AQUATIC ECOSYSTEM SIMULATOR

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AIMS AND OBJECTIVES

EDUCATIONAL

- To provide a flexible learning aid for experimental study of community function and dynamics on the computer, separate from the processes of mathematical modelling and programming.

- To provide substitute experiences for aspects of the curriculum which would otherwise be impossible to satisfy in reality due to restrictions of time and resources; in particular, long term experimental studies on the natural environment, in which many interacting physical, chemical, and biological elements change over time.

- To enrich knowledge and understanding of ecology and environmental issues through simulation and interpretation of convincing and realistic data, which emulate physico-chemical conditions, ecological processes, and experiences existing in the "real world"

- To promote acquisition and development of high order skills such as hypothesis testing, problem-solving, enquiry learning, and critical evaluation of quantitative data.

BIOLOGICAL

- To simulate the physico-chemical and trophic dynamics of generalised freshwater ecosystems (e.g. lakes, large rivers and canals) containing functional groups (guilds) of organisms forming planktonic and benthic food webs.

- To simulate primary production limited by seasonal variations in solar radiation (light and temperature) and nutrients (silicate, nitrate, phosphate, and carbon dioxide, derived from the inflow of water, plus recycling by respiration, excretion, and detritus decomposition) with associated fluctuations in water quality (conductivity, pH, and dissolved oxygen).

- To simulate temporal and spatial variations in the biomass of primary producers (planktonic and benthic green algae, cyanobacteria, diatoms and aquatic macrophytes) and secondary producers (zooplankton, benthic invertebrates, and fish) with associated dynamic interactions between the trophic levels, including the essential role of detritus as a food source.

- To simulate realistic alternative scenarios (e.g. mesotrophic-temperate, eutrophic-temperate, hypereutrophic-tropical, and oligotrophic-arctic systems) using default parameters.

- To permit the execution of a range of simulated experiments (e.g. on eutrophication, climate change, trophic cascades, food-chain dynamics, and competitive exclusion) through manipulation of realistic system variables.

AQUATIC ECOSYSTEM SIMULATOR
OPTIONS

ECOSYSTEM	
Arctic	Use default parameters for an Oligotrophic ecosystem in a cold climate near the Arctic circle. The water column is permanently well mixed. The surface is covered by ice in winter and the maximum flow of water is in summer.
North-Temperate 1	Use default parameters for a lowland Eutrophic ecosystem in a warm North-Temperate climate. The water column is thermal stratified in summer when the flow of water is minimum. The maximum flows are in spring and autumn when the water column overturns. There is no covering of ice in winter.
North-Temperate 2	Use default parameters for a highland Mesotrophic ecosystem in a cool North-Temperate climate. The surface is covered by ice in winter. The water column does not thermally stratify and is permanently well mixed. The maximum flows are in spring and autumn with minimum flow in summer.
Tropical	Use default parameters for a Hyper-eutrophic ecosystem in a moist Tropical climate, North of the Equator, near the Tropic of Cancer, which has one wet season and one dry season. The water column is permanently warm and thermally stratified. The maximum flow of water is in the wet season and the minimum flow is in the dry season.
File	Use the ecosystem with manipulated parameters saved in a Microsoft Windows Text (*.txt) file
SIMULATION	
START	Perform an initial simulation, using default or saved parameters.
DELETE	Erase all simulated data, and reset all parameters to zero.
EXIT	Quit the program, and return to Microsoft Windows.
GRAPHICS	
GRAPHS	Display a cascade of line-graphs.
CHARTS	Display a cascade of charts.
TABLES	Display a cascade of tables.
PHOTOS	Display photographs of aquatic ecosystems and organisms.
Graphics Options are Enabled	The selection and display of line-graphs, charts, photographs, and tables is permitted.
EXPERIMENTS	
Manipulation of Variables is Enabled	The manual alteration of certain parameters is permitted.
Include Random Driving Variables	Random variations in light, temperature, water flow, vertical mixing, and inflow nutrient concentrations occur during the simulation. (Default values are non-random.)
CONSTANTS	Display a table of fixed parameters, which cannot be manipulated.
VARIABLES	Display a table of variable parameters which can be manipulated.
UPDATE	Continue the simulation, with manipulated parameters, and end of year values from the last simulation.
RESTART	Return to the initial simulation using default or saved parameters.
FILES	
Save Text	Save all variables and constants in a Microsoft Windows Text (*.txt) file
Save Bitmap	Save a line-graph, chart, or table of simulated data as a Microsoft Windows Bitmap (*.bmp) file.
Save Excel	Populate a Microsoft Excel spreadsheet with simulated data
Open Word	Open a Microsoft Word document

TROPHIC STATUS

The average annual phytoplankton biomass, expressed as chlorophyll, is used to assess the trophic status of aquatic ecosystems. The following categories are recognized:

Trophic Status	Chlorophyll (mg/m^3)
Ultra-oligotrophic	< 0.7
Oligotrophic	0.8 – 2.1
Mesotrophic	2.2 - 6.2
Eutrophic	6.3 – 19.2
Hyper-eutrophic	> 19.2

This experiment tests the hypothesis that trophic status varies with respect to the nutrient concentrations in the inflowing water. It also tests the theory that carnivores are eliminated first from a stressed food chain, followed by herbivores, and finally detritivores, which may survive in the absence of primary production.

1: Select **North-Temperate 1** as the **ECOSYSTEM**. Observe the initial values of the state variables. Click **START** for the initial simulation of a eutrophic ecosystem. View the **Summary of Simulated Data.** Select the **GRAPHICS** options to observe photos, graphs, charts, and data tables.

2: Select **VARIABLES**. Under **AVERAGE INFLOW NUTRIENTS (mg/m^3)** click in the **Silicate (Inflow)** box and enter **5000.** Enter **50** in **Nitrate (Inflow)** and **5** in **Phosphate (Inflow).** Click **UPDATE** to continue the simulation with manipulated variables and end of year values. Observe the change in trophic status from eutrophic to mesotrophic.

3: Click **VARIABLES.** Enter **20** in **Nitrate (Inflow)** and **2** in **Phosphate (Inflow)**. (**Silicate (Inflow)** remains at **5000** to support diatoms.) **UPDATE** and observe the degradation in trophic status to oligotrophic. Primary producers with high nutrient requirements (Cyanobacteria and floating macrophytes) are eliminated, but a complete food chain is sustained.

4: Click **VARIABLES.** Enter **10** in **Nitrate (Inflow)** and **1** in **Phosphate (Inflow)**. **UPDATE** and observe the decline in primary and secondary production with the exclusion of top carnivores (Piscivorous fish) from the oligotrophic ecosystem.

5: Click **VARIABLES.** Enter **500** in **Silicate (Inflow)** **5** in **Nitrate (Inflow)** and **0.5** in **Phosphate (Inflow)**. (The threshold nutrient concentrations below which aquatic primary production ceases). **UPDATE** and observe the ultra-oligotrophic ecosystem in which two more trophic level of carnivores (Planktivorous Fish and Carnivorous Zooplankton) are excluded.

6: Click **VARIABLES.** Enter **400** in **Silicate (Inflow)** **4** in **Nitrate (Inflow)** and **0.4** in **Phosphate (Inflow)**. **UPDATE** and observe the elimination of the phytoplankton and periphyton; however a food-chain still survives, based on detritus. Observe the **Ingestion** graphs, indicating that **Benthic Herbivores** switch to ingestion of detritus in the absence of periphyton, so their **Food Chain Efficiency** is erroneous. Click **VARIABLES** and eliminate the food chain using values of **0** for **Initial Detritus (Planktonic), Initial Detritus (Benthic)** and **Terrestrial Detritus** then **UPDATE** several times.

7: Click **DELETE** to erase the simulation, or return to **Step 1** to perform another experiment (e.g. Repeat **Steps 1 to 6,** but check **Include Random Driving Variables**, for more realistic simulations, in which the physico-chemical variables exhibit random variations reflecting natural conditions, but unusual events may occur) or **EXIT** to quit the program.

FOOD CHAIN

These experiments test the validity of the food chain concept, which is an over-simplification of reality. Many species do not ingest just one food source, but switch their diets according to the types of food available at different stages in their life cycles; therefore they do not belong to one trophic level. Some species are not members of a food chain (e.g. migrants passing through an ecosystem without feeding, which do not contribute to the energy flow). Violations of the food chain concept confound the construction of pyramids of biomass, and complicate the estimation of food chain efficiencies.

1: Species are classified as herbivores or carnivores when their preferred food sources are living plants or animals; however, herbivores and carnivores may also ingest detritus, either incidentally, or when their preferred food sources are scarce. Select **ARCTIC** as the **Ecosystem** and **START.** Observe the inclusion of detritus as a food source in the graphs of **Ingestion** by **Zooplankton, Benthic Herbivores**, and **Planktivorous Fish**. The ingestion of detritus confounds the calculation of **Food Chain Efficiencies**, because detritus is not included in the calculations. Click **VARIABLES** and change the **Maximum Growth Rate** of **Diatoms, Cyanobacteria**, and **Green Algae** to **0** division/day then **UPDATE.** Observe the elimination of **Phytoplankton** and **Periphyton;** however the **Zooplankton**, **Benthic Herbivores** and **Planktivorous Fish** are not excluded as a result of the scarcity of food. Observe in the graphs of **Ingestion** by **Zooplankton**, **Benthic Herbivores**, and **Planktivorous Fish** that detritus becomes the main food source, and this results in erroneous **Food Chain Efficiencies**.

2: Most Arctic fish species in oligotrophic ecosystems are migrants, because there is insufficient food to support their energy requirements throughout the year. Some Piscivorous fish (e.g. adult Atlantic Salmon) migrate into freshwater from the sea to reproduce, but they do not feed in freshwater. The inclusion of such fish in biomass pyramids and estimates of food chain efficiency is anomolous. Click **RESTART** to return to the default simulation of the **ARCTIC** ecosystem. Observe the top-heavy **Pyramid of Biomass** and the excessive **Food Chain Efficiency** of **Piscivorous Fish**. Observe the graphs of **Fish**, **Migration,**and **Ingestion** by **Piscivorous Fish**. Note that the increased biomass of **Piscivorous Fish** in the Arctic summer is a result of migration, not through energy flow in the food chain. Click **VARIABLES** and increase the **Average Solar Radiation** to **15** and the **Range in Solar Radiation** to **15** MJ/m2/day then **UPDATE**. Observe the biomass of **Fish** and **Migration**, and note that when the climate is changed, the migratory fish are excluded.

3. Piscivorous fish do not always derive energy from lower trophic levels. They may prey on other piscivorous fish in the same trophic level, including cannabalism of their own species. **DELETE** to erase the previous simulation. Select **NORTH-TEMPERATE 1** as the **Ecosystem** and **START.** Observe the graphs of **Fish Biomass** and **Ingestion** by **Piscivorous Fish** which show that fish in lower trophic levels are the preferred prey. Click **VARIABLES** and reduce the **Maximum Ingestion Rate** of **Benthic Fish** and **Planktivorous Fish** to **0.05** then **UPDATE**. Observe the graphs of **Fish Biomass** and note that the biomass of **Piscivorous Fish** is sustained. Display the graph of **Ingestion** by **Piscivorous Fish** and observe the switch in diet to Piscivorous Fish in the same trophic level, in response to the lack of preferred prey. **EXIT** to quit the program.

POLLUTION

These experiments test the hypothesis that the predicted impacts of discharging excessive concentrations of nutrients into an aquatic ecosystem include changes in the biomass of primary and secondary producers, with associated changes in photosynthesis, respiration, and water quality (e.g. conductivity, dissolved oxygen, and pH.)

1: Select **North-Temperate 2** as the **ECOSYSTEM.** Click **START** and observe the graphs of **Inflow Nutrients**, **Phytoplankton, Periphyton, Macrophytes**, **Primary Production**, **Respiration**, **Conductivity**, **Dissolved Oxygen**, and **pH**. Click **VARIABLES** and under **POLLUTION CONTROL** enter **90** in **Time of Start (days); 60** in **Duration of Control (days); 300** in **± Nitrate (mg/m3**); and **30** in **± Phosphate (mg/m3**). These values simulate the discharge of an organic effluent (e.g. sewage or agricultural waste, enrichiched with nutrients) into the inflow for 60 days from day 90 to day 150

2: Click **UPDATE** and observe the change in **Inflow Nutrients** (including silicate, which increases in proportion to nitrate and phosphate). Record the changes in **Primary Production** and the concomitant stimulation of **Phytoplankton** and **Periphyton** biomass. Observe the associated impacts of organic pollution on the ecosystem, e.g. the changes in **Respiration**, **Dissolved Oxygen**, **Conductivity**, **pH**, and the fluctuations in the biomass of **Macrophytes, Zooplankton** and **Benthic Invertebrates** (including the exclusion of invertebrates which are sensitive to changes in dissolved oxygen).

3: Click **DELETE** to erase the data. Select **North Temperate 1** as the **ECOSYSTEM** and **START** the initial simulation. Click **VARIABLES** and enter **3** in **Duration of Simulation (Years)**. Under **AVERAGE INFLOW NUTRIENTS (mg/m^3)** enter **150000** in **Silicate (Inflow), 300** in **Nitrate (Inflow)** and **30** in **Phosphate (Inflow).** Click **UPDATE** and observe the impact of eutrophication, with an elevation in trophic status from **eutrophic** to **hyper-eutrophic.**

4: Control eutrophication by removing phosphate and nitrate. Click **VARIABLES**, and under **POLLUTION CONTROL** enter **365** in **Time of Start (days), 365** in **Duration of Control (days), –150** in **± Nitrate (mg/m3**); and **-15** in **± Phosphate (mg/m3**). The negative values simulate the removal of a nutrient-rich discharge from the inflow for one year, between years 1 and 3. Click **UPDATE** and observe the changes in the biomass of **Phytoplankton, Periphyton, Macrophytes, Zooplankton, and Benthic Invertebrates** associated with the removal of the nutrient-rich effluent.

5: Click **VARIABLES** and repeat with different concentrations (e.g. **–50** in **± Nitrate (mg/m3**); and **-5** in **± Phosphate (mg/m3**). Continue with a wider range of ± nitrate and phosphate concentrations (assuming a 10:1 ratio), and examine the relationships between the changes in the nutrient concentrations and the changes in the biomass of primary producers.

6: Click **DELETE** to erase the simulated data . Return to **Step 1** to perform another experiment on eutrophication,
(e.g. in **Arctic, North-Temperate 2,** and **Tropical** ecosystems) or **EXIT** to quit the program.

CLIMATE CHANGE

This experiment tests the hypothesis that global and seasonal variations in primary and secondary production in aquatic ecosystems depend on (and are consequently correlated with) spatial and temporal variations in solar radiation.

1: Select **Arctic** as the **ECOSYSTEM** and **START** the simulation with default values. Observe that the period of maximum primary and secondary production is restricted to the short period of high solar radiation during the summer.

2: Click **VARIABLES** and under **CLIMATE CHANGE** enter **14** MJ/m^2/dayfor **Average Solar Radiation** and **15** for **Range in Solar Radiation** (as in the **Temperate 2** Ecosystem). Click **UPDATE** several times, and observe that the period of maximum primary and secondary production extends from spring to autumn (as in the **Temperate 2** ecosystem).

3: Click **VARIABLES** and under **CLIMATE CHANGE** enter a value of **25** MJ/m^2/day for **Average Solar Radiation** and **5** for **Range in Solar Radiation** (as in the **Tropical** ecosystem). Click **UPDATE** several times and observe that primary and secondary production is now continuous throughout the year (as in the **Tropical** ecosystem).

4: Click **DELETE** to erase the data. Select **North Temperate 2** as the **ECOSYSTEM** and **START** the simulation. Click **VARIABLES** and under **CLIMATE CHANGE** enter a value of **5** MJ/m^2/day for the **Average Solar Radiation** and **25** for the **Range in Solar Radiation** (as in the **Arctic** ecosystem) to simulate another ice–age. Click **UPDATE** and observe the restriction of maximum primary and secondary production to the summer period (as in the **Arctic** ecosystem).

5: DELETE the simulated data and return to **Step 1** to perform a more detailed global warming experiment. Select **Arctic** as the **ECOSYSTEM** and **START** with default values. Click **VARIABLES** and increment the **Average Solar Radiation** by **1** (to **6**) and decrement the **Range in Solar Radiation** by **1** (to **24**). **UPDATE** and observe the changes. Increment the **Average** by **1** (to **7**) and decrement the **Range** by 1 (to **23**). **UPDATE** and observe the changes. Continue increasing the **Average** by 1 and decrementing the **Range** by 1 in successive steps. Observe the changes after each **UPDATE** until the **Average** is **25** and the Range is **5**, when the climate has been changed to Tropical, with one wet season and one dry season.

6: To simulate a Tropical Equatorial climate (with two wet seasons and two dry seasons) click **VARIABLES**, enter **25** for **Average Solar Radiation**, **5** for **Range in Solar Radiation**, **91.25** for **Time of Maximum Solar Radiation (days)** and **182.5** for **Periodicity of Solar Radiation Curve (days)** then **UPDATE.**

7: What would happen if the solar radiation received on earth was insufficient to support photosynthesis? (e.g. if the sun expired, or a dust cloud from a volcanic eruption or nuclear explosion shrouded the atmosphere). Click **VARIABLES**, change **Average Solar Radiation** to **1**, **Range in Solar Radiation** to **1** and **UPDATE** several times to predict if primary production is still possible under such extreme conditions. **EXIT** to quit the program.

TROPHIC CASCADES AND BIOMANIPULATION

In theory, if the abundance of predators (e.g. piscivorous fish) in an aquatic ecosystem is increased (e.g. by fishery management) the abundance of prey (e.g. planktivorous fish) should decrease, due to high predation pressure. Diminished predation from planktivorous fish should cause an increase in the biomass of zooplankton, and the consequent elevation in grazing pressure should cause the phytoplankton biomass to decrease. This is termed a "**top-down trophic cascade".**

Alternatively, a **"bottom-up cascade"** occurs when the biomass of the prey is not determined by predation, but depends ultimately on the physico-chemical variables (e.g. nitrate, phosphate, silicate and solar radiation) which limit primary production at the base of the food chain.

In reality, the dynamics of aquatic food webs are not so simple, and **biomanipulation** (i.e. changes in trophic structure created by man) does not always result in a trophic cascade. The intensity of a trophic cascade depends on many interactions, and the intrinsic biological characteristics of the organisms in each trophic level appear to be instrumental. An experiment is described to test this hypothesis.

1: Select **NORTH TEMPERATE 1** as the ecosystem. **START** the simulation and record the **Phytoplankton, Zooplankton,** and **Fish** biomass. Click **VARIABLES** and increase the initial biomass of **Piscivorous Fish** to **1000 mg/m^3** to simulate biomanipulation. **UPDATE** and observe the graph of **Fish biomass**. The piscivorous fish do not surpress their prey, but decline to a value which can be sustained by the available biomass of planktivorous and benthic fish. The biomass of planktivorous fish, zooplankton, and phytoplankton do not change and a top down trophic cascade is not simulated.

2. DELETE the simulated data. Repeat the biomanipulation on **ARCTIC**, **NORTH TEMPERATE 2**, and **TROPICAL ECOSYSTEMS**. The results of this and other experiments (e.g. manipulation of nitrate, phosphate, and solar radiation) indicate that the trophic dynamics of the ecosystems are controlled by "bottom-up" and not "top-down" mechanisms.

3: Top-down mechanisms can be simulated only if the instrinsic biological characteristics of the organisms are manipulated. e.g. select **NORTH TEMPERATE 1** as the ecosystem. **START** the simulation and record the biomass of **Phytoplankton, Zooplankton**, and **Planktivorous Fish**. Click **VARIABLES** and change the **Half Saturation Coefficient** for **Herbivorous Zooplankton on Phytoplankton** to **60 mg/m3,** the **Half Saturation Coefficient** for **Piscivorous Fish on Planktivorous Fish** to **2 mg/m3,** and the **Maximum Ingestion Rate of Zooplankton (Herbivorous)** to **0.7/day. UPDATE** and observe the decreases in biomass of **Phytoplankton** and **Planktivorous fish** and the increase in the biomass of **Zooplankton.**

4: DELETE and perform another experiment (e.g. manipulate the **Half Saturation Coefficients** and **Maximum Ingestion Rates** of **Benthic fish** to simulate a top-down cascade on **Benthic Invertebrates** and **Periphyton**) or **EXIT** to quit the program.

LIMITING FACTORS

The abundance of diatoms in the spring and autumn, with a decline in diatom biomass during the summer, is a characteristic feature of North-Temperate aquatic ecosystems. These experiments test three hypotheses to identify the factors which account for the decline in the biomass of diatoms in summer: (a) inhibition of growth due to low concentrations of limiting nutrients (b) high grazing pressure from herbivores and /or (c) increased rates of vertical sinking down the water column.

1: Select **North-Temperate 2** as the **ECOSYSTEM**. Click **START** and observe the graphs of **Phytoplankton Biomass**, **Periphyton Biomass**, **Planktonic Nutrients** and **Limiting Nutrients**. Observe the decline in the biomass of diatoms, and the reductions in the **Planktonic Nutrients** and the **Limiting Nutrients** values for nitrate, phosphate, and silicate in the summer.

2: Increase the concentrations of growth limiting nutrients to determine if the decline in diatoms was caused by nutrient limitation. Click **VARIABLES** and under **AVERAGE INFLOW CONCENTRATIONS** enter **150000** mg/m^3 for **Silicate (Inflow), 300** mg/m^3 for **Nitrate (Inflow)** and **30** mg/m^3 for **Phosphate (Inflow)** then **UPDATE.** Observe that the biomass of diatoms no longer declines in summer, because **Limiting Nutrients** do not inhibit growth. Click **DELETE** to erase the data.

3: Select **North-Temperate 1** as the **ECOSYSTEM**. Repeat the same experiment as in Steps 1 and 2 (above) for the **North-Temperate 2** ecosystem. Observe that the decline in biomass of both planktonic and benthic diatoms still occurs in the summer, even when **Limiting Nutrients** do not inhibit growth, so it appears that nutrient limitation is not responsible.

4: Reduce the rates of ingestion of diatoms by herbivores to determine if the summer decline in diatom biomass is related to grazing pressure. Click **VARIABLES** and under **MAXIMUM INGESTION RATE** enter **0.2** /day for **Zooplankton (Herbivorous)** and **0.2** / day for **Benthic Herbivores** then **UPDATE.** Observe that the biomass of diatoms in the periphyton no longer decline in the summer, indicating that high grazing pressure is a factor which causes the decline.

5: The biomass of planktonic diatoms still declines in summer when the grazing pressure is reduced, indicating that another factor is responsible for the decline. Click **Mortality** and **Phytoplankton Sinking** to observe the maximum sinking rate of diatoms during low flow, minimal mixing, and thermal stratification in summer, when the water column is static and not turbulent. When the water is turbulent, well mixed, and not thermally stratified (during spring and autumn), then planktonic diatoms do not sink so fast, and remain longer in suspension. (Conversely, planktonic Cyanobacteria and Green Algae sink less during the summer). Under **MAXIMUM SINKING RATE**, reduce the value to **0.01 m**/day for **Planktonic Diatoms** then **UPDATE** and observe **Phytoplankton Sinking.** The biomass of diatoms no longer declines in the summer when the rate of sinking is reduced, indicating that an increase in sinking rate is responsible for the summer decline.

6: Carry out further experiments to determine the limiting factors which cause the biomass of phytoplankton and periphyton to decline in the winter in **North Temperate** and **Arctic** ecosystems, or **EXIT** to quit the program.

FLOODS

These experiments test the hypothesis that floods (excessive flows of water) influence the community dynamics of aquatic ecosystems. Floods may cause aquatic organisms to be displaced and possibly excluded from their normal habitats. Planktonic organisms and floating macrophytes may be washed downstream and lost by efflux to the outflow. Benthic organisms and submerged macrophytes may be eroded from the substratum and entrained by the flow. Fish often migrate when the flow of water increases. The high turbidity of flood water may reduce light penetration and limit photosynthesis.

1: Select **TROPICAL** as the **Ecosystem** and **START.** Observe the relatively constant biomass of **Phytoplankton**, **Periphyton, Aquatic Macrophytes**, **Zooplankton** and **Fish** throughout the year. Biomass is maintained despite the increased loss of organisms by efflux to the outflow during the wet season, displayed in the graph of **Mortality (Efflux to Outflow)**.

2: Click **VARIABLES** and under **HYDROLOGY** simulate a flood by entering **100** m^3/sec in **Flood Water Flow**. **UPDATE** and observe the graphs which display the impact of the flood during the wet season on the biomass of **Phytoplankton**, **Periphyton, Aquatic Macrophytes**, **Zooplankton**, and **Fish**.

3: Note the increased turbidity of the water, indicated by the the change in the vertical attenuation of **Solar Radiation**, which is associated with a reduction in **Primary Production**. Observe also the decrease in **Hydraulic Retention Time** in the **Hydrology** graph. When the retention (or residence) time of water stored in an aquatic ecosystem is low, then the phytoplankton, zooplankton and floating macrophytes do not have sufficient time to multiply. A retention time of at least one week is generally required to maintain a high biomass of planktonic and floating organisms in freshwater ecosystems.

4: Floods may be associated with anomolous pyramids of biomass and erroneous food chain efficiencies if organisms switch their diets, and/or are displaced or excluded from their habitats, and/or if fish migration is promoted. **DELETE** the previous simulation, select **ARCTIC** as the Ecosystem and **START.** Observe the graphs which display the increase in biomass of **Phytoplankton**, **Periphyton, Aquatic Macrophytes**, **Zooplankton,** and **Fish** during the summer. Click **VARIABLES** and under **HYDROLOGY** simulate a flood by entering a **Flood Water Flow** of **100** m^3/sec. **UPDATE** and observe the graphs which display the impact of the summer flood (including the lowering of the **Hydraulic Retention Time** to less than one week) on the biomass of **Phytoplankton**, **Periphyton, Aquatic Macrophytes** and **Zooplankton**. Note the relationship between the **Flood Water Flow** and the **Migration** of fish. Observe the impact of the flood on the **Pyramids of Biomass**. Observe the graphs of **Ingestion** of food by zooplankton, benthic invertebrates, and fish, and determine if the flood was associated with switches in diet, resulting in erroneous **Food Chain Efficiencies**.

5: Repeat the experiments described in Steps 1-4 to investigate the impact of floods on **NORTH TEMPERATE 1 and NORTH TEMPERATE 2** ecosystems (where the maximum water flows occur during the spring and autumn) or **EXIT** to quit the program.

COMPETITIVE EXCLUSION

This experiment tests the hypothesis that organisms are excluded from a community if they lack the intrinsic biological abilities to compete for resources (e.g. nutrients and space) with co-existing organisms.

1: Select **Tropical** as the **ECOSYSTEM** and **START** the simulation with default values. Observe the relatively constant biomass of Diatoms, Green Algae, and Cyanobacteria in the graph of **Phytoplankton biomass**.

2: Click **VARIABLES** and observe the **Half Saturation Coefficients** (the nutrient concentrations that promote half the maximum growth rates). Increase the value for **Planktonic Cyanobacteria on Phosphate** to **50** mg/m^3.

3: Click **UPDATE** and observe the exclusion of the Cyanobacteria in the the graph of **Phytoplankton Biomass**.

4: Click **VARIABLES**. Double-click in the **Half Saturation Coefficient** for **Planktonic Cyanobacteria on Phosphate** and return the default value. Increase the **Half Saturation Coefficient** for **Planktonic Green Algae on Nitrate** to **1000** mg/m^3. **UPDATE** and observe the exclusion of the Green Algae and the recovery of the Cyanobacteria in the graph of **Phytoplankton Biomass**.

5: Click **RESTART** to return to the initial default simulation. Click **VARIABLES** and change the **Maximum Sinking Rate** of **Planktonic Diatoms** to **1 m/day** and the **Maximum Growth Rate** of **Diatoms** to **1 division/day**. **UPDATE** and observe the exclusion of the Diatoms in the graph of **Phytoplankton biomass.** Click **RESTART** to return to the initial default simulation

6: Observe the graph of **Zooplankton biomass**. Click **VARIABLES** and change the **Half Saturation Coefficient** for **Carnivorous Zooplankton on Zooplankton** to **5000 mg/m3**. **UPDATE** and observe the exclusion of carnivorous zooplankton in the graph of **Zooplankton biomass**. Click **RESTART** to return to the initial default simulation

7: Observe the graph of **Fish biomass**. Click **VARIABLES** and change the **Maximum Ingestion Rate** of **Planktivorous Fish** to **0.02 /day** (i.e. 2% of the biomass of the fish per day). **UPDATE** and observe the exclusion of planktivorous fish in the graph of **Fish biomass**. Click **RESTART** to return to the initial default simulation.

8: Click **DELETE** to erase the data, or perform more experiments to test the exclusion hypothesis (e.g. by manipulating variables which control the instrinsic abilities of organisms to compete for resources) or **EXIT** to quit the program.

SOURCES OF INFORMATION

Bowker D. W. & Randerson P. F. (1989). A computer simulation of the trophic dynamics of an aquatic system. *Journal of Biological Education*, 23: 32-36

Closs G., Downes B.J. & Boulton A. (2004) *Freshwater Ecology: A Scientific Introduction*. Blackwell Science. Oxford.

Dodds W.K. (2002) *Freshwater Ecology: Concepts and Environmental Applications*. Academic Press. San Diego.

Moss B. (1998) *Ecology of Freshwaters: Man and Medium, Past to Future*. Blackwell Science. Oxford.

Pauly D. & Christensen V. (2002) Chapter 10: Ecosystem Models. In: *Handbook of Fish Biology and Fisheries.* Ed. by P. J. B. Hart & J. D. Reynolds, Blackwell Science, Oxford

Reynolds C.S. (1984) *The Ecology of Freshwater Phytoplankton*. Cambridge University Press. New York.

Reynolds C.S. (2006) *Ecology of Phytoplankton*. Cambridge University Press. New York.

Spain J.D. (1982) BASIC Microcomputer Models in Biology. Addison-Wesley. Reading, MA (USA).

Straskraba M., & Gnauck A.H. (1985) *Freshwater ecosystem modelling and simulation*. Developments in Environmental Modelling 8. Elsevier. Amsterdam.

Vollenweider R.A. & Kerekes J. (1982) *Eutrophication of Waters, Monitoring, Assessment and Control*. OECD. Paris.

Wetzel R.G. (2001) *Limnology: Lake and River Ecosystems.*. Academic Press. San Diego.

Wiegert R.G. (1993) Chapter 9. Compartment Models. In: *Biological Data Analysis: A Practical Approach*. Ed. by J.C.Fry. Oxford University Press.

WOW. (2004) Water on the Web - Monitoring Minnesota Lakes on the Internet and Training Water Science Technicians for the Future - A National On-line Curriculum using Advanced Technologies and Real-Time Data. (http://WaterOntheWeb.org). University of Minnesota-Duluth, Duluth, MN

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