EUZONE: Simulating the Evolution of Aquatic Ecosystems

Abstract In the spirit of contemporary artificial life research, EUZONE provides a virtual laboratory for the emergence of complex ecosystems from simple primitives. However, whereas most alife systems abstract away many real-world environmental constraints, EUZONE employs detailed physical and chemical models in combination with evolutionary algorithms to support the emergence of carbon-based aquatic ecosystems. With an emphasis on planktonlike organisms, this research focuses upon the self-organization and evolution of (a) lower levels of aquatic food webs, (b) Gaian interactions between primitive organisms and their physical environments, and (c) species interactions governed by varying life-history strategies.

Keywords Gaia theory, plankton, ecosystem evolution, genetic algorithms, genetic programming

1 Introduction

This research involves the simulated emergence and evolution of aquatic microorganism communities, with a special focus upon the bidirectional relationship between these populations and their physicochemical environments. The EUZONE system enables investigations into both (a) the effects of local habitats upon the nature of their biota, in terms of the emerging ethologies and population dynamics, and (b) the reverse influence, that of organisms upon their habitats. These feedback loops between biota and their environments embody Gaia theory [13] which essentially broadens the scope of evolution from organisms and populations to entire ecosystems.

EUZONE is an acronym for euphotic zone, the upper layer of the ocean where net phytoplankton (i.e., algae) growth occurs. Below this layer, which can range from a few to a few hundred meters deep (depending upon the prevailing atmospheric and oceanographic conditions), the attenuated solar irradiance is too weak to support significant photosynthesis. Aquatic life originates in the euphotic zone in the sense that algae harness solar energy and consume inorganic compounds (carbon dioxide, nitrates, and phosphates) to produce carbohydrates and proteins—thus forming the lowest level of the food web and the basis for most other aquatic biomass. The growth or blooming of phytoplankton is therefore labeled primary production.

EUZONE goes beyond conventional plankton simulation by introducing evolution, via genetic algorithms and genetic programming. If Gaia theory is correct, then as plankton evolve, inorganic aspects of the ecosystem, such as chemical concentrations, temperatures, and even climate, should also change. In addition, plankton are at the lowest level of the aquatic food web, so their evolution will surely affect higher trophic levels. In short, plankton appear to be “lever points” [11] in several important complex systems, and EUZONE positions them at the center of its modeling paradigm.
2 Plankton and Gaia Theory

The original motivation for EUZONE stems from research into the effects of phytoplankton upon the uptake of atmospheric carbon dioxide [19], along with readings in Gaia theory [3, 13]. These two subjects are intimately linked, because evidence suggests [24] that plankton can affect the climate over very long (i.e., thousand-year) time scales by altering atmospheric CO₂ levels and thus temperatures, via the greenhouse effect (or lack thereof). In addition, on a short (i.e., hourly) time scale, plankton can alter weather patterns through the release of large quantities of dimethysulfide, which serves as a condensation nucleus for cloud formation [14]. Whether short term or long term, the message is the same: A simple life form can greatly influence a large-scale physical process, which, in turn, feeds back upon the life form. A casual loop exists, and any of its components can affect any of the others.

Environmental scientists accept the effects of the physical environment upon the biota, but the reverse influence, the trademark of Gaia theory, is still controversial. For example, mass-balance diagrams for carbon dioxide [18] indicate that plankton account for 10% of the CO₂ transfer from atmosphere to ocean floor, while physical processes such as air-sea diffusion and convection take care of the rest. Some argue that this alone proves the relative unimportance of plankton in regulating large-scale physical processes. However, although 10% may seem insignificant, consider the consequences of removing the algal mechanisms of atmospheric CO₂ uptake. Whereas atmospheric carbon levels currently rise at the very disconcerting rate of 3.4 gigatons/year, that rate would quadruple if plankton photosynthesis were to stop completely and no other mechanisms could handle the surplus atmospheric CO₂. The mere fact that atmospheric CO₂ levels are rising indicates that the other mechanisms are already overloaded. So 10% is indeed quite significant: Large-scale changes in phytoplankton photosynthesis could have profound carbon-cycle, and hence climatic, effects.

The Gaia hypothesis [13] implies that

... the temperature, oxidation state, acidity, and certain aspects of the rocks and waters are at any time kept constant, and that this homeostasis is maintained by active feedback processes operated automatically and unconsciously by the biota. The conditions are only constant in the short term and evolve in synchrony with the changing needs of the biota as it evolves. Life and its environment are so closely coupled that evolution concerns Gaia, not the organisms or the environment taken separately [emphasis added]. (p. 106)

The relationship between plankton and climate comprises some of the strongest evidence to date for Gaia theory [14]. Thus, plankton modeling provides an excellent starting point for simulating evolution as it "concerns Gaia."

The immediate aims of our EUZONE research are more modest than the simulated emergence of homeostatic relationships between plankton and climate; EUZONE currently lacks an atmospheric model and is therefore restricted to the evolution of simple aquatic ecosystems. However, EUZONE does include elements of aquatic carbon chemistry, which enable investigation of another aspect of Gaia theory: the ability of autotrophs (e.g., phytoplankton) to alter the chemical composition of the biosphere to the extent that it supports oxygen-consuming heterotrophs (e.g., zooplankton). Our present focus is therefore in the euphotic zone, in the hope that correlations between the evolution of plankton and that of their ecosystem will (a) shed light on the true "levering" ability of these tiny organisms, and (b) motivate an extension of EUZONE to an ocean-atmosphere model for investigating evolution in a truly Gaian sense.
3 The Dynamics of Plankton Blooms

The euphotic zone is a very dynamic area whose depth and general ability to support primary production can vary both seasonally and daily. Cloud cover, latitude, and phytoplankton concentration all affect subsurface levels of solar radiation, and hence the euphotic zone's depth. The ambient biota along with physical oceanographic processes affect nutrient supplies (e.g., nitrates and phosphates) in the euphotic zone, making it more or less amenable to continued primary production.

The upper mixed layer (UML) overlaps the euphotic zone and plays an equally vital role in primary production. As the name suggests, the UML is the well-mixed upper layer of the ocean. Mixing coefficients are high near the surface due to wind-induced turbulence, whereas mixing coefficients at depth can be several orders of magnitude lower. Because phytoplankton are passive passengers of mixing and advective (i.e., flow) processes, they are at the mercy of the UML. If it is deep, the average plankton will cycle between the surface and perhaps several hundred meters depth in the course of hours or days. When UML depth exceeds euphotic zone depth, part of this cycle time will be spent at depths that do not support photosynthesis. Thus, under the assumption of a bountiful nutrient supply, UML depth has a generally inverse relationship to primary production.

Moving vertically up the food web, phytoplankton are consumed by zooplankton, who in turn are eaten by fish. Zooplankton also consume bacteria, which often compete with phytoplankton for nutrients. The growth of zooplankton constitutes secondary production. All organisms in the food web, including algae, perform respiration, which is essentially the reverse process of photosynthesis, because its reactants are carbohydrates, proteins, and oxygen, and its products are carbon and compounds such as ammonia and urea, which can eventually be broken down into nutrients. In short, respiration recycles nutrients and essentially turns the food chain into a self-sustaining feedback system over time scales.

However, under certain physical conditions, primary production can proceed relatively undeterred, even in the absence of nutrient recycling. Basically, a phytoplankton bloom can exhaust the euphotic zone of nutrients in a matter of days or weeks. At this point, blooming stops and algae die and sink out of the euphotic zone. However, if a bout of bad weather stirs up the surface, the UML may descend 50 to 100 or more meters, thereby mixing deep nutrients up into the euphotic zone. As soon as the weather clears, the UML stabilizes at a shallow 5–20 m depth, sunlight returns, and a new blooming period can begin.

The euphotic zone and UML are just two pieces in the complex puzzle of algal bloom dynamics, but they illustrate an important point: Primary production, and hence many other links in the aquatic food web, cannot be thoroughly understood or predicted without considerable knowledge of the ambient physical conditions. Thus, despite the relative simplicity of phytoplankton biology, the accurate simulation of primary production requires detailed physical information. It can therefore take several years to gather the necessary empirical data and build the appropriate computer models for determining the location, date, and extent of algal blooms [20].

In contrast, the EUZONE project ignores the idiosyncrasies of actual bloom events while taking a general evolutionary perspective to investigate issues such as the effects of ambient physical factors upon the types of plankton-based ecosystems that evolve. For example, is there less tendency for a nutrient-recycling system to evolve in an environment with generally calm, sunny weather interspersed with regular bouts of high wind? From a Gaian perspective, EUZONE can help answer questions concerning biological influences upon ambient physical conditions. For instance, can photosynthesis in an oxygen-depleted environment eventually raise oxygen levels enough to

Artificial Life Volume 3, Number 4

309
create niches for aerobic organisms? Finally, from a life-history viewpoint [25], EUZONE supports inquiries into relationships between temporal heterogeneities in the ambient physical factors, and, for example, the evolution of timing patterns for the progression of zooplankton between various dormant and active life stages; or between seasonal climatic stability and age of parental reproductive maturity and clutch size (i.e., number of young).

4 The EUZONE System

EUZONE interleaves two fundamental processes: environmental simulation and biological evolution. The former is designed to reflect real-world physical, chemical, and biological interactions, although several factors that most environmental modelers would specify as constants are parameterized. For example, the length of a year can be changed to raise or lower the solar cycle’s period. This flexibility adds an “alternate world” semantics to many EUZONE experiments, despite the carbon basis of all its organisms. Biological evolution is accomplished via genetic programming (GP) and genetic algorithms (GAs). Each organism’s genotype consists of a GP s-expression specifying its general behavior, and a GA bit array encoding a few dozen physical, biochemical, and life-history parameters.

EUZONE combines Eulerian (i.e., grid-centered) and Lagrangian (i.e., particle-centered) dynamics to simulate the transfer of chemicals and the movement of organisms, respectively. The environment is a two-dimensional grid, representing a vertical cross section of a body of water (i.e., one horizontal and one vertical dimension). The grid is noncylindrical because “surface” and “bottom” need to be distinguished if concepts such as “sinking” and “light attenuation with depth” are to have their usual meanings. It is also noncylindrical to leave open the possibility for varying latitudes or longitudes (and hence varying physical atmospheric factors such as light or temperature) along the horizontal dimension.

EUZONE simulations are continuous time based, with every time step consisting of a Eulerian and Lagrangian phase. In the Eulerian phase, chemicals are advected and diffused between grid cells, and factors such as sunlight and mixed-layer depth are updated. In the Lagrangian phase, each organism executes its phenotype (i.e., the translated version of its GP and GA genotype), exchanges materials with its grid cell and/or other organisms in that cell, and is influenced by the environment.

4.1 The Eulerian Phase

In this grid-centered phase, grid-cell chemical concentrations are updated using a finite-difference model based on standard advection/mixing principles [23]:

$$\frac{dQ}{dt} = -w \frac{\partial Q}{\partial z} - u \frac{\partial Q}{\partial x} + \frac{\partial}{\partial z} \left( A_v \frac{\partial Q}{\partial z} \right) + \frac{\partial}{\partial x} \left( A_h \frac{\partial Q}{\partial x} \right)$$

(1)

$Q =$ concentration of TC (total carbon), $O_2$ (oxygen), $CH_4$ (methane), or $NO_3$ (nitrate), $x$, $z =$ horizontal and vertical spatial directions, respectively, $u$, $w =$ horizontal and vertical current velocities ($dx/dt$ and $dz/dt$, respectively), $A_h$, $A_v =$ horizontal and vertical mixing coefficients, respectively.

Each horizontal and vertical grid-cell border houses a horizontal or vertical mixing coefficient, respectively. EUZONE accepts $A_h$, $A_{v_{min}}$, and $A_{v_{max}}$ as input variables. All horizontal cell boundaries then receive $A_h$, while all vertical boundaries in the UML
receive \( A_{v}^{\text{max}} \), and all those below the UML receive \( A_{v}^{\text{min}} \). The depth of the UML is determined by an input constant or time-series generator function.

Given the day of the year, hour, longitude, and latitude, the system computes the solar angle of declination [23], which is used to compute irradiance (energy flux per unit area) on the water surface, \( I_{0} \), in the absence of cloud cover. Attenuation of solar radiation is then computed down through the water column using Beer's law [16] adapted for cloud cover:

\[
I_{z} = (1 - c) I_{0} e^{-kz}
\]

\( I_{z} \) = irradiance at depth \( z \) meters  
\( k \) = attenuation coefficient of light in water  
\( c \) = cloud cover

Both \( c \) and \( k \) are dynamic variables in EUZONE. The user can supply time-series generator functions for cloud-cover data, while the attenuation coefficient is modified as a function of plankton concentration [20], thus accounting for another critical factor in plankton dynamics, self-shading, wherein high concentrations of phytoplankton significantly reduce sunlight, and hence photosynthesizing possibilities, in the layers below.

By specifying grid dimensions, longitude, latitude, time of year, UML depth, mixing coefficients, cloud cover, the initial concentrations of various chemicals, and assorted other factors, EUZONE users gain considerable control over the Eulerian phase to create a wide variety of environmental backdrops for evolutionary experiments. However, the user has even greater flexibility in defining the framework for the Lagrangian phase.

### 4.2 The Lagrangian Phase

In this particle-based phase, individual agents interact with one another and the environment. Each particle in EUZONE represents a “cloud” of organisms that are “planktonlike,” because (a) each performs only a simple set of activities, and (b) the default values for key parameters such as maximum photosynthesis, basal respiration, and feeding rates correspond to those of real phyto- and zooplankton.

#### 4.2.1 The Genetic Programming Genotype

The behavioral routine of each cloud consists of a GP s-expression, which is executed in its entirety on every time step that the cloud is in an “active” state. The GP primitive functions are listed below, with the lengths of their argument lists in parentheses:

- \text{REPRO1}(0)\): asexual reproduction
- \text{REPRO2}(0)\): sexual reproduction
- \text{EAT}(1)\): either eat nitrate (i.e., perform photosynthesis) or eat plankton
- \text{EATP}(0)\): eat plankton
- \text{PHOTO}(0)\): perform photosynthesis
- \text{MV}(2)\): move a given direction (up/down) along a given axis (vertical/horizontal)
- \text{GRAD}(2)\): compute the gradient of a quantity (light, nitrate, oxygen, etc.) along an axis
- \text{GMV}(3)\): move up/down the gradient of a quantity along an axis
- \text{AMT}(1)\): examine an internal property of the agent such as age or biomass
- \text{EXCON}(1)\): examine an external (i.e., grid-cell) concentration of a quantity

Artificial Life Volume 3, Number 4
A few logical, control, and arithmetic primitives such as AND, OR, PROG2, IF, >, and NOT are also provided.

To affect the ‘‘closure property’’ [12] of genetic programming, each function returns an integer value and accepts integer inputs. The latter serve as indices into lists of various factors. For example, the three input parameters to GMV specify the axis (horizontal or vertical), the entity whose gradient should be measured (irradiance, oxygen, nitrate, methane, etc.) along that axis, and whether to move up or down the gradient.

Figure 1 illustrates a typical plankton’s s-expression. To interpret these, EUZONE uses standard depth-first evaluation. The branches of ANDs and ORs are only evaluated as long as the final truth value is still in doubt. Hence, if the first argument to an OR is nonnegative (i.e., has a truth value of ‘‘true’’), then the second argument is not evaluated. Operators for movement, grazing, photosynthesis, and reproduction are limited to one application per individual per time step. Reproduction is governed by a set of conditions such as a threshold biomass, age, and so forth. So the presence of REPRO1 or REPRO2 in a phenotype only means that reproduction will be considered. Most functions return a 1 when successful and a 0 otherwise, whereas GRADIENT returns -1, 1, or 0 depending upon whether a gradient is negative, positive, or zero, and EXCON and AMT merely return the measured values.

Beginning with the leftmost subtree in Figure 1, the GRADIENT function measures the gradient of oxygen (-2) in either the z or x direction, depending upon whether photosynthesis is successful or not, respectively. Because (a) most oxygen is produced near the surface due to greater sunlight and higher photosynthesis rates, and (b) the z axis is 0 at the surface and increases with depth, the gradient of oxygen along the z axis is normally negative, so GRADIENT would return -1. If photosynthesis does not occur (due to darkness or lack of nitrates), then EUZONE measures the oxygen gradient in the x direction, which can yield 1, -1, or 0, although 0 is most unlikely, and 1 and -1 are equally likely. In short, regardless of whether photosynthesis is successful or not, the GRADIENT function will probably return 1 or -1 as the argument to EAT. Either value commands EAT to graze for other plankton.
If grazing succeeds, then the EUZONE interpreter moves into the second call to GRADIENT and evaluates the leftmost subtree rooted at MV (move). This tells the plankton to move in the negative direction (−1) along the z (−3) axis, that is, to swim toward the surface. If movement results in a change of grid cell, then MV returns 1, otherwise 0. This tells EXCON to measure either the irradiance (1) or temperature (0) in the current cell. This is essentially a wasted operation, because the measured value does not govern any control decisions in this s-expression. However, the side effect of upward movement is clearly useful when the individual is photosynthesizing and/or grazing.

Because most calls to MV result in some change of position, the call to GMV will only be useful for its side effects, due to the limit of one movement operation per time step. In this case, GMV’s leftmost subtree houses an attempt at sexual reproduction. The middle subtree includes a grazing attempt, which is only taken if the earlier call to EAT was either (a) an attempt at photosynthesis, or (b) an unsuccessful attempt at grazing. The LESS-THEAN subtree returns a 0, which goes unused, because GMV only evaluates its arguments but will not perform the movement operation in this particular tree. If the leftmost call to EAT is unsuccessful, then the third branch of the IF-ELSE is executed, resulting in the taking of a temperature measurement, another wasted operation.

Finally, the second branch of the main root is called, regardless of the outcome of the first branch. The IF statement has a positive/true antecedent, so the interpreter evaluates both expressions in the PROG2. The first, an IF-ELSE, has a negative/false antecedent and therefore executes the ELSE clause, an attempt at sexual reproduction. The second, another EAT, includes an attempt at asexual reproduction. So, if the only unsatisfied condition for sexual reproduction were the presence, then asexual reproduction would result instead. The rightmost EAT will then involve attempted grazing (1) or photosynthesis (0), depending upon the outcome of REPRO1. As a final operation, the main root will then perform a useless gradient measurement with the entity and axis determined by the results of the IF-ELSE and IF, respectively.

Despite the ad hoc organization of the s-expression in Figure 1, the program does include five key activities: photosynthesis, grazing, upward movement, sexual- and asexual reproduction, and each activity’s subtree or node will be reached during most executions of the s-expression, as opposed to being the consequent of an IF with a constant negative antecedent, for example. Hence, in the course of a simulated day, this plankton will swim to the surface, photosynthesize, and graze. If it increases its biomass by a specified amount (encoded in the GA portion of the genotype) and is within its reproductive age range (also part of the GA), it will look for a viable mate, that is, one that also satisfies all of the reproductive preconditions but need not have a reproductive operator in its own s-expression. If a mate is available, sexual reproduction will occur; if not, asexual cloning (with mutation) will result. So this is really not such a dumb plankton cloud after all! In fact, it had the most biomass of 200 different clouds (i.e., was the most fit) at the 72-day mark (approximately the 20th generation) of the particular EUZONE run in which it arose.

4.2.2 The Genetic Algorithm Genotype

Genetic programs were chosen as the basis for behavioral routines to allow a more open-ended behavior space and a more heterogeneous population. However, certain homogeneities apply: All clouds possess values for the basic physical, biochemical, and life-history parameters, and these values can evolve over generations. A GA chromosome is therefore the natural representational choice for these parameters. The EUZONE interface permits the specification of maximum and minimum values for these parameters, thus allowing varying degrees of evolutionary control.
The genetically determined physical parameters include

1. sinking rate: velocity at which inactive or dead organisms sink to the bottom.
2. respiration rate: percentage of biomass respired by a living organism each day.
3. decay rate: percentage of a dead organism’s biomass that is respired (by unmodeled microorganisms such as bacteria) each day.
4. filter rate: water volume that a grazing plankton can filter per hour.
5. chlorophyll to carbon ratio: relates an organism’s biomass to its photosynthetic capacity.
6. carbon to nitrogen ratio: relates an organism’s biomass to nutrients (nitrates) consumed.

The genetically determined life-history parameters include

1. longevity: maximum age of the cloud.
2. Emergence age: time at which the cloud switches from a dormant egg/larvae stage to an active adult stage.
3. minimum/maximum reproductive age: youngest/oldest age at which the cloud can reproduce.
4. minimum reproductive size: threshold biomass for reproduction.
5. Clutch size: number of young (i.e., new clouds) produced during reproduction.
6. Initial parental energy contribution: percentage of the parent’s total biomass that is divided up among the young at birth.
7. Parental feeding contribution: portion of the parent’s daily carbohydrate production/intake that is transferred to the young.
8. Care duration: percentage of the child clouds’ lives during which the parent (that initiated reproduction) continues to provide food.

Obviously, parameters such as those involving parental care can seriously corrupt the analogy to real plankton. However, EUZONE’s interface permits the specification of legal ranges for each of the life-history and biochemical parameters, so simulations restricted to planktonlike behavior might have a range of [0, 0] for parental-care variables. In general, the life-history parameters were added to support the evolution of

- interacting emergence timing patterns wherein, for example, certain predator species shift from dormant to active during peaks in prey biomass and/or vulnerability [17].
- different clutch sizes and parental care strategies depending upon the harshness and predictability of the environment [25].

Similarly, the biochemical parameters were included in the genotype to investigate the possibility that certain biochemical constants, like the carbon-nitrogen ratio (otherwise known as the redfield ratio), have evolved to their present values due to millennia of organismic-environmental interactions. Furthermore, the presence of both sexual and
asexual alternatives in the genetic program permits investigations into environmental
effects upon reproductive type [6, 15].

4.2.3 Photosynthesis and Respiration

The average plankton cloud moves about the environment, performing autotrophic and/or heterotrophic activities. These contribute to the cloud's biomass, measured in micromoles carbohydrate. The state equation for the carbohydrate mass, $M_c$, of a plankton cloud is

$$\frac{dM_c}{dt} = PM_c + G(M_c) - RM_c$$

$P$ = photosynthesis rate
$R$ = respiration rate
$G(M_c)$ = net result of all predator/prey interactions involving $M_c$

Each cloud, whether exhibiting predominantly autotrophic or heterotrophic characteristics, performs some respiration on each time step, with rates depending upon the activity level. Only those clouds with PHOTO or (EAT 0) in their genetic program will actually perform photosynthesis. Other activities such as movement and filter feeding/grazing will increase the respiration rate.

Irradiance and nutrient supply determine the rate of photosynthesis, with either quantity acting as the limiting factor. The irradiance factor, $F_i$, is determined by [20]

$$F_i = 1 - e^{(-a I_z)/P_m}$$

$P_m$ = maximum photosynthesis rate
$a = $ photosynthesis rate per unit of light
$I_z$ = irradiance at depth $z$

The effect of a grid cell's nutrient/nitrate concentration, $N$, upon photosynthesis is given by the Michaelis-Menten relationship:

$$F_n = \frac{N}{k_n + N}$$

$k_n$ = half-saturation constant for nitrate consumption

From these two factors, the photosynthesis rate, $P$, representing the rate of carbohydrate production, is computed as [20]:

$$P = P_m \min(F_i, F_n)$$

Two important chemical reactions (Equations 7 and 8) cover photosynthesis (left to right) and respiration (right to left) in EUZONE:

$$\text{TC} + \text{H}_2\text{O} \leftrightarrow \text{O}_2 + \cdot \text{CH}_2\text{O}$$

$$\text{NO}_3^- + 2\text{H}_2\text{O} \leftrightarrow 2\text{O}_2 + \text{NH}_3 + \text{OH}^-$$

$$\text{TC} \equiv \text{CO}_2 + \text{HCO}_3^- + \text{CO}_3^{2-}$$
TC: total carbon
CH$_2$O: carbohydrate
NO$_3^-$: nitrate (the only nutrient modeled)
NH$_3$: ammonia
CO$_3^{\text{aq}}$: carbonate
HCO$_3^-$: bicarbonate
OH$: hydroxion

TC denotes the mixture of carbon dioxide, carbonate, and bicarbonate. TC is dominated by the latter two compounds. For example, surface sea water has an average 90% bicarbonate to 9.5% carbonate to 0.5% carbon dioxide [5]. The exact proportions vary with respect to ambient temperature, salinity, and pressure, but, in general, a qualitative change (i.e., increase or decrease) in TC mirrors the corresponding change in each of the three constituents.

The ratio of carbon to nitrogen uptake during photosynthesis generally conforms to the Redfield ratio, which is often assumed to be the constant 6.78 [5] although the actual value varies between 6 and 7 depending upon the plankton species and environment. This entails that reaction 7 occurs 6.78 times more often than reaction 8 during both photosynthesis and respiration.

In sum, when a plankton cloud photosynthesizes, (a) nitrate and irradiance levels determine the photosynthesis rate, $P$, according to Equations 4–6, (b) $P$ and the cloud’s carbohydrate mass, $M_c$, determine $\Delta M_c$, the number of moles of newly created cloud carbohydrate, (c) $\Delta M_c$ can be equated with CH$_3$O in Equation 7, thus indicating the number of moles of TC taken up from the cloud’s grid cell, (d) the Redfield ratio permits the derivation of NO$_3^-$ (i.e., nitrate taken up from the cell) from CH$_3$O, and (e) the total amount of produced oxygen is derived from CH$_3$O, NO$_3^-$ and Equations 7 and 8. Thus photosynthesis converts carbon and nitrate from the grid cell into cloud carbohydrate and ammonia, while releasing oxygen to the grid cell.

The respiration process is essentially the inverse of photosynthesis, but differences between aerobic and anaerobic conditions account for a bit of added complexity. Assuming a Redfield ratio of 6.78, Equations 7 and 8 imply that approximately 1.3 mol of oxygen are consumed during the respiration of 1 mol of carbon (in carbohydrate). However, if ambient oxygen levels are insufficient, then anaerobic respiration will occur, producing a half mole TC and a half mole CH$_4$, methane, for each mole of respired carbohydrate. Furthermore, anaerobic respiration is 20 times less efficient than aerobic respiration [8]. Hence, 20 times more carbohydrate is needed to perform the same task in a low-oxygen environment.

In EUZONE, plankton cloud activities such as swimming and filter feeding entail a carbohydrate cost that varies according to the oxygen levels of the surrounding grid cells. The action occurs, regardless of these levels, and the cost, whether aerobic or anaerobic, is paid afterward.

### 4.2.4 Heterotrophic Filter Feeding

When one plankton cloud feeds upon others, the feeding cloud is treated as a school of zooplankton. Assuming the average size of a zooplankton to be 0.16 μmol of carbohydrate [17], the school’s cardinality is $M_c/0.16$. Assuming that each zooplankton filters $1.1 \times 10^{-7}$ L/sec [17], then the total filtered volume of the school is $V_f = (M_c/0.16) \times 1.1 \times 10^{-7}$ L. Both filter rate and zooplankton size are part of the GA genome, with defaults set to $1.1 \times 10^{-7}$ and 0.16, respectively.

EUZONE’s feeding model assumes that every cloud in the feeding school’s cell is preyed upon, with exceptions for children and feeding-mask incompatibilities (Section 4.2.7). The percentage of the prey cloud consumed is $V_f/V_g$, where $V_g$ is the
volume of the grid cell (Although the grid is two-dimensional, EUZONE assumes each
grid cell is 1 m long in the third dimension, thus supporting volume ratio computa-
tions). Hence, $M_p \times (V_i / V_r) \times E_i$ mol of carbohydrate are transferred from the prey
to the predator cloud, where $M_p$ is the prey’s carbohydrate mass, and $E_i$ is the feeding
efficiency. The remaining $M_p \times (V_i / V_r) \times (1 - E_i)$ mol are converted to grid-cell carbon
(i.e., TC in Equation 7); an amount of $\text{NO}_3^-$ sanctioned by the Redfield ratio is also
returned to the grid cell. This essentially simplifies a more complicated route by which
the undigested remains of prey are converted back into carbon and nitrate via bacterial
processes.

In sum, a heterotrophic plankton cloud consumes a percentage of all other clouds
in its grid cell, where the percentage depends upon the predator cloud’s biomass and
thus upon the volume of water that its school of heterotrophs can filter in one time step.

4.2.5 Reproduction

When REPRO1 is executed in a cloud’s s-expression, the preconditions for asexual
reproduction are tested: Is the cloud’s age between its minimum and maximum repro-
ductive ages, and does the cloud have more than the threshold reproductive carbohy-
drate? If these are satisfied, $n$ (clutch size) copies of the parent’s genotype are produced,
and possibly mutated. The parent’s life-history parameters then determine the initial
biomass given to each child and the degree and duration of parental care. The child’s
life-history parameter determines when it will become active. Dormant clouds do not
execute their s-expressions but do respire at one-fourth the basal metabolic rate.

Sexual reproduction, via REPRO2, works similarly, except that (a) the parent cloud,
P1, that initiates REPRO2, must share a grid cell with another cloud, P2; (b) both P1 and
P2 must satisfy the reproductive preconditions; and (c) the GP and GA components of
P1’s and P2’s genotypes are crossed over and possibly mutated before assigning them
to the children. P1 becomes responsible for the children’s early care, which entails
that the young follow P1 wherever it goes, and a life-history-determined percentage of P1’s
carbohydrate production/intake is divided among the young.

4.2.6 Movement

A plankton cloud possessing MV (move) or GMV (gradient move) primitives can actively
“swim” through the grid. A constant swimming velocity is assumed but is increased
(decreased) when the cloud swims with (against) the current. Respiration rates are
correspondingly higher for swimming plankton. Nonswimming clouds are passively
advected and diffused by the environment, with each cloud’s motion vector containing
ambient current and diffusive random-walk components.

4.2.7 Masked Feeding Reproduction

Each cloud has a “looks” array, which is a simple bit vector derived from the cloud’s ge-
etic program, where each bit represents the presence or absence (in the s-expression)
of one of the GP primitives. In addition, each cloud possesses masks for feeding and
mating. When cloud P1 encounters a potential mate (or prey), P2, it compares its looks
to those of P2, using P1’s mate (feed) mask to determine the bits at which P1’s looks
and P2’s looks (a) must match, (b) must not match, or (c) can do either (i.e., “don’t
care”). The EUZONE interface allows the user to determine the percentage of “don’t
care” bits in the feeding and mating masks.

Masks are provided for the eventual identification of species and food webs, where
clouds of the same species will have similar mating masks, and competitor species at
a given trophic level will have similar feeding masks. As part of the genotype, masks
are crossed over and mutated during sexual reproduction.
4.3 Main Cycles
A EUZONE simulation consists of an outer “evolutionary” cycle surrounding an inner “life” cycle. The former begins by initializing a population of plankton clouds using either a user-selected input file of genotypes, or randomly generated s-expressions and bit arrays. A life cycle is then run, wherein EUZONE (a) initializes grid-cell chemical concentrations, and (b) repeatedly performs the Eulerian and Lagrangian operations described above.

New clouds are born via reproduction and die due to either excessively low biomass or old age. If the population size falls below a user-defined threshold, extinction is signaled.

At the close of the life cycle, EUZONE may begin a new evolutionary loop by performing a complete generation shift: A whole new set of clouds are derived via fitness-proportionate selection and GA/GP recombination and mutation. A cloud's fitness is computed recursively as its biomass plus the sum of its asexually produced offsprings' fitnesses and half the sum of its sexually produced offsprings' fitnesses. The environment is then reset, and another life cycle begins. In many cases, only one evolutionary cycle is performed, but the life cycle may span several “natural” generations. This is the purer form of evolutionary simulation, because implicit fitness alone determines reproductive success in the life cycle.

5 Ecosystem Emergence and Evolution

The following example illustrates the emergence and evolution of an aquatic ecosystem in EUZONE. The particular scenario was designed to investigate an integral aspect of Gaia theory: the ability of one lifeform to alter the environment in a manner that affects the evolution of other lifeforms. Specifically, the simulation begins with an oxygen-free environment and a randomly generated population of plankton clouds. These surroundings are not conducive to filter feeding, because this activity increases the respiration rate, and in low-oxygen environments, respiration will be predominantly anaerobic, thus consuming much more (i.e., 20 times) biomass than aerobic respiration. However, photosynthesis creates oxygen, so if the earlier plankton generations can gradually add enough oxygen to the environment to make filter feeding a feasible strategy, then the ecosystem will slowly evolve from primarily autotrophic to a mixture of autotrophs, heterotrophs, and hybrids (i.e., those that photosynthesize and graze).

5.1 The Gaian Scenario
The input scenario for this and all other EUZONE simulations consists of parameters for the aquatic grid and the plankton genotypes. The simulated water column is 30 m deep and 1,000 m wide and divided into 10 rows and five columns. The top 20 m constitute the UML, with initial nitrate concentrations of 1 μmol/L within and 2 μmol/L below the UML. Oxygen concentrations are 0 everywhere. The grid is assumed to reside at the equator, so each day consists of 12 hours of sunlight (regardless of season), with an assumed maximum intensity of 150 μmol/ms around 2:00 p.m. For each simulated 30-day period, the first 27 days are cloud free, while the final 3 days have 50% cloud cover. This introduces a periodic disturbance of lower frequency and amplitude than the day-night cycle, but the effects are nonetheless profound.

The relevant physical parameters, as encoded in the GA chromosomes, include a basal respiration rate of 2% biomass/day, a decay rate of 10% biomass/day, a sinking velocity of 2 to 6 m/h, and for foragers, an assimilation coefficient of 100% (i.e., no waste) and a filtering rate of 1.5 ml/h. Because the evolution of physical parameters is not the subject of this experiment, most values are set to constants or allowed to vary only slightly.
Key life-history parameters, also encoded in the GA chromosomes, include a longevity of 3 to 5 days, an initial dormant stage of from 0% to 50% of longevity, a reproductive age range lying within the master range of 25% to 100% of longevity, and a clutch size of 1 to 10 individuals. In addition, a cloud's biomass must be at least 2% to 5% above its birth biomass in order to reproduce, and the children are then assumed to divide up evenly 100% of the parent or parents' biomass. Hence, reproduction is a plankton cloud's "final act," as it is with several forms of aquatic life. Several of the life-history parameters are given sizeable ranges, since their evolution can provide useful additional information concerning the inhabitability of the environment.

The GP trees are restricted to a maximum depth of 6, with the function set given above and a terminal set of all integers in the closed range of −3 to 3. Both the GP and GA genomes have a mutation rate of 0.1/individual and a single-point crossover rate of 0.7. The initial population size is 100, and the maximum size is 200. The simulation is run for 20,000 hours (833 days, 8 hours).

5.2 Emergence
The initial population of randomly generated genotypes contains only a few useful strategies. Most plankton merely sink to the bottom, possibly photosynthesizing and/or grazing once their dormant period ends. However, a few individuals have the ability to both swim to the surface and to photosynthesize, clearly a winning combination. As seen in Figure 2, three clouds have this ability. However, one of them remains dormant for too long, and once active, it makes repeated trips to the bottom, where it is preyed upon by a dying (but still active) population of bottom-feeders. Hence, it is unable to produce and retain enough biomass during its lifetime to qualify for reproduction. Another remains near the surface and increases its biomass but has no reproductive operator in its genotype. The third surface photosynthesizer becomes active early, stays near the surface, and possesses the asexual reproduction gene. After only 3 days, it spawns nine child clouds and emergence is underway!

The nine children sink to the bottom during their short initial dormant periods (Figure 3) and then swim to the surface, photosynthesize and/or graze. These children grow and reproduce within a few days. By Day 12, the surface is full of plankton clouds (Figure 4). Most individuals can only photosynthesize, whereas a few graze and a few are hybrids. The reproductive cycles of these clouds are relatively synchronous due to their common ancestry (and inherited life-history parameters), so dormant newborns tend to sink out in waves (Figure 5), with the surface nearly free of plankton immediately after the last wave has descended and before the first wave has emerged from dormancy and resurfaced. These waves appear approximately every 40 hours and therefore fail to optimally match the solar cycle.

By the 80th day, roughly 40 generations have come and gone. As shown in Figure 6, the population is still concentrated at the surface, with most clouds behaving as autotrophs or hybrids. The reproductive cycles are no longer synchronous, so each time frame reveals a dozen or more dormant children sinking to the bottom. Because the population has long since reached the size limit of 200, most parents can produce only a few children. This preponderence of small clutches leads to an increase in genetic diversity, as shown by the increasing genotypic entropy for the first 60 days (1,440 hours) in Figure 7. The increase begins after 160 hours, or approximately four generations. Prior to that, the initially random (high entropy) population was slowly being replaced by descendents of the first successful photosynthesizers, all of which had similar genotypes, thus driving genotypic entropy from above 5 to below 2.

The upper population size limit includes all dead/decaying plankton, so if a parent tries to produce n children when the limit has been reached, EUZONE gathers n or less (depending upon availability) dead plankton and forces them to decompose in-
Figure 2. Day 2 of the Gaian simulation. Most plankton have ineffective phenotypes and merely sink to the bottom. However, a few have risen to the surface to photosynthesize. Shape coding conveys the activities of each plankton cloud: (a) photosynthesizing: thin spines on exterior, (b) grazing: large mouthlike opening on right side, (c) consumed by grazer(s): small sliver removed from left side, (d) swimming: tail fin on left side. Color coding of grid cells indicates relative oxygen concentration from high (red) to low (blue).

stantaneously, thus returning all of their nitrates and carbon to their current grid cell and extracting the necessary oxygen, since decomposition is chemically equivalent to respiration under EUZONE's simplified aquatic chemistry.

In the first 160 h, the total biomass decreases by two orders of magnitude from 2,600 to 30 mol of carbohydrate (Figure 8). This is largely due to the death (without reproduction) of nearly the entire initial population and their replacement by second-, third-, or fourth-generation descendants of the initial photosynthesizers. In multi-egg clutches, the descendants are smaller than their parents, and the 3 to 5 day lifetime does not give ample time to attain their parents' size. But after four generations, this effect bottoms out, clutch size decreases, and total biomass begins to rise.

5.3 Evolution
When total biomass rises (Figure 8a), the net amount of photosynthesis exceeds that of respiration, so the environmental concentration of oxygen increases (Figure 8b), while those of carbon and nitrate decline. The net production of oxygen at the surface, along with the increased biomass there, provides a more friendly environment for oxygen-consuming activities such as filter feeding. Hence, the number of grazers gradually increases over the first 120 days, with almost all of them residing at the surface or in the upper water column.

Bottom feeders are scarce (Figure 9a), as expected, because oxygen concentrations...
are four orders of magnitude lower at depth than at the surface. Those bottom feeders that do arise are largely restricted to anaerobic respiration, which burns 20 times more biomass than aerobic respiration to perform the same job. Hence, bottom feeders have trouble accumulating biomass and reproducing. The continued presence of a few bottom feeders stems from mutation and crossover effects that reintroduce this variant into each new generation, even though neither parent was necessarily a bottom feeder.

After 240 days (5,760 hours), the number of bottom feeders begins to increase (Figure 9a), and after 400 days (9,600 hours), the number of births occurring at the bottom starts to rise, indicating that more plankton are spending more time there, that is, that it has become more liveable (Figure 9b). In addition, the average length of the dormant period begins a gradual decline after 200 days. This is often an indication of a more hospitable environment, since long dormant periods can be useful in difficult habitats. In EUZONE, the basal respiration rate of dormant organisms is only 25% of the basal rate of active individuals. So when the environment affords few opportunities for biomass increase, a long dormant period can minimize one’s losses. For autotrophs, the optimal strategy is to be born at the end of a day, remain dormant overnight (autotrophs respire also) and then emerge from dormancy the next day. For heterotrophs, an early emergence is generally beneficial, but less so in a low-prey and/or highly anaerobic environment.

After about 500 days (12,000 hours), bottom activity increases even more as the oxygen concentration rises to within an order of magnitude less than the surface level (0.25 vs. 1.7 μmol/L). The ecosystem now consists of three basic types, listed in increasing or-

Figure 3. Day 3 of the Gaian simulation. One of the surface autotrophs gains enough biomass to reproduce asexually. The newborn clouds sink to the bottom during their dormant period and then become active and rise to the surface to photosynthesize and/or graze.
der of population size: (a) bottom-dwelling hybrids, (b) surface-dwelling hybrids, and (c) vertically migrating hybrids that spend the daylight hours on the surface and then return to the bottom at night. In addition, a few simple autotrophs and heterotrophs still exist.

The availability of oxygen and prey (due to the increase in total biomass) now makes grazing and photosynthesizing feasible for every cloud, hence the preponderance of hybrids. Furthermore, these conditions allow the majority of clouds to spend some of their active time on the bottom, where the supply of food is plentiful, due to the sinking of dormant “egg” clouds. In fact, the active hybrids seem to follow the sinking eggs (Figures 10 and 11). The reproductive cycles have synchronized again, but this time in concert with the day-night cycle: Most eggs are spawned during a 4-hour evening span. This adaptation to the periodic environment provides an effective life-history strategy:

Individuals are born in the evening, sink to the bottom and become active sometime during the next day. They then rise to the surface to photosynthesize and graze. By the evening of their first active day, their biomass may have reached the reproductive threshold, enabling them to spawn eggs. Otherwise, they follow sinking eggs to the bottom for nocturnal grazing, and return to the surface at daybreak. If their biomass exceeds the reproductive threshold during nocturnal foraging, then eggs are spawned immediately, thus accounting for the increased incidence of bottom birth. (Figure 11)

As shown in Figure 8, the population’s total biomass has fluctuations of both low-
amplitude, high-frequency and high-amplitude, low-frequency. The former stem from the diurnal (i.e., day-night) cycle, while the latter reflect the influence of the cloudy 3-day period that ends each month. Note that the scope of these overcast effects varies, with some causing biomass to decrease by less than 25% and others exacting a 75% or greater loss. A longer simulation might provide sufficient data for assessing the complexity and self-organized criticality [2] of this ecosystem via the search for a power-law distribution in the plot of occurrence frequencies of each size of weather-induced biomass loss.

5.4 The High-Oxygen Scenario
To help evaluate the degree to which plankton in the Gaian scenario have modified their environment in a manner that facilitates the emergence of new species, a control scenario is needed. One possible control case would involve plankton that produce no oxygen during photosynthesis. Such a population would quickly go extinct, because phytoplankton need oxygen for their own aerobic respiration. Further assumptions about the relative inefficiency of anaerobic respiration could be relaxed, but then the model would drift further from that used to simulate the Gaian case and give few grounds for comparison. So compared to the trivial case of no oxygen production, the Gaian scenario clearly exhibits a certain degree of Gaian: Autotrophs modify the environment by producing oxygen, which supports heterotrophic lifestyles.

To help verify that it was indeed the oxygen, and not just the increased prey biomass,
that supported heterotrophic emergence, a scenario was run that differed from the Gaian case only in terms of its initial oxygen concentration: 10 μmol/L. A comparison of Figures 8 and 12 reveals only small differences in total biomass, particularly during the first half of each simulation period. However, Figures 9 and 13 show a considerably higher degree of bottom feeding and bottom births in the high-oxygen scenario, particularly during the simulation’s first half.

This simple comparison supports the claim that oxygen is a vital factor in the emerg-
gence of bottom grazing, and hence that the Gaian scenario does indeed exhibit a key aspect of Gaia theory: the ability of microscopic organisms to alter the environment to a significant enough degree to support the emergence of other organism populations.

6 Application Areas

EUZONE is designed for investigating theories in evolutionary aquatic ecology. These theories often predict the emergence of a particularly favorable behavior, set of trophic interactions, or entire ecosystem, based on initial environmental conditions. In other cases, theories may predict the trajectory of an ecosystem through "ecosystem space" due to external perturbations and/or internal instabilities. The EUZONE interface provides a plethora of degrees of freedom for defining aquatic environments and potential genotypes. This, combined with EUZONE's close adherence to the physics, chemistry, and biology of carbon-based life, will hopefully provide ecologists with a fruitful research and teaching tool.

One interesting EUZONE application area involves the emergence of different aquatic ecosystems in different parts of the world. Whereas higher latitudes have seasonal solar variability, which leads to fluctuations in water temperature, which, in turn, cause extreme annual variations in the depth of the upper mixed layer; lower latitudes have a relatively constant solar pattern that tends to keep the UML warm and shallow. After
a plankton bloom near the equator, the shallow, stable UML prevents a resupply of nutrients via mixing processes. Biological remineralization would therefore appear to be vital to sustained plankton growth at lower latitudes. Conversely, at higher latitudes, the fluctuating UML will periodically reinject nutrients into the euphotic zone, thus obviating the need for remineralization.

An obvious question arises: Is a remineralizing ecosystem more likely to evolve at lower than at higher latitudes? Because both latitude and the procedure for determining UML depth (as a function of time) are variables in EUZONE, different environments can be established wherein solar patterns reflect the chosen latitude, and mixing rates conform to the UML. Comparisons of the ecosystems that evolve in each situation should shed some light on this and other questions regarding regional dependence of ecosystem characteristics.

Another topic for EUZONE-based investigation is the evolution of life histories. Winemiller [25] sketches a three-dimensional life-history space defined by three variable axes:

\[ \alpha = \text{age of reproductive maturity}, \]
\[ \mu = \text{fecundity (i.e., clutch size)}, \]
\[ \lambda = \text{juvenile survivorship—includes environmental harshness and parental care}. \]

A life-history strategy is then defined as a point in this space.

Using empirical studies of several fish species, Winemiller illustrates interesting relationships between life-history strategies and environments. For example, “opportunists,” characterized by low values on all three axes, are particularly common in
unpredictable environments. This seems appropriate, because opportunism entails a high turnover rate (of both individuals and genes). This leads to a quick and extensive search of the genetic space to find something that will survive in an ever-changing environment; once found, it can quickly colonize using the same strategy. In stable environments, an “equilibrium” strategy, characterized by high $\alpha$ and $\lambda$ but low $\mu$, is often prevalent. This entails a large parental investment in a few children. Equilibrium strategists are also common in density-dependent settings, because it makes little sense to have several young when resources are limited. Finally, in seasonal environments, “periodic strategists” (high $\alpha$ and $\mu$, low $\lambda$) often arise. They have large batches of young in pulses that correspond to the best periods for juvenile survival. However, the large clutch size makes parental care difficult, thus reducing $\lambda$.

To test relationships between life-history strategies and environments in EUZONE, one can vary the environmental harshness and/or periodicity using variables such as initial nitrate and oxygen concentrations, maximum solar irradiance, latitude, UML depth, feeding efficiency, and so forth. Comparisons among the evolved values of life-history parameters under different environmental settings could then help to support or refute life-history theories based on synthetic alife rather than analytic approaches.

As a simple example of life-history evolution, Figure 14 shows results from a EUZONE simulation in which the population adapted to the day-night cycle by evolving a minimum reproductive age of approximately 24 hours and giving birth predominantly in the evenings.

Finally, elements of EUZONE’s original motivation, Gaia theory, can be tested by
starting the system in a given chemical state and observing whether the collective behavior of plankton clouds are sufficient to both alter that state and form strong feedback loops between biological and chemical elements. These loops would then permit the entire system to change continuously in response to biotic evolution.
7 Current Status

The EUZONE model runs in Allegro Common Lisp on both WINDOWS and UNIX platforms, while the multiwindow interface for scenario setup and run-time viewing is currently restricted to WINDOWS. The user can also define probes for different variables, whose values can be displayed during the simulation and/or saved to files for postsimulation viewing in EUZONE or MATLAB. Partial states of the system can also be saved and later rerun as “movies.”

Figure 15 shows a snapshot from a EUZONE session. The background window displays the aquatic world, with plankton clouds color, size, and shape coded, and grid cells colored or shaded to reflect their concentrations of any of several chemical or physical entities. The pop-up Plankton Inspector facilitates detailed viewing of the individual cloud properties, and the Phenotype Viewer displays the GP s-expressions in tree form. Dynamic time series of several probed variables are also displayed.

8 Related Work

EUZONE provides a virtual laboratory for the evolution of ecosystems as in several other projects: ECHO [10, 11], PolyWorld [26], RAM [21], MIRROR [9], and Petworld [7]. The key difference lies in our real-world modeling approach to the physics and chemistry of the aquatic environment. In this sense, EUZONE resembles the artificial fish work of Terzopoulos, et al. [22], although the two systems cover opposite ends of the aquatic food chain.

Artificial fish also accentuate another key difference between EUZONE and several
alife systems: Our planktonlike agents are quite dumb, having essentially no memory or perceptual abilities except for trivial gradient-sensing mechanisms. Basically, these agents serve as little more than mobile chemical transformers with the additional abilities of reproducing and storing carbon and nitrogen as biomass. Our basic goal is to evolve low-level ecosystems wherein the agents create and maintain chemical and physical gradients, food webs, and nutrient-recycling loops. In this respect, EUZONE mirrors work in metabolism [1] and hypercycle [4] emergence, except that our desired cyclic interactions involve both chemicals and biological agents.

Although Lovelock [13] performed several interesting simulations to support Gaia theory, all involved a fixed set of organism types/species as in standard predator-prey or competitor models. By including variable genotypes, EUZONE enables a more robust investigation into the emergence of Gaian relationships, whether "earth-like" or of a more "possible world" nature.

EUZONE shares the common goal of all alife systems: to nurture self-organization. However, by grounding the system in real-world environmental models, we forfeit the high level of abstraction that enables many alife systems to evolve interesting patterns painlessly. The above test cases required several days of run time on a SUN workstation, and much longer tests will be required in the future.

Figure 14. Progression of 100-hour birth distributions from (a) the first 1,000 hours to (b) the 10,000-hour period to (c) the 19,000-hour period. Note the peaks every 24 hours in (c).
9 Discussion and Future Work

This research applies artificial life to environmental simulation in an effort to evolve aquatic ecosystems resembling those seen in nature. EUZONE is designed to support primary and secondary production, along with nutrient recycling, so the necessary primitives are in place for evolving the foundational layers of a food web. The marine ecology literature indicates that these lower echelons can be relatively self-sustaining, assuming frequent solar input.

Although the above EUZONE runs portray the emergence and evolution of aquatic ecosystems, they only exhibit the initial stages of the Gaian phenomena that motivate this research. To support the emergence of regulatory loops between biota and the biosphere, the hallmark of Gaia theory, EUZONE's environmental models need enhancement. First, the aquatic chemistry module must include a carbon-species component that covers the relationships between total carbon (TC), carbon dioxide, carbonate, and bicarbonate [19]. This model is important when considering the effects of plankton upon atmospheric CO₂, because only a small percentage of the carbon consumed during photosynthesis actually comes from CO₂. In addition, simple atmospheric chemistry and thermodynamic-modules, along with an air-sea interaction module, are necessary to link plankton to climate. These relatively straightforward additions will then enable EUZONE's plankton clouds to affect atmospheric cloud cover, CO₂, and methane. This will in turn influence temperature via both (a) cloud blocking of solar irradiance and (b) greenhouse warming due to CO₂ and methane.

Another focus of ongoing EUZONE research is the evolution of life-history strategies.
The scenarios above illustrate the adaptation of a few key life-history parameters to a periodic environment, but more complex patterns are surely possible, given longer simulations and more carefully crafted scenarios. In this case, EUZONE’s model seems relatively complete, but further analysis is required regarding the proper initial ranges of life-history parameters relative to the temporal and spatial scales of fluctuations in the simulated environment.

In general, EUZONE illustrates that realistic environmental models and alife techniques can be combined into evolutionary models of natural ecosystems. However, the complexities of these models create an imposing search space, one that EUZONE has only begun to explore.

References


