cover.
- **Hypoxic Zones:** Dense hyacinth mats block light, suppressing photosynthesis and reducing oxygen levels. This creates hypoxic conditions that kill fish and accelerate oxygen depletion through decomposition.
- **Algal Blooms:** Triggered by nutrient pulses (e.g., from agricultural runoff), algae may bloom rapidly, outcompeting hyacinths until light becomes limiting.
- **Trophic Collapse:** Severe oxygen depletion can eliminate herbivorous fish, allowing hyacinth overgrowth and leading to food shortages for higher trophic levels.
- Seasonal Shifts: System behavior changes with the season summer heatwaves intensify hypoxia, while winter cooling slows hyacinth growth and metabolic rates.

2. Social Agents and Feedback

Although the system is ecological in nature, it demonstrates dynamics like social interactions:

- **Competition:** Water hyacinth and algae compete for the same resources—light and nutrients. When hyacinth dominates, it shades out algae, reducing the food supply for algivorous fish and increasing their risk of starvation.
- **Predator–Prey Feedback:** An increase in weevil populations can reduce hyacinth biomass, improving dissolved oxygen (DO) levels and supporting fish survival. However, if fish begin preying on weevil larvae, biological control weakens. Hyacinth may rebound, exposing the system's nonlinear and potentially unstable feedback loop.
- **Agents as Decision-Makers**: Fish select habitats based on oxygen and food availability (e.g., herbivores avoid hypoxic zones).
  Weevils prefer dense hyacinth patches for egg-laying, optimizing reproductive success.
- **Feedback Mechanisms:**
  - **Positive Feedback:** More hyacinths → less light and oxygen → fewer fish → reduced herbivory → further hyacinth spread.
  - **Negative Feedback:** Weevils consume hyacinths → biomass declines → oxygen improves → fish populations recover.

3. Nonlinear Interactions and Social communication

- **Tipping Points:** Even slight increases in nutrient levels can trigger rapid, exponential hyacinth growth. Meanwhile, dissolved oxygen (DO) declines nonlinearly minor environmental shifts can lead to sudden ecosystem collapse.
- **Threshold Effects:** Hyacinth growth follows an S-shaped curve: slow initial spread, rapid expansion after reaching a critical biomass, then plateauing due to space or resource limits.
  Weevils have negligible impact until their population surpasses a critical threshold, after which plant control accelerates.
  A ~2°C rise in temperature can trigger summer hypoxia, shifting the system abruptly.
- **Seasonality:** Seasonal temperature changes affect hyacinth growth rates, weevil reproduction, and fish spawning cycles. These asynchronous patterns introduce variability and complexity into the system's behavior.

4. Path dependence

Historical context matters: Early weevil introduction may prevent hyacinth dominance, but delayed action could lead to irreversible collapse.

Management outcomes depend on ecological context. For instance, nutrient reduction may support algal competition with hyacinths, but only when adequate light reaches the lower water.

5. Data Scarcity

- **Limited Field Data:** Empirical studies on weevil–hyacinth interactions in Egypt are scarce.
- **Risk-Free Experimentation:** ABM allows testing of hypothetical scenarios (e.g., introducing weevils during drought) without ecological or economic consequences.

6. Level of Complexity

- **Multi-Trophic Web:** The system involves multiple interacting trophic levels—herbivorous, planktivorous, and predatory fish; aquatic plants; algae; and weevils—each influencing and responding to changes in others.
- **Environmental Stochasticity:** Unpredictable events like nutrient runoff pulses or heatwaves introduce variability, disrupting equilibrium and triggering nonlinear responses.
- **Spatial Heterogeneity:** Variations in depth and flow create microhabitats. Shallow areas may favor hyacinth colonization, while deeper zones can serve as thermal or oxygen refuges.

7. Environmental Influence (Dynamic Drivers)

- **Seasonal Flow Variability:** Shifting water currents disperse hyacinths during high flow or trap them in stagnant zones during dry periods, reshaping spatial dynamics.
- **Nocturnal Light Conditions:** Simulated moonlight affects predator-prey interactions by altering visibility at night, influencing hunting success and prey behavior.

- **The use of ABM**

While traditional models (e.g., differential equations, statistical regressions) often rely on aggregate averages and static assumptions, ABM captures heterogeneity, spatial structure, feedback, and emergent behaviors, essential for modeling ecosystems like this.

1. Capturing Individual Variability and Adaptive Behavior

Limitations of Traditional Models: Treat populations as uniform (e.g., average fish biomass), ignoring diversity in traits or behavior.

ABM Advantages:

- Models' individuals with unique attributes (e.g., oxygen tolerance, foraging behavior).
- Weevils advance through life stages; hyacinths grow based on local resources.
- Behavior adjusts dynamically to environmental cues (e.g., fish avoid hypoxic zones).

Example: Predatory fish dominate high-oxygen zones while smaller fish migrate; weevils cluster on healthy hyacinths, dispersing as resources deplete.

2. Explicit Spatial Representation

Limitations of Traditional Models: Often assumes uniform environments, missing localized dynamics like light blockage or nutrient hotspots.

ABM Advantages:

- Hyacinth mats reduce oxygen only beneath them.
- Fish and weevils respond to patch-specific conditions (e.g., oxygen, nutrients).
- Spatially explicit modeling captures migration, clustering, and localized hypoxia.

Example: A hypoxic shallow zone caused by dense hyacinth cover contrasts with nearby deeper refuge areas.

3. Simulating Nonlinear and Emergent Phenomena

Limitations of Traditional Models: Struggle with feedback loops, thresholds, and abrupt transitions (e.g., ecosystem collapse).

ABM Advantages:

- Models tipping points (e.g., sudden die-offs at low DO levels).
- Captures unintended consequences (e.g., weevils reduce hyacinths → algae bloom).
- Emergent patterns arise from simple local rules, no need to impose global structure.

Example: A small nutrient spike might seem harmless, but once a threshold is crossed, it leads to system-wide algal blooms.

4. Enabling Safe, Cost-Free Experimentation

Limitations of Real-World Trials: Risky, expensive, and constrained by external variables.

ABM Advantages:

- Runs virtual experiments at low cost and zero ecological risk.
- Easy test interventions (e.g., timing of weevil release, runoff reduction).
- Supports adaptive management through "what-if" scenarios.

Example: Simulations may show that nutrient control combined with biocontrol yields better outcomes than either strategy alone.

5. Functioning Under Data Scarcity

Limitations of Traditional Models: Require precise parameters, which may not exist (e.g., weevil survival rates in Egypt).

ABM Advantages:

- Supports inference from lab/partial field data. Allows uncertainty via sensitivity analysis.
- Reveals directional outcomes even when exact values are unknown.

Example: The model can show whether weevils tend to control hyacinths across a plausible range of feeding rates

6. Integrating Multiple Temporal and Spatial Scales

Limitations of Traditional Models: Typically silo short-term processes (e.g., growth) from long-term impacts (e.g., ecosystem collapse).

ABM Advantages:

- Simultaneously tracks micro (daily growth, movement) and macro (seasonal trends) dynamics.
- Connects local interactions (e.g., algae and hyacinth competition) to river-wide consequences (e.g., hypoxia zones).

Example: A brief summer heatwave accelerates hyacinth growth, setting the stage for autumn trophic collapse.

Model Framework: Agents, Properties, Environment, Rules, and Timestep

- **Agents:**

- **Water Hyacinths**: a fast-growing, free-floating aquatic plant native to South America that spreads rapidly through vegetative runners, forming dense mats that harm aquatic ecosystems. In Egypt, it became naturalized before the end of the 19th century and continues to pose environmental and economic problems by clogging waterways, reducing biodiversity, and increasing disease risk.
- **Weevils**: Neochetina eichhorniae: is a weevil used to control the invasive water hyacinth plant. It feeds only on water hyacinth, reducing its growth and spread, and has been introduced in many countries as an effective natural control method.
- **Fish**: an animal that lives in water, is covered with scales, and breathes by taking water in through its mouth, or the flesh of these animals eaten as food.
- **Algae**: Primarily aquatic, photosynthetic organisms that are often simple in structure and range from unicellular microalgae, like diatoms, to multicellular forms, such as giant kelp.

They are not a single taxonomic group but a loose assembly of organisms that share similar traits, particularly their photosynthetic capability and chlorophyll content.

- **Agents Properties**

The following is a description of each agent's characteristics

Water Hyacinths (Invasive Species):

- Growing based on temperature, nutrients, and density
- Reproduce vegetatively
- Reduce water flow and oxygen levels

Weevils (biological control agents):

- Have life stages (egg, larva, adult)
- Feed on hyacinths
- Reproduce based on environmental conditions

Fish (three types):

- Herbivorous (eat plants)
- Planktivorous (eat algae)
- Predatory (eat other fish)
- Each has different oxygen tolerances and behaviors

Algae:

- Compete with hyacinths for nutrients
- Food source for planktivorous fish

- **Environment (Spatial)**

Simulates a meandering river without banks:

- Depth variations
- Floodplains
- Irrigation channels

Agent-to-Agent Relations

By observing the behavior of the agents, in addition to using references, the following rules were established:

1. Water Hyacinths

- **Intra-Species Competition:** High-density patches experience reduced individual growth due to light and nutrient limitation (density-dependent regulation).
- **Interaction with Weevils:** Weevil larvae consume plant tissue, weakening hyacinths and curbing their spread.
- **Interaction with Fish:** Herbivorous fish graze on hyacinth leaves, contributing to biological control.

2. Weevils (Biocontrol Agents)

Interaction with Hyacinths: Adults lay eggs on robust hyacinths; larvae feed on internal tissues, decreasing plant vitality

3. Fish (Three Trophic Levels)

- **Herbivores:** Feed on hyacinths and algae, connecting primary producers to higher trophic levels.
- **Planktivores:** Consume algae; indirectly compete with herbivores for food.
- **Predators:** Regulate herbivorous and planktivorous fish through top-down control.

4. Algae

- **Competition with Hyacinths:** Compete for nutrients and light, growth declines under dense hyacinth cover.
- **Interaction with Fish:** Serve as a primary food source for herbivorous and planktivorous fish, shaping fish distribution and survival

- **Agent-to-Self Relations**

1. Water Hyacinths

Water hyacinths reproduce asexually through vegetative propagation when their local biomass and energy exceed a critical threshold. In favorable conditions—such as high nutrient availability, warm temperatures, and low competition, this leads to rapid expansion and dense mat formation. However, overcrowding can eventually reduce individual growth rates due to competition for light and nutrients.

2. Weevils

Weevils transition through distinct life stages: egg, larva, and adult. Each stage exhibits specific behaviors. Larvae feed on hyacinth tissue, while adults search for suitable hyacinth patches to lay eggs. The success of each stage depends on environmental conditions and the presence of healthy host plants. Limited access to hyacinths or suboptimal habitats can disrupt their development cycle.

3. Fish

Fish behave according to internal states such as energy levels, oxygen needs, and reproductive readiness. They grow, feed, and reproduce based on these physiological cues. Fish also move dynamically through the environment, seeking optimal conditions for survival. Their actions are not fixed but adapt to changing oxygen levels, food availability, and seasonal cues.

4. Algae

Algae grow rapidly in nutrient-rich environments with adequate light. Their populations can expand quickly, but high densities lead to self-shading and nutrient depletion, which suppress further growth. This creates natural limits to algal blooms unless sustained by continuous nutrient input. Algae also contribute to oxygen fluctuations through daytime photosynthesis and nighttime respiration

- **Agent-to- Environment Relations**

1. Hyacinths Alter the Environment

- **Nutrient Uptake:** Extract nitrogen and phosphorus from water, limiting nutrient availability to algae.
- **Light Obstruction:** From dense floating mats that block sunlight penetration, reducing photosynthesis below.
- **Flow Reduction:** Dense root networks slow water movement, enhancing sediment deposition.

2. Fish Respond to Environmental Conditions

Oxygen Sensitivity: Avoid hypoxic zones created by hyacinth decay; mortality increases under sustained low DO levels.

Temperature Dependence: Affects metabolic rates and spawning; warmer temperatures may accelerate growth or induce stress.

3. Weevils and Habitat Suitability

Shallow Water Preference: Constrained to areas where hyacinths persist; avoid turbulent or deep-water zones.

4. Algae and Oxygen Production

Photosynthesis Contribution: Generate oxygen during daylight, temporarily enhancing aquatic oxygen levels, especially critical for fish survival.

- **Environment-to-Agent Interactions**

1. Seasonal Variability

Temperature Fluctuations: Warm periods boost hyacinth and weevil activity but lower oxygen solubility, stressing fish.

Flow Changes: Rainy seasons increase the flow and disperse mats; dry seasons favor mat formation and stagnation.

2. Nutrient Runoff

Agricultural Input: Triggers algal blooms which, upon decomposition, contribute to oxygen depletion and ecosystem imbalance.

3. Oxygen Levels as a Limiting Factor

Fish Mortality: Severe hypoxia—often under dense hyacinth cover—leads to fish die-offs and trophic disruptions.

- **Environment-to-Environment Interactions**

1. Nutrient Cycling

Decomposition Feedback Dead plant and algal material releases nutrients, fueling future blooms or hyacinth regrowth.

2. Oxygen Dynamics

Photosynthesis vs. Respiration: Oxygen is produced during the day but consumed at night by plant/algal respiration and decomposition processes, potentially resulting in net oxygen loss

3. River Flow and Habitat Structure

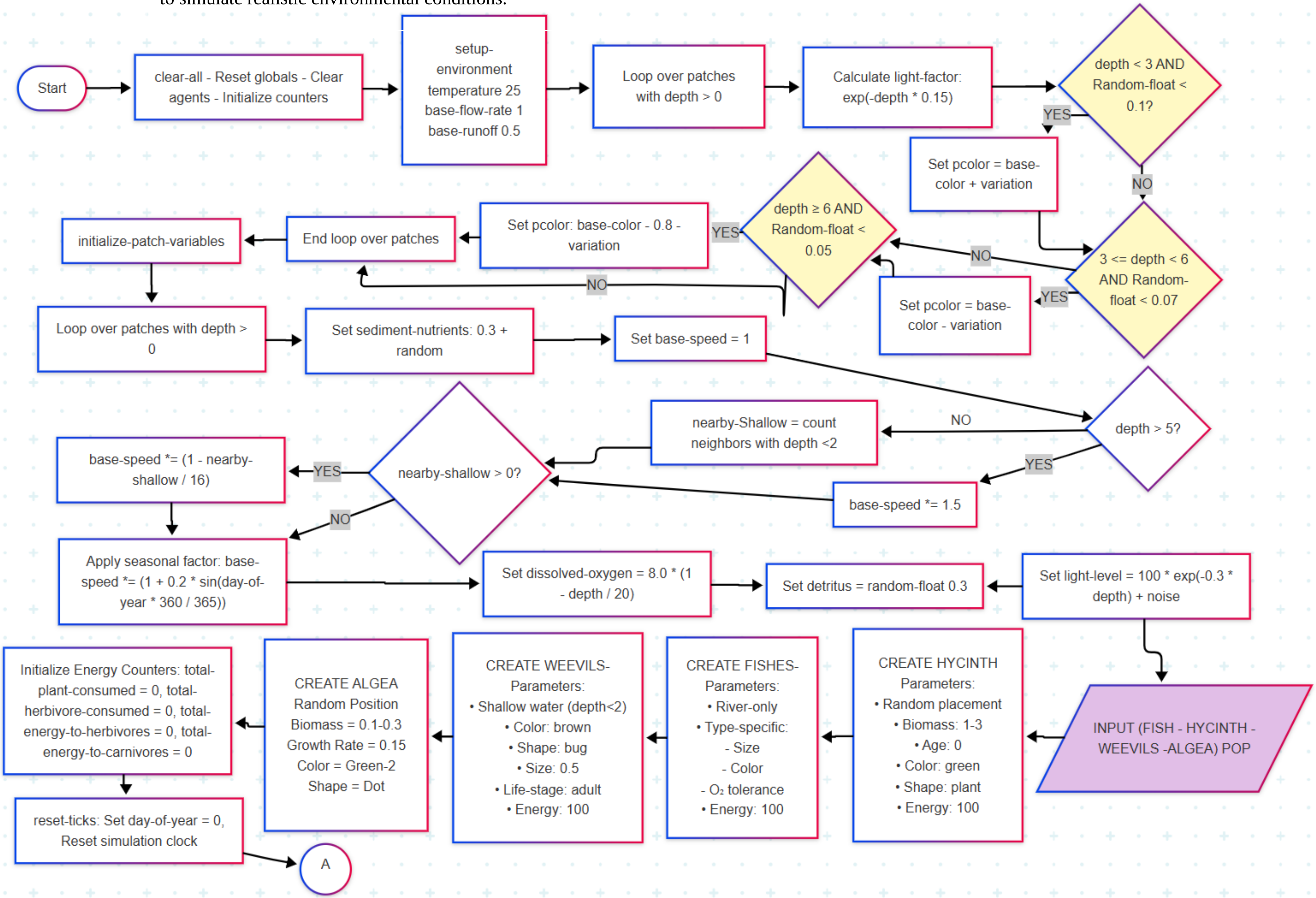
Hydrological Influence: Strong currents fragment hyacinth mats and restore oxygenation; stagnant zones foster mat formation and hypoxia.

4. Time step

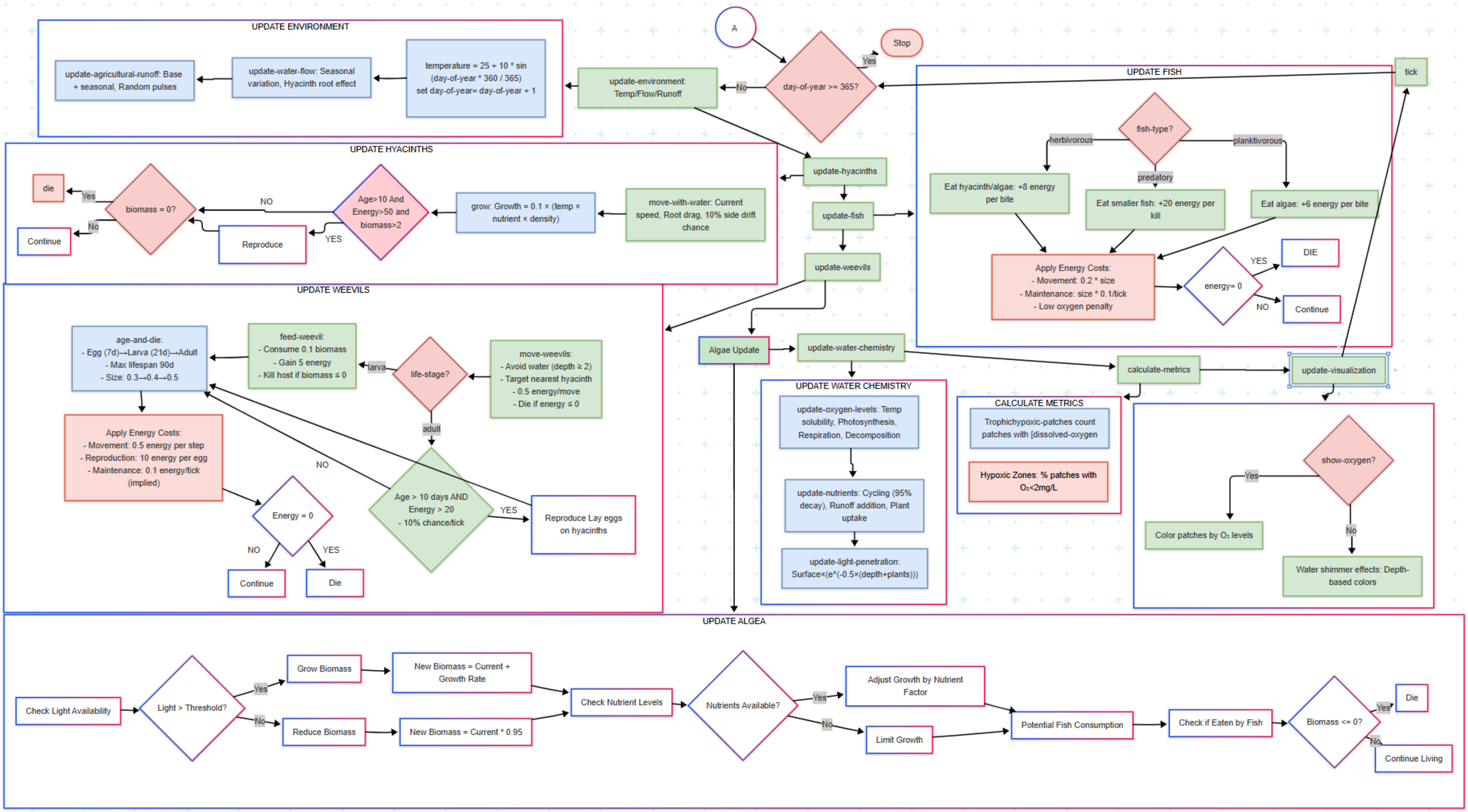
Daily timesteps (per 365 days) with seasonal variations

FLOW CHART:

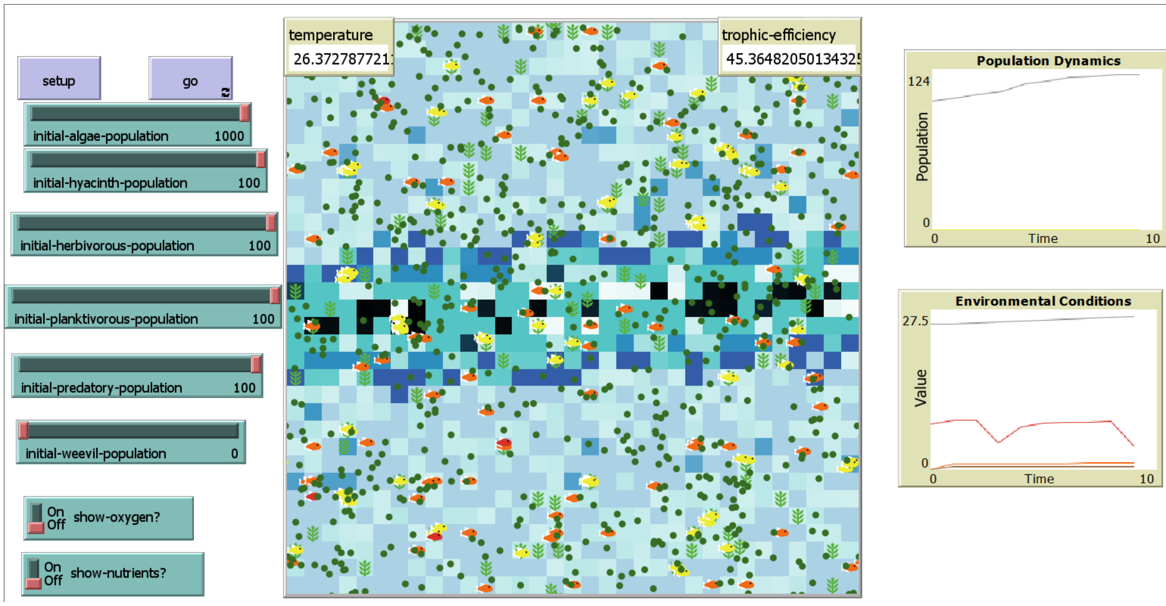
The flowchart begins with initializing the simulation environment. This includes clearing all previous data, resetting global variables, initializing agents, and setting up environmental parameters. It then proceeds to loop through all patches with a depth greater than zero, calculating light factors and assigning patch colors based on depth and random variations to simulate realistic environmental conditions.



The second part of the flowchart represents the **main simulation loop**, where the ecosystem dynamics are updated for each simulation tick. It includes updating environmental conditions such as temperature, water flow, and agricultural runoff. Organism behaviors are modeled in detail, including the life cycles and interactions of **fish**, **weevils**, and **hyacinths**—covering feeding, movement, reproduction, and mortality. Additionally, **water chemistry** is continuously adjusted based on factors like oxygen levels, nutrient cycling, and light penetration. The system also tracks ecological metrics and visual outputs, providing real-time feedback on oxygen levels, hypoxic zones, and overall ecosystem health



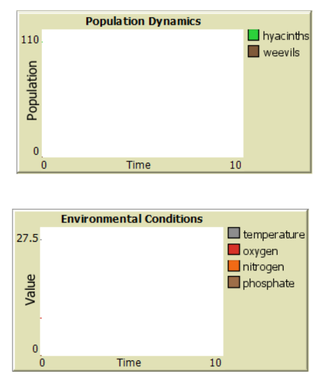
▪ UI/UX



The model's layout in NetLogo

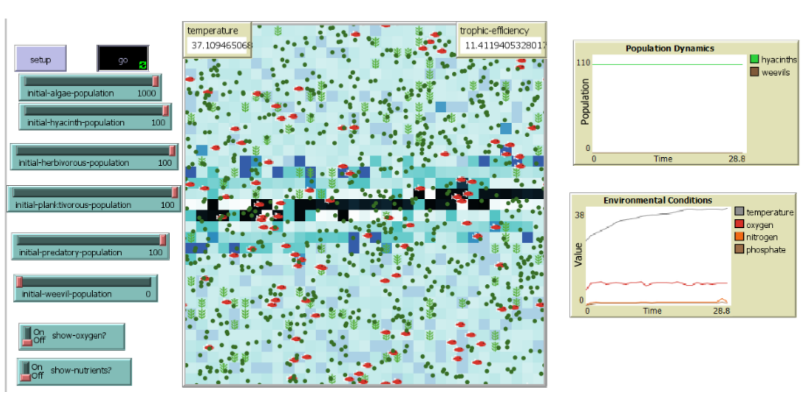
▪ Discussing the different results from the model:

To evaluate the effects of different ecological interactions and control strategies on water hyacinth dynamics and overall ecosystem health, three simulation runs were conducted using varying initial conditions. These runs were implemented through the model's interface and tracked using built-in plots over a 365-day simulation period. Each run explored the presence or absence of biological control agents (weevils) and their impact on plant biomass, trophic efficiency, and overall ecological balance within the simulated aquatic ecosystem.



First run when **Weevils = 0** :

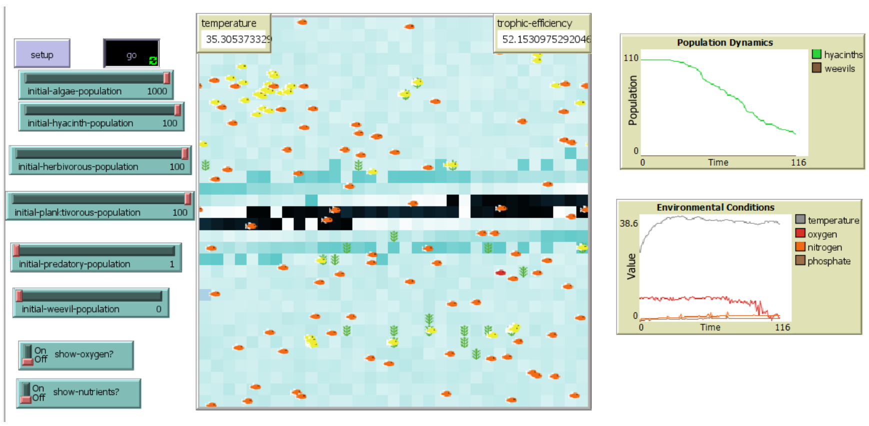
The result, when the weevils were absent, was that the water hyacinth population did not significantly decline over the 365-day simulation period. This is because there is no natural predator to regulate their spread and reduce their biomass. This, in turn, prevents sunlight from



reaching the submerged plants and algae, causing them to decompose beneath the water hyacinth mats, and the trophic efficiency — representing the energy transfer through the food web — declined rapidly and ultimately dropped to zero, reflecting a breakdown of the ecosystem's functional structure.

Second run when **Weevils = 0** & **Predatory fish = 1** :

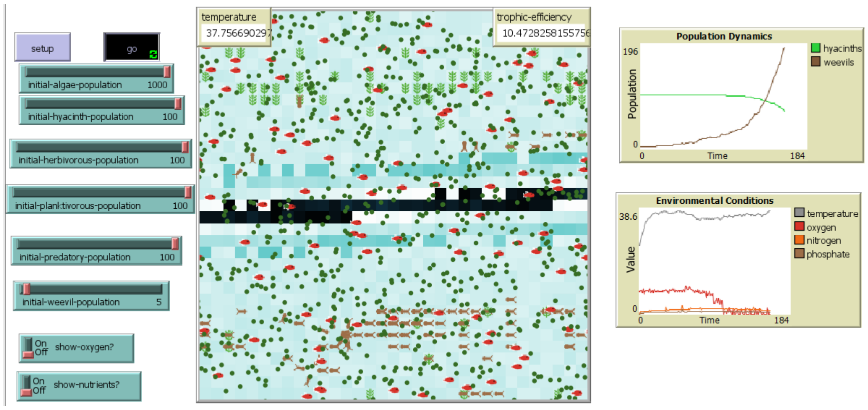
In the second run, when weevils and predatory fish were both absent, the outcome was completely different from the previous scenario. Even in the absence of weevils, the water hyacinth population decreased. This occurred because the absence of predatory fish that typically prey on planktivorous and herbivorous fish allowed these fish populations to thrive. As a result,



the herbivorous and planktivorous fish were able to feed on algae and water hyacinth, which are their primary food sources. This led to an increase in their energy levels and, consequently, trophic efficiency. Due to this higher food efficiency, the populations of both algae and water hyacinth declined.

Third run when **Weevils = 5** :

In this scenario, five weevils were introduced at the beginning of the simulation. Over time, the weevils reproduced by laying their eggs on the water hyacinth, where their larvae feed directly on the plant tissues. This biological control mechanism gradually reduced the biomass of water hyacinth. As the weevil population increased, the feeding pressure intensified until the hyacinth population was significantly suppressed or nearly eliminated.



And this is summary Table for trials comparison:

Scenario	**Weevils**	**Fish Composition (Planktivorous, Herbivorous, Predatory)**	**Hyacinth Biomass**	**Trophic Efficiency**
Run 1: No control	0	All fish types = 100	High	Rapidly declines to 0
Run 2: No predators or weevils	0	Predatory fish = 1; Planktivorous & Herbivorous = 100	Decreases (fish control)	Increases
Run 3: (5) Weevils	5	All fish types = 100	Strong decrease (biological control)	Improves with balance

- **The verification and the validation of the model:**

1. Model Verification:

The model was verified through two key steps to ensure it was functioning correctly and producing internally consistent results. First, the entire codebase was inspected for syntax and logic errors. All procedures including agent initialization, interaction rules, environmental updates, and indicator calculations (e.g., trophic efficiency) were reviewed and confirmed to execute without runtime errors. The model was compiled successfully in NetLogo, and variables were properly initialized and updated throughout each simulation tick.

Second, the model's behavior was tested under a variety of input scenarios to confirm that it responded logically to different ecological conditions. These tests included runs with and without biological control agents (weevils), the removal of top predators and varying initial populations of algae and fish. In each case, the model displayed expected emergent behaviors such as the dominance of water hyacinth in the absence of control, cascading trophic effects when predatory fish were removed, and fluctuations in biodiversity and dissolved oxygen in response to species interactions. These results confirm that the model behaves in a consistent and ecologically realistic manner under diverse conditions.

2. Model Validation (Micro and Macro-Level):

The model was validated at both the micro and macro levels to assess how accurately it reflects real-world ecological dynamics.

At the micro level, individual agent behaviors were closely examined to ensure that their interactions followed ecologically sound rules. This included verifying that herbivorous fish selectively consumed algae and hyacinths, weevils targeted water hyacinth for feeding and reproduction, and agents responded correctly to local oxygen conditions (e.g., fish mortality in hypoxic zones). These behaviors were consistent with biological expectations and scientific literature, confirming the credibility of the model’s interactions.

At the macro level, the model successfully replicated key large-scale ecological phenomena associated with water hyacinth invasion. For example, in scenarios without biological control, the simulation produced expansion of hyacinth coverage. Similarly, the model captured the cascading effects of hyacinth dominance on ecosystem-wide indicators, including a sharp decline in dissolved oxygen levels, and a drop in biodiversity. The accuracy of these emergent dynamics supports the validity of the model’s structural design and its potential utility for forecasting and ecological scenario testing at the system level.
Together, these validation strategies confirm that the model accurately captures both the individual-level interactions (micro validation) and the system-wide ecological patterns (macro validation), enhancing confidence in its application for ecological forecasting and scenario testing.

- **Three suggested extensions:**

1. **Mechanical Removal of Water Hyacinth (Human Intervention):**

This proposed extension introduces a periodic manual or mechanical removal process that reflects real-world intervention strategies such as mechanical harvesting, herbicide application, and manual cutting. Incorporating this mechanism would allow for a comparative analysis between biological control (e.g., weevils) and non-biological management methods. In practice, especially in regions like Egypt, mechanical removal is a common but economically burdensome solution, with annual costs reportedly reaching over 150 million LE.

2. **Genetic Adaptation or Resistance in Water Hyacinth:**

This proposed extension simulates the possibility of genetic adaptation or resistance developing in water hyacinth over time, particularly in response to long-term exposure to biological control agents such as weevils. In this scenario, a subset of the hyacinth population may evolve traits that reduce the effectiveness of weevil feeding, such as thicker tissue, faster regeneration, or chemical defenses. Although not currently modeled, adding this component would reflect a more realistic ecological dynamic, where invasive species can adapt and become more difficult to control.

3. **Habitat Fragmentation or Physical Barriers (Spatial Constraints on Ecosystem Dynamics):**

This extension proposes the inclusion of physical barriers or environmental fragmentation within the aquatic ecosystem, such as dams, weirs, pollution zones, or disconnected irrigation channels. These structures can restrict the movement of aquatic organisms—including weevils, fish, and even water flow—and may result in isolated sub-systems within the river or lake. While the model assumes a continuous, connected environment, introducing spatial heterogeneity would more accurately reflect real-world water systems, particularly in regions like the Nile Delta where hydrological infrastructure is widespread.

4. **Introduction of a Second Invasive Species (Multiple Invasion Dynamics):**

This extension explores the impact of introducing a second invasive species into the simulated aquatic ecosystem, such as toxic algae (e.g., Microcystis) or an invasive fish species that competes with or preys on native species. While the current model focuses solely on the dynamics of water hyacinth as a single invasive threat, in reality, ecosystems are often exposed to multiple simultaneous invasions. This extension would allow the simulation to capture the compounding effects of multiple invaders on biodiversity, dissolved oxygen levels, and food web stability.

The following is the table for summarizing these extensions:

Extension Idea	What It Adds	Real-World Parallel
Mechanical Removal	Tests human control strategies	Government or manual removal in canals
Genetic Resistance	Adds long-term risk realism	Biological control becoming ineffective
Habitat Fragmentation	Introduces spatial constraints	Dams, pollution zones, disconnected systems
Second Invasive Species	Simulates complex, multi-invader dynamics	Common in global aquatic ecosystems

- **General ideas for the model:**

From the model, general ideas can be obtained such as:

- In our model, we study how water hyacinths spread rapidly and its ecological impact. **However**, we can simulate the spread and ecological impact of any invasive species, not only water hyacinths.

- Our model shows how organisms compete for limited environmental resources. **However**, it can also generalize as we can simulate the competition in social or economic systems like the competition between companies for market share.

- In our model, water hyacinths spread quickly if nothing stops them. It’s the same in how misinformation quickly spreads from one person to another on social media.

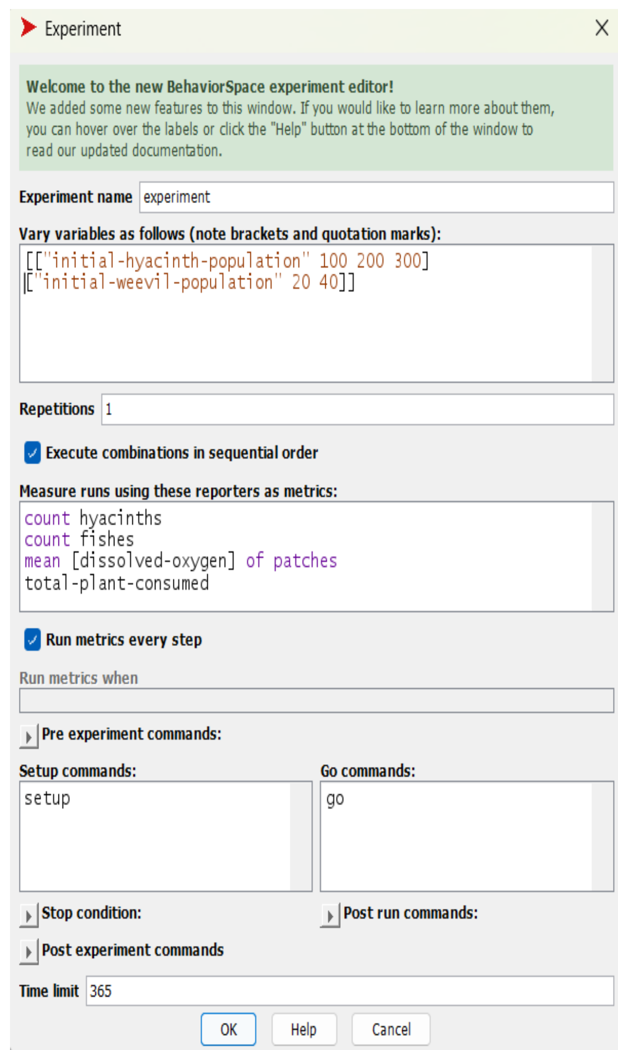
- Our model depends on seasons and daily time steps to influence environmental behave and there is no reason to restrict them to the Invasive Water Hyacinth model only as the climate change depends on them also.

- In our model, oxygen levels drop as hyacinths grow excessively, creating hypoxic zones. It can be generalized that any situation where excessive use of resources leads to deplete common supplies.

- In our model, we use weevils as a biological control agent to reduce the numbers of hyacinths. **However**, this can be applied to vaccination campaigns against diseases, as vaccination is a control agent that reduces the disease.

▪ Behavior Space:

In this study, the **BehaviorSpace** tool in NetLogo was employed to investigate the ecological dynamics of an aquatic system influenced by varying initial populations of water hyacinths and weevils. A **2 × 3 full-factorial experimental design** was implemented, with **initial-hyacinth-population** set at 100, 200, and 300, and **initial-weevil-population** at 20 and 40. This resulted in six distinct parameter combinations. Each simulation run spanned **365 ticks**, representing one year of model time, allowing the observation of long-term trends and interactions within the ecosystem. The experiment was designed to address the central research question: **How does the introduction of an invasive aquatic plant species like water hyacinth (*Eichhornia crassipes*) affect the ecological balance, dissolved oxygen levels, and aquatic biodiversity in a simulated ecosystem?**



Throughout the simulations, several key output variables were monitored: the **count of hyacinths**, the **count of fishes**, the **mean dissolved oxygen** across patches as an indicator of water quality, and the **total plant consumed**, which served as the primary response variable. By systematically analyzing the effect of different initial plant and insect densities, the model explores the ecological impact of invasive species and biological control strategies. Ultimately, this modeling approach supports efforts to **preserve aquatic biodiversity** by evaluating how water hyacinth infestations, and their potential biological regulation via weevils, influence ecosystem stability, resource availability, and habitat health.

BehaviorSpace results (NetLogo 6.4.0)	Table version 2.0						
Final Code.nlogo							
experiment							
05/20/2025 07:11:21:732 +0300							
min-pxcor	max-pxcor	min-pycor	max-pycor				
-16	16	-16	16				
[run number]	initial-hyacinth-population	initial-weevil-population	[step]	count hyacinths	count fishes	mean [dissolved-oxygen] of patches	total-plant-consume
4	200	40	0	200	300	8.201164886	0
3	200	20	0	200	300	4.665284178	0
2	100	40	0	100	300	7.384719669	0
6	300	40	0	300	300	7.934996593	0
5	300	20	0	300	300	7.613212468	0
1	100	20	0	100	300	7.756449131	0
2	100	40	1	100	274	8.742451999	9.55
4	200	40	1	200	274	9.082549359	9.95
6	300	40	1	300	266	8.304588793	10.17951
3	200	20	1	200	274	8.149508578	10.35
5	300	20	1	300	279	9.116788302	10.21819
2	100	40	2	100	252	8.832723041	17.81364
4	200	40	2	200	254	7.396900424	18.64399
3	200	20	2	200	252	8.17308322	18.77623
6	300	40	2	300	253	8.052190625	18.98228

The dataset generated from the BehaviorSpace experiment consists of **2 × 3 = 6 unique parameter combinations**, each run for **365 ticks** (time steps), resulting in a total of **2,190 observations** (365 × 6). Key variables include the **run number**, which identifies each simulation run, and the initial populations of water hyacinths (**initial-hyacinth-population**) and their biological control agents, weevils (**initial-weevil-population**). The **step** variable represents the current simulation tick. At each step, the number of hyacinths (**count hyacinths**) and fishes (**count fishes**) in the system are recorded. The **mean dissolved oxygen of patches** reflects the average oxygen concentration in the water, an important indicator of aquatic ecosystem health. Finally, **total-plant-consumed** tracks the cumulative amount of plant biomass consumed during the simulation, serving as the primary response variable to assess the ecological impact of invasive species and biological control efforts.

- ## Fitting linear regression model:

When the model was initially fitted, a strong quadratic pattern was observed in the resid uals, indicating that the linear model was inadequate. To better capture the non-linear relationsh ips in the data, the model was refitted to include quadratic terms. Additionally, a log transformat ion was applied to the initial weevil population, and the mean dissolved oxygen level was exclu ded due to its statistical insignificance.

```
> full_model_quadratic <- lm(total.plant.consumed ~initial.hyacinth.population+
+                            log(initial.weevil.population)+ I(count.hyacinths^2) +
+                            I(count.fishes^2) ,
+                            data = data)
> summary(full_model_quadratic)

Call:
lm(formula = total.plant.consumed ~ initial.hyacinth.population +
    log(initial.weevil.population) + I(count.hyacinths^2) + I(count.fishes^2),
    data = data)

Residuals:
    Min      1Q  Median      3Q     Max
-6.9169 -1.2073  0.0488  1.2916  5.4401

Coefficients:
                                 Estimate Std. Error  t value Pr(>|t|)
(Intercept)                     3.536e+01  3.014e-01  117.303   <2e-16 ***
initial.hyacinth.population     1.216e-02  3.882e-04   31.324   <2e-16 ***
log(initial.weevil.population)  6.541e+00  8.639e-02   75.709   <2e-16 ***
I(count.hyacinths^2)            3.019e-06  1.431e-06    2.109    0.035 *
I(count.fishes^2)              -6.545e-04  4.407e-06 -148.492   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.395 on 2191 degrees of freedom
Multiple R-squared:  0.932,    Adjusted R-squared:  0.9319
F-statistic:  7510 on 4 and 2191 DF,  p-value: < 2.2e-16
```

The model coefficients are all statistically significant, as indicated by their very small p-values (all less than 0.05, most < 2e-16), which means there is strong evidence that each predictor variable has a meaningful effect on the total plant consumed.

- The **intercept** is highly significant (p < 2e-16), representing the expected baseline level of plant consumption when all predictors are zero.
- The coefficient for **initial hyacinth population** is positive and highly significant (p < 2e-16), confirming that increasing initial hyacinth numbers leads to higher plant consumption.
- The **log of initial weevil population** also has a highly significant positive coefficient (p < 2e-16), indicating that as weevil numbers increase, plant consumption significantly increases, though the log transformation accounts for a nonlinear effect.
- The quadratic term for **count hyacinths** is significant (p = 0.035), showing a smaller but still meaningful nonlinear effect.
- The quadratic term for **count fishes** is highly significant (p < 2e-16) with a negative coefficient, suggesting a strong nonlinear (possibly inhibitory) effect of fish abundance on plant consumption.

The **R-squared value of 0.932** means that about 93.2% of the variability in total plant consumption is explained by this model, which indicates an excellent fit and high explanatory power. The **adjusted R-squared (0.9319)** confirms this while adjusting for the number of predictors in the model, showing that the model is not overfitting. Based on the output, the estimated regression equation can be written as:

$$\widehat{total.plant.consumed} = 35.36 + 0.01216 \times initial.hyacinth.population + 6.541 \times \log(initial.weevil.population) + 0.000003019 \times (count.hyacinths)^2 - 0.0006545 \times (count.fishes)^2$$

- **Intercept (35.36):**
  This is the expected value of total plant consumed when all predictor variables are zero. It serves as the baseline level of plant consumption in the model.
- **initial.hyacinth.population (0.01216):**
  For each additional unit increase in the initial hyacinth population, the total plant consumed increases by approximately 0.01216 units, holding all other variables constant. This indicates that higher initial hyacinth abundance leads to greater plant consumption.
- **log(initial.weevil.population) (6.541):**
  A one-unit increase in the logarithm of the initial weevil population is associated with an increase of about 6.541 units in total plant consumed. This shows a strong positive effect of weevils, the biological control agents, on plant consumption.
- **(count.hyacinths)^2 (0.000003019):**
  The positive coefficient for the squared count of hyacinths suggests that the effect of hyacinth abundance on plant consumption accelerates as the number of hyacinths increases, indicating a nonlinear relationship.
- **(count.fishes)^2 (-0.0006545):**
  The negative coefficient for the squared count of fishes indicates a complex nonlinear effect where increasing fish numbers tend to reduce total plant consumption, possibly due to ecological interactions or inhibitory effects.

Conclusion:

From this project, we learned that Agent-Based Modeling (ABM) is the best way to represent complex ecological systems. Building and analyzing our model (the invasive water hyacinth) helped us to understand how small local interactions can lead to ecosystem collapse or grow. We also realized the importance of micro and macro-level thinking. This model building experience helped us to explore expected and surprising consequences and realize the importance of computational modeling in all fields.

In our agent-based simulations, the invasive water hyacinth quickly takes over when left unchecked, choking out light and oxygen and sending the whole ecosystem off balance. Introducing just a handful of weevils brings the plant under control, but we also saw that healthy fish populations and local environmental factors play a huge role in determining how quickly balance can be restored.

By observing each plant, insect and fish make its own simple decisions, the model reveals unexpected tipping points and feedback loops that you’d never capture in a traditional equation. That makes ABM not just a fine research tool, but a practical sandbox where managers can test “what-if” strategies whether that’s adding biological controls, boosting fish numbers, or combining methods to find the mix that really works on the ground.

Appendix:

Model coding:

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
Invasive Water Hyacinth Impact on Egyptian
Ecosystem
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
extensions [profiler]
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
              GLOBAL VARIABLES
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
globals [
  ; Environmental parameters
  temperature
  water-flow-rate
  agricultural-runoff
  light-intensity
  base-flow-rate
  base-runoff
  ; Water chemistry
  dissolved-oxygen
  nitrogen-level
  phosphate-level
  ; Analysis metrics
  shannon-index
  hypoxic-area
  trophic-efficiency
  ; Seasonal tracking
  day-of-year
]
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
                AGENT BREEDS
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Define breeds for different agents
breed [hyacinths hyacinth]
breed [weevils weevil]
breed [fishes fish]
breed [algae alga]
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
              PATCH VARIABLES
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;

; Define patch variables
patches-own [
  depth
  sediment-nutrients
  detritus
  light-level
  current-speed
  substrate-type
  turbidity
  floodplain?
  algal-bloom?
  moonlight
]
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
              AGENT VARIABLES
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Agent-specific variables
hyacinths-own [
  biomass
  age
  reproduction-rate
  root-density
  energy
]
weevils-own [
  age
  life-stage
  feeding-rate
  size
  energy
]
; Fish variables
fishes-own [
  size
  energy
  age
  oxygen-tolerance
  fish-type
]
algae-own [
  biomass
  growth-rate
]
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
              SETUP PROCEDURES
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
; Setup procedure
to setup
  clear-all
  setup-environment
  setup-hyacinths
  setup-fish-populations
  setup-weevils
```

```
  setup-algae
  reset-ticks
end
; Main simulation procedure
to go
  if ticks >= 365 [ stop ]
  if day-of-year >= 365 [ stop ]
  update-environment
  update-hyacinths
  update-fish
  update-weevils
  update-water-chemistry
  calculate-metrics
  update-visualization
  tick
end
; Environment setup
to setup-environment
  ; Initialize river environment
  create-riverbed
  setup-riverbank-features
  initialize-patch-variables
  set day-of-year 0
  set temperature 25 ; Initial temperature
in Celsius
  set base-flow-rate 1
  set base-runoff 0.5
end
; Create realistic riverbed
to create-riverbed
  setup-meandering-channel
  setup-depth-profile
  assign-substrate-types
  setup-floodplains
  color-riverbed-initial
end
; Setup detailed riverbank features
to setup-riverbank-features
  ask patches [
    let base-color 96 - (depth * 0.4)
    ; Enhanced underwater environment
    if depth > 0 [
      ; Natural light penetration effects
      let light-factor exp (- depth * 0.15)
      ; Depth-based features
      if depth < 3 [
        ; Shallow water details
        if random-float 1 < 0.1 [
          ; Sunlight ripples
          set pcolor base-color + (light-
factor * random-float 0.4)
        ]
      ]
      if depth >= 3 and depth < 6 [
        ; Mid-depth details
        if random-float 1 < 0.07 [
          ; Water column effects
          set pcolor base-color - random-
float 0.3
        ]
      ]
      if depth >= 6 [
        ; Deep water atmosphere
        if random-float 1 < 0.05 [
          ; Deep water currents
          set pcolor base-color - 0.8 -
random-float 0.4
        ]
      ]
    ]
  ]
end
; Initialize patch variables with natural
variations
to initialize-patch-variables
  ask patches [
    if depth > 0 [
      ; Natural sediment distribution
      set sediment-nutrients 0.3 + random-
float 0.7
      ; Calculate current based on depth
and position
      set current-speed calculate-current-
speed
      ; Realistic oxygen distribution
      let base-oxygen 8.0 + random-float
0.5
      set dissolved-oxygen base-oxygen * (1
- (depth / 20))
      ; Natural detritus distribution
      set detritus random-float 0.3
      ; Realistic light penetration
      set light-level 100 * exp (- 0.3 *
depth) + random-float 10
    ]
  ]
end
; Calculate current speed based on location
and season
```

```
to-report calculate-current-speed
  let base-speed 1
  ; Faster in deeper water
  if depth > 5 [
    set base-speed base-speed * 1.5
  ]
  ; Slower near shores
  let nearby-shallow count neighbors with
[depth < 2]
  if nearby-shallow > 0 [
    set base-speed base-speed * (1 -
(nearby-shallow / 16))
  ]
  ; Add seasonal variation
  let season-factor sin (day-of-year * 360
/ 365)
  set base-speed base-speed * (1 + 0.2 *
season-factor)
  report base-speed
end
; Hyacinth setup and management
to setup-hyacinths
  create-hyacinths initial-hyacinth-
population [
    move-to one-of patches
    set biomass 1 + random-float 2
    set age 0
    set color green
    set shape "plant"
    set reproduction-rate base-
reproduction-rate
    set root-density 1
    set energy 100
  ]
end
; Update hyacinth growth and reproduction
to update-hyacinths
  ask hyacinths [
    move-with-water
    grow
    reproduce
    if biomass <= 0 [ die ]
  ]
end
; Hyacinth growth procedure
to grow
  let growth-amount base-growth-rate *
temperature-factor * nutrient-factor *
density-factor
  set biomass biomass + growth-amount
  set energy energy + (growth-amount *
10)  ; Convert growth to energy
  ; Energy cost for maintenance
  set energy energy - 0.1
  ; Check energy
  check-energy
end
; Temperature influence on growth
to-report temperature-factor
  let optimal-temp 28
  let temp-tolerance 10
  report exp (- ((temperature - optimal-
temp) ^ 2) / (2 * temp-tolerance ^ 2))
end
; Nutrient availability factor
to-report nutrient-factor
  let local-nutrients mean [sediment-
nutrients] of neighbors
  report min (list 1 (local-nutrients /
0.5))
end
; Density-dependent growth factor
to-report density-factor
  let local-density count hyacinths in-
radius 3
  report exp (- local-density / 10)
end
; Update environmental conditions
to update-environment
  update-temperature
  update-water-flow
  update-agricultural-runoff
end
; Temperature update based on seasonal
patterns
to update-temperature
  set temperature 25 + 10 * sin (day-of-
year * 360 / 365)
  set day-of-year day-of-year + 1
  if day-of-year >= 365 [ set day-of-year 0
]
end
; Calculate biodiversity metrics
to calculate-metrics
  calculate-shannon-index
  calculate-hypoxic-zones
  calculate-trophic-efficiency
end
; Shannon-Wiener biodiversity index
calculation
```

```
to calculate-shannon-index
  let herbivore-count count fishes with
[fish-type = "herbivorous"]
  let planktivore-count count fishes with
[fish-type = "planktivorous"]
  let predator-count count fishes with
[fish-type = "predatory"]
  let plant-count count hyacinths
  let algae-count count algae


  let species-counts (list herbivore-count
planktivore-count predator-count plant-
count algae-count)
  let total-population sum species-counts
  if total-population > 0 [
    let proportions map [ population-count
-> population-count / total-population ]
species-counts
    set shannon-index (- sum (map [ p ->
ifelse-value (p > 0) [p * ln p] [0] ]
proportions))
  ]
end
; Calculate areas with low oxygen
to calculate-hypoxic-zones
  let total-patches count patches
  let hypoxic-patches count patches with
[dissolved-oxygen < 2]  ; Areas with less
than 2 mg/L oxygen
  set hypoxic-area (hypoxic-patches /
total-patches) * 100  ; Convert to
percentage
end
; Fish population setup
to setup-fish-populations
  setup-fish-type "herbivorous" initial-
herbivorous-population 1.5 yellow 3
  setup-fish-type "planktivorous" initial-
planktivorous-population 1.0 orange 4
  setup-fish-type "predatory" initial-
predatory-population 2.0 red 5
end
to setup-fish-type [type-name initial-pop
fish-size fish-color tolerance]
  create-fishes initial-pop [
    ; Place only in river patches
    move-to one-of patches with [is-river?]
    set fish-type type-name
    set size fish-size
    set color fish-color
    set shape "fish"
    set energy 100
    set oxygen-tolerance tolerance
  ]
end
; Update fish behavior
to update-fish
  ask fishes [
    let my-size size
    if fish-type = "herbivorous" [
      move-to-food patches in-radius 5 with
[any? hyacinths-here or any? algae-here]
      eat-hyacinth-or-algae
    ]
    if fish-type = "planktivorous" [
      move-to-food patches in-radius 5 with
[any? algae-here]
      eat-algae
    ]
    if fish-type = "predatory" [
      move-to-food patches in-radius 5 with
[any? fishes-here with [fish-type !=
"predatory" and size < my-size]]
      eat-fish
    ]
    check-energy
  ]
end
to move-to-food [food-patches]
  let best-patch nobody
  if any? food-patches [
    set best-patch min-one-of food-patches
[distance myself]
  ]
  if best-patch != nobody and best-patch !=
patch-here [
    let movement-cost 0.2 * size
    if energy > movement-cost * 2 [
      face best-patch
      forward 1
      set energy energy - movement-cost
    ]
  ]
  if best-patch = nobody [
    if energy > 0.5 [
      rt random 360
      fd 1
      set energy energy - 0.5
    ]
```

```
  ]
end
to eat-hyacinth-or-algae
  if any? hyacinths-here [
    let target-plant max-one-of hyacinths-
here [biomass]
    if target-plant != nobody [
      ask target-plant [ set biomass
biomass - 0.05 if biomass <= 0 [ die ] ]
      set energy energy + 8
    ]
  ]
  if any? algae-here [
    let food-eaten 0
    ask algae-here [
      if food-eaten < 0.05 [
        let eat-amount min (list 0.05
biomass)
        set biomass biomass - eat-amount
        set food-eaten food-eaten + eat-
amount
        if biomass <= 0 [ die ]
      ]
    ]
    set energy energy + (food-eaten * 6)
  ]
end
to eat-algae
  if any? algae-here [
    let food-eaten 0
    ask algae-here [
      if food-eaten < 0.05 [
        let eat-amount min (list 0.05
biomass)
        set biomass biomass - eat-amount
        set food-eaten food-eaten + eat-
amount
        if biomass <= 0 [ die ]
      ]
    ]
    set energy energy + (food-eaten * 6)
  ]
end
to eat-fish
  let prey fishes-here with [fish-type !=
"predatory" and size < [size] of myself]
  if any? prey [
    let target min-one-of prey [energy]
    if target != nobody and random-float 1
< 0.3 [
      ask target [ die ]
      set energy energy + 20
    ]
  ]
end
; Weevil setup and behavior
to setup-weevils
  create-weevils initial-weevil-population
[
    move-to one-of patches with [depth < 2]
; Only spawn on non-river patches
    set color brown
    set shape "bug"
    set size 0.5
    set life-stage "adult"
    set feeding-rate 0.1
    set energy 100
  ]
end
to update-weevils
  ask weevils [
    move-weevils
    if life-stage = "larva" [
      feed-weevil
    ]
    reproduce-weevils
    age-and-die
    check-energy
  ]
end
to move-weevils
  ; Prevent weevils from moving into river
patches (depth >= 2)
  if [depth] of patch-here >= 2 [ die stop
]
  if any? hyacinths-here [
    if random-float 1 > 0.2 [
      feed-weevil
      stop
    ]
  ]
  let target-plant min-one-of hyacinths in-
radius 5 [distance myself]
  if target-plant != nobody [
    let next-patch patch-ahead 1
    if [depth] of next-patch < 2 [
      face target-plant
      forward 1
      set energy energy - 0.5
    ]
```

```
  ]
  if target-plant = nobody [
    let next-patch patch-ahead 1
    rt random 360
    if [depth] of next-patch < 2 [
      fd 1
      set energy energy - 0.5
    ]
  ]
  if energy <= 0 [ die ]
end
; New procedure for weevil feeding
to feed-weevil
  let target-plant one-of hyacinths-here
  if target-plant != nobody [
    ask target-plant [
      set biomass biomass - 0.1
      if biomass <= 0 [ die ]
    ]
    ; Gain energy from feeding
    set energy energy + 5
  ]
end
; Water chemistry updates
to update-water-chemistry
  update-oxygen-levels
  update-nutrients
  update-light-penetration
end
to update-oxygen-levels
  ask patches [
    ; Base oxygen from temperature-
dependent solubility
    let solubility 14.652 - 0.41022 *
temperature + 0.007991 * (temperature ^ 2)
- 0.000077774 * (temperature ^ 3)


    ; Adjust for depth (deeper water has
less oxygen)
    let depth-factor 1 - (depth / 15)
    ; Adjust for photosynthesis and
respiration
    let plant-effect sum [biomass] of
hyacinths-here * 0.1
    let decomposition-effect detritus *
0.05
    ; Add effect of water movement (more
movement = more oxygen)
    let movement-effect current-speed * 0.2
    ; Calculate final oxygen level
    set dissolved-oxygen (solubility *
depth-factor) + plant-effect -
decomposition-effect + movement-effect
    ; Add small random fluctuations
    set dissolved-oxygen dissolved-oxygen +
(random-float 0.2 - 0.1)
    ; Ensure oxygen stays within realistic
bounds
    set dissolved-oxygen max (list 0 (min
(list dissolved-oxygen 12)))
    ; Update detritus
    set detritus max (list 0 (detritus +
      ; Add detritus from dead organisms
      (0.01 * count hyacinths-here) +
      ; Natural decomposition
      (detritus * 0.05)))
  ]
end
to update-nutrients
  ask patches [
    ; Natural nutrient cycling
    set nitrogen-level nitrogen-level *
0.95 ; Natural decay
    set phosphate-level phosphate-level *
0.95
    ; Add nutrients from agricultural
runoff
    if agricultural-runoff > 0 [
      set nitrogen-level nitrogen-level +
agricultural-runoff * 0.1
      set phosphate-level phosphate-level +
agricultural-runoff * 0.05
    ]
    ; Nutrient uptake by plants
    let plant-uptake sum [biomass] of
hyacinths-here * 0.01
    set nitrogen-level max (list 0
(nitrogen-level - plant-uptake))
    set phosphate-level max (list 0
(phosphate-level - plant-uptake))
  ]
end


to update-light-penetration
  ask patches [
    let surface-light 100
    let plant-cover sum [biomass] of
hyacinths-here
```

```
    let extinction-coefficient 0.5
    set light-level surface-light * exp (-
extinction-coefficient * (depth + plant-
cover))
  ]
end
; Update water flow patterns
to update-water-flow
  let season-factor sin (day-of-year * 360
/ 365) ; Seasonal variation
  set water-flow-rate base-flow-rate * (1 +
season-factor)
  ask patches [
    set current-speed water-flow-rate * (1
- 0.1 * sum [root-density] of hyacinths-
here)
  ]
end
; Update agricultural runoff
to update-agricultural-runoff
  let season-factor sin (day-of-year * 360
/ 365)
  set agricultural-runoff base-runoff * (1
+ season-factor)
  if random-float 1 < 0.1 [ ; Random
agricultural input pulses
    set agricultural-runoff agricultural-
runoff * (1 + random-float 1)
  ]
end
; Death procedures
to check-death
  ; Die immediately if energy is zero or
negative
  if energy <= 0 [ die ]
  ; Lose energy based on size (larger fish
use more energy)
  set energy energy - (size * 0.1)
  ; Gradual effects of low oxygen instead
of instant death
  if dissolved-oxygen < oxygen-tolerance [
    ; Reduce energy faster in low oxygen
conditions
    set energy energy - (1 + (oxygen-
tolerance - dissolved-oxygen))
  ]
  ; Age-related death chance increases with
age
  if age > (lifespan * 0.8) [
```

```
    if random-float 1 < (age - (lifespan *
0.8)) / (lifespan * 0.2) [ die ]
  ]
end
; Reproduction procedures
to reproduce-fish
  if age > 30 and energy > reproduction-
threshold and
     dissolved-oxygen > oxygen-tolerance
and
     temperature > 20 and temperature < 30
and
     random-float 1 < base-reproduction-
rate [
    let mates fishes in-radius 2 with
[fish-type = [fish-type] of myself and self
!= myself and age > 30]
    if any? mates [
      set energy energy - (reproduction-
cost * 1.5)
      let candidate-patches patches in-
radius 2 with [not any? fishes-here]
      if any? candidate-patches [
        hatch 1 [
          move-to one-of candidate-patches
          set energy initial-fish-energy
          set age 0
          set fish-type [fish-type] of
myself
          set oxygen-tolerance [oxygen-
tolerance] of myself
          set size [size] of myself
          set color [color] of myself
        ]
      ]
    ]
  ]
end
to reproduce  ; for hyacinths
  if age > 10 and energy > 50 and biomass >
2 and random-float 1 < reproduction-rate [
    let local-density count hyacinths in-
radius 2
    if local-density < 8 [
      let offspring-biomass biomass * 0.3
      set biomass biomass - offspring-
biomass
      set energy energy - 20
      let candidate-patches patches in-
radius 2 with [not any? hyacinths-here]
```

```
      if any? candidate-patches [
        hatch 1 [
          move-to one-of candidate-patches
          set biomass offspring-biomass
          set age 0
          set reproduction-rate
[reproduction-rate] of myself
          set root-density 0
          set energy 50
        ]
      ]
    ]
  ]
end
to reproduce-weevils
  if life-stage = "adult" and age > 10 and
energy > 20 and random-float 1 < weevil-
reproduction-rate [
    let hyacinth-patches patches in-radius
2 with [any? hyacinths-here]
    if any? hyacinth-patches [
      set energy energy - 10
      hatch 1 [
        move-to one-of hyacinth-patches
        set life-stage "egg"
        set age 0
        set feeding-rate [feeding-rate] of
myself
        set size 0.3
      ]
    ]
  ]
end
to age-and-die  ; for weevils
  set age age + 1
  if age > weevil-lifespan [ die ]
  ; Life stage transitions
  if life-stage = "egg" and age > egg-
duration [
    set life-stage "larva"
    set size 0.4  ; Larvae are slightly
bigger than eggs
  ]
  if life-stage = "larva" and age > larva-
duration [
    set life-stage "adult"
    set size 0.5  ; Adults are full size
  ]
end
```

```
; Update visualization with professional
effects
to update-visualization
  if show-oxygen? [
    ask patches [
      let o2-color scale-color blue
dissolved-oxygen 0 12
      set pcolor max list 0 (min list 140
(o2-color - 0.3 + random-float 0.6))
    ]
  ]
  if show-nutrients? [
    ask patches [
      let nutrient-level (nitrogen-level +
phosphate-level)
      let base-color scale-color green
nutrient-level 0 2
      set pcolor max list 0 (min list 140
(base-color - 0.2 + random-float 0.4))
    ]
  ]
  ; Professional dynamic water shimmer when
not showing data
  if not show-oxygen? and not show-
nutrients? [
    ask patches [
      if random-float 1 < 0.06 [  ; Subtle,
frequent shimmer
        let blue-color scale-color blue
depth 2 12
        let green-color scale-color green
depth 2 12
        let shimmer (sin (ticks / 10 +
pxcor * 0.18 + pycor * 0.23) * 1.2)
        let base-color ((blue-color * 0.7)
+ (green-color * 0.3))
        let final-color base-color +
shimmer
        ifelse depth < 2.2 [
          set pcolor max list 0 (min list
140 (final-color + 3 + random-float 0.7))
        ] [
          ifelse depth < 5.5 [
            set pcolor max list 0 (min list
140 (final-color + random-float 0.5))
          ] [
            set pcolor max list 0 (min list
140 (final-color - 2 - random-float 0.7))
          ]
        ]
```

```
      ]
    ]
  ]
end
; Calculate trophic efficiency
to calculate-trophic-efficiency
  let producer-biomass sum [biomass] of
hyacinths
  let herbivore-biomass sum [energy] of
fishes with [fish-type = "herbivorous"]
  let carnivore-biomass sum [energy] of
fishes with [fish-type = "predatory"]
  ; Avoid division by zero
  if producer-biomass > 0 [
    let herbivore-efficiency herbivore-
biomass / producer-biomass
    let carnivore-efficiency 0
    if herbivore-biomass > 0 [
      set carnivore-efficiency carnivore-
biomass / herbivore-biomass
    ]
    set trophic-efficiency (herbivore-
efficiency + carnivore-efficiency) / 2
  ]
end
; Simulation parameters
to-report base-growth-rate
  report 0.1
end
to-report reproduction-threshold
  report 150
end
to-report base-reproduction-rate
  report 0.05
end
to-report reproduction-cost
  report 50
end
to-report initial-fish-energy
  report 100
end
to-report weevil-reproduction-rate
  report 0.1
end
to-report egg-duration
  report 7
end
to-report larva-duration
  report 21
end
to-report weevil-lifespan
  report 90
end
to-report lifespan
  report 365
end
; New procedure for algae setup
to setup-algae
  create-algae initial-algae-population [
    setxy random-xcor random-ycor
    set biomass 0.1 + random-float 0.2
    set growth-rate 0.15
    set color green - 2
    set shape "dot"
  ]
end
; Helper reporter to check if a patch is
within the river
to-report is-river?
  report true  ; All patches are river now
end
; New procedure to check energy levels
to check-energy
  if energy <= 0 [ die ]
end
; --- MEANDERING CHANNEL ---
to setup-meandering-channel
  let amplitude (max-pycor / 4)
  let wavelength (max-pxcor / 2)
  ask patches [
    let channel-center-y (amplitude * sin
(pxcor / wavelength * 2 * pi))
    set floodplain? (abs (pycor - channel-
center-y) < (max-pycor / 2.5))
    set depth 0 ; will be set in next step
  ]
end
; --- DEPTH PROFILE ---
to setup-depth-profile
  let amplitude (max-pycor / 4)
  let wavelength (max-pxcor / 2)
  ask patches [
    let channel-center-y (amplitude * sin
(pxcor / wavelength * 2 * pi))
    let dist-from-center abs (pycor -
channel-center-y)
    ifelse dist-from-center < (max-pycor /
6) [
```

```
      set depth 10 - (dist-from-center *
1.5) + random-float 0.5
    ] [
      set depth 3 - (dist-from-center *
0.3) + random-float 0.5
    ]
    if depth < 0 [ set depth 0 ]
  ]
end
; --- SUBSTRATE TYPES ---
to assign-substrate-types
  ask patches [
    if depth < 2 [ set substrate-type
"sand" ]
    if depth >= 2 and depth < 4 [ set
substrate-type "silt" ]
    if depth >= 4 and depth < 7 [ set
substrate-type "clay" ]
    if depth >= 7 [ set substrate-type
"rock" ]
  ]
end
; --- FLOODPLAINS ---
to setup-floodplains
  ask patches [
    if floodplain? and depth < 2 [ set
floodplain? true ]
  ]
end
; --- INITIAL COLORING ---
to color-riverbed-initial
  ask patches [
    set floodplain? false
  ]
  ask patches [
    let base-color 0
    if substrate-type = "sand" [ set base-
color 98 ]
    if substrate-type = "silt" [ set base-
color 105 ]
    if substrate-type = "clay" [ set base-
color 95 ]
    if substrate-type = "rock" [ set base-
color 85 ]
    if floodplain? [ set base-color base-
color + 2 ]
    set pcolor base-color
  ]
end
; --- HYACINTH MOVEMENT (REALISTIC) ---
to move-with-water
  let local-current [current-speed] of
patch-here
  if local-current > 0.5 and [depth] of
patch-here > 0 [
    let target-patch patch-at 1 0 ; east
    if target-patch != nobody and [depth]
of target-patch > 0 [
      move-to target-patch
    ]
    if random-float 1 < 0.05 [
      let drift-patch patch-at 1 (one-of [-
1 1])
      if drift-patch != nobody and [depth]
of drift-patch > 0 [
        move-to drift-patch
      ]
    ]
  ]
End
```

The flow chart code:

Portion 1 (Setup):

https://www.mermaidchart.com/app/projects/0b7d21fd-f729-47e8-8b4c-f7122f751450/diagrams/4b4cba92-51e4-4e31-873c-afd4e43935e0/version/v0.1/edit

Portion 2:

https://www.mermaidchart.com/app/projects/0b7d21fd-f729-47e8-8b4c-f7122f751450/diagrams/1b2e0c6b-bf67-487b-9573-cc658a4bec6e/version/v0.1/edit

The behavior space code:

```
data <-
read.csv("C:/Users/nadam/OneDrive/Desktop/DATA.csv")
head(data)
summary(data)
# Load necessary libraries
library(lmtest)    # For diagnostic tests
library(car)       # For VIF calculation
library(gvlma)     # For comprehensive
model assessment
library(performance) # For model checking
plots
library(ggplot2)   # For advanced plotting


full_model_quadratic <-
lm(total.plant.consumed
~initial.hyacinth.population+
                           log(initial.weev
il.population)+ I(count.hyacinths^2) +
                           I(count.fishes^2
) ,
                           data = data)
summary(full_model_quadratic)

# Normality of Residuals
# QQ plot for visual inspection
qqnorm(resid(full_model_quadratic), main =
"Q-Q Plot of Residuals")
qqline(resid(full_model_quadratic))

# Homoscedasticity (Constant Variance)
# Residuals vs Fitted plot
plot(fitted(full_model_quadratic),
resid(full_model_quadratic),
     xlab = "Fitted Values", ylab =
"Residuals",
     main = "Residuals vs Fitted Values")
abline(h = 0, col = "red")
model_quadratic=lm(total.plant.consumed
~initial.hyacinth.population+
                            initial.weevil.
population+ count.hyacinths +
                            I(count.fishes^
2),
                          data = data)
```

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