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An enhanced artificial ecosystem: Investigating emergence of ecological niches

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Abstract

This paper describes the new version of EcoSim, an individual-based predator-prey ecosystem simulation, using the updated 7-points Overview-Design concepts-Details (ODD) standard protocol for describing the individual-based models. New sensing and action concepts have been added to the fuzzy cognitive map (FCM) of the individuals. In addition, new physical traits have been added to the current genome allowing different niches to emerge. Experimental results demonstrated that different ecological niches emerged with a co-evolution of highly differentiated behavior and physical traits.

Introduction

Among biological disciplines, behavioral ecology has a strong tradition of accounting for the role of organism–environment interactions in behavior [1]. Behavioral ecology and the related field of optimal foraging theory [2] model animal behavior in terms of optimal adaptation to environmental niches. The goal is not to test whether organisms actually behave optimally, but to use normative expectations to interpret behavioral data and/or generate testable hypotheses. One approach for understanding the behavior of complex ecosystems is individual-based modeling which provides a bottom-up approach allowing for the consideration of the traits and behavior of individual organisms. Ecological modeling is still a growing field, at the crossroad between theoretical ecology, mathematics and computer science [3]. Since natural ecosystems are very complex (in terms of number of species and of ecological interactions), ecosystem models aim to characterize the major dynamics of ecosystems, in order to synthesize the understanding of such systems, and to allow predictions of their behavior. Ecosystem simulations also can help scientists to understand theoretical questions regarding the evolutionary process, the emergence of species, and the emergence of learning capacities. One of the main interests of such ecosystem simulations is that they offer a global view of the evolution of the system, which is difficult to observe in nature. However, the scope of ecosystem simulations has always been limited by the computational possibilities of their time. Today, it is possible to run simulations that are more complex than what has ever been done before, due to the available high performance computing resources.

There exists several ecosystem simulation platforms with various features. For example, Echo is one of the first such ecosystem models. It is a "genetic ecosystem model in which evolving agents are simulated in a resource-limited environment" [4]. In Echo, each agent, when obtaining the required resources to copy its genome, replicates itself with some mutations. The agents, by interaction with other agents (combat, trade, or mating) or from the environment, can acquire resources. Polyworld is another software developed by Larry Yaeger [5] to evolve artificial intelligence through natural selection and evolutionary algorithms. It displays a graphical environment in which a population of trapezoid agents search for food, mate, and create offspring. The population is typically only in the hundreds, as each individual is rather complex and the environment consumes considerable computer resources. In this model, each individual makes decisions based on a neural network which is derived from each individual's genome. Avida is another artificial life software platform to study the evolutionary biology of self-replicating and evolving computer programs (digital organisms) [6], which was inspired by the Tierra system [7]. Unlike Tierra, Avida assigns every digital organism its own protected region of memory, and executes it with a separate virtual CPU. A second major difference is that the virtual CPUs of different organisms can run at different speeds. The speed at which a virtual CPU runs, is determined by a number of factors, but most importantly, by the tasks that the organism performs: logical computations that the organisms can carry out to reap extra CPU speed as a bonus.

EcoSim [8] is a large scale evolving predator-prey ecosystem simulation that can be used to perform studies in theoretical biology and ecology [9, 10]. It has been shown that EcoSim generate patterns as complex as those observed in real ecosystems [11]. Several studies have been done using EcoSim. Devaurs and Gras have shown that the behavior of this model is realistic by comparing the species abundance patterns observed in the simulation with real communities of species [12]. Furthermore, the chaotic behavior [11] with multi-fractal property [13] of the system has been proved as the ones observed in real ecosystems [14] and Golestani et al. have measured the effect of small geographic barriers on the speciation in EcoSim [9]. The effectiveness of the spatial distribution of individuals in the speciation has been investigated by Mashayekhi and Gras [15]. Marwa et al. demonstrated that introduction and predator removal from an ecosystem have widespread effects on the survival and evolution of prey by altering their genomes and behavior [16]. Finally, Mashayekhi et al. proved that the extinction mechanisms in EcoSim are similar to those of real communities [10].

Ecological niches describe the way of life of a species which is unique to that species. They explain how an organism or a population responds to the distribution of resources, competitors, and predator. For example, one species may increase its size when the resources are abundant or when the predators are scarce, or one species can run faster to avoid the competitors or predators. In fact, niches describe the species' role or function within the community and how it adapts to life in its habitat.

In addition to presenting the new version of EcoSim following the updated 7-points Overview-Design concepts-Details (ODD) standard protocol [17], we investigate the effect of physical traits in forming ecological niches in EcoSim. The paper is organized as follows: in the next section, we present the ODD description of the modified version of EcoSim. Thereafter, we present the results of analyses of population and diversity of species of the simulation.

ODD Description of EcoSim

EcoSim is an individual-based ecosystem simulation, designed to simulate agents' behavior in a dynamic, evolving ecosystem. The agents (or individuals) of EcoSim are prey and predators acting in a simulated environment. In order to study the effect of evolution of physical traits, several features have been added to the current version of EcoSim such as: new individuals' perceptions of their environment, new actions, and new physical traits, which we call the physical genome. The ODD description [10] of the modified version of EcoSim is given below.

Purpose

EcoSim was designed to simulate agents' behavior in a dynamic and evolving ecosystem. The main purpose of EcoSim is to study biological and ecological theories and construct a complex adaptive system which leads to a generic ecosystem platform with behaviors similar to those found in existing ecosystems. Due to the complexity, scale, and resource requirement of studying these theories in real biological systems, simulations of this nature are quite necessary. EcoSim uses a fuzzy cognitive map (FCM) [18] to model the agent's behavior. The agent's FCM, being coded in its genome, allows the evolution of the agent behavior through the epochs of the simulation.

Entities, state variables, and scales

Individuals. EcoSim has two types of individuals: predator and prey. Each individual possesses two types of traits: acquired and inherited traits (Table 1). The former varies depending on the environmental conditions and the latter is encoded in the individual's genome and is fixed during its lifetime. The age and speed are initialized to zero for new born individuals while energy, a crucial property of the individual, is initialized based on the amount of the parents' energy which is invested at the breeding time (*State of Birth* or *SOB*). Afterward, energy is provided to the individuals by the resources (food) they find in their environment. Prey consume grass, which is dynamic in quantity and location, whereas predators hunts for prey individuals. Strength of the individual is calculated based on the current energy, maximum energy, and age of the individual. Young and old individuals have less strength.

The genome of each individual consists of two parts: a physical genome that represents the physical characteristics of the individual and the FCM, which form its behavioral model.

Table 1: Several physical and life history characteristics of individuals from 5 independent runs (The values for the inherited features are the values at initialization and for the acquired features, they are the average values over 20000 time steps)

Type	Characteristic	Predator	Prey
Inherited	Maximum Energy	800 units	650 units
	Maximum Age	42 time steps (±6)	46 time steps (±18)
	Vision	20 cells maximum	13 cells maximum
	Maximum Speed	11 cells / time step	6 cells / time step
	Minimum age of reproduction	6 time steps	6 time steps
	State of Birth	30	30
	Defense	N/A	0
	Cooperative Defense	N/A	0
Acquired	Average Energy	753(±175)	804(±275)
	Average Age	17(±3.4)	19(±4.5)
	Average speed	3 (±0.8)	9.4(±2.6)
	Average Strength	1562(±395.5)	1275(±376)

Each individual performs one unique action during a time step, based on its perception of the environment. At each time step, each agent spends energy depending on the selected action (e.g. breeding, eating, running), and also on the complexity of its behavioral model (number of existing edges in its FCM) as well as its physical genome. (See equations 1, energy penalty for prey, and equation 2, energy penalty for the predator)

$$P = \frac{FC - 100}{3.1} + S^{1.5} + \left(\frac{ME}{18}\right)^{1.25} + \left(\frac{V}{4}\right)^{2} + \left(\frac{MS}{5}\right)^{1.5} + \left(\frac{D}{18}\right)^{1.7} + \left(\frac{CD}{18}\right)^{1.7} + (max(0, 7 - RA))^{2.1} \quad (1)$$

$$P = \frac{FC - 100}{3.1} + S^{1.5} + \left(\frac{ME}{15}\right)^{1.4} + \left(\frac{V}{4}\right)^{1.9} + \left(\frac{MS}{5}\right)^{1.5} + (max(0, 7 - RA))^{2.3} \quad (2)$$

In these equations, *FC* is the number of edges in the FCM, *S* is the current speed, *ME* is the maximum energy, *V* is the vision range, *MS* is maximum speed, and RA is the minimum reproduction age. *D* and *CD* stand for defense and cooperative defense, respectively.

Cells and virtual world. The smallest units of the environment are cells. Each cell represents a large space which may contain an unlimited number of individuals and/or some limited amount of food. The virtual world consists of a matrix of 1000×1000 cells. The world is large enough such that an individual moving in the same direction during its whole life cannot even cross half of the world and therefore migration patterns can be observed,. The virtual world wraps around to remove any spatial bias. In addition, the dimensions of the world are adjustable but expanding the dimensions increases the computational complexity of the simulation.

Time step. Each time step involves the time needed for each agent to perceive its environment, to make a decision, to perform its action, to update the species membership, to perform speciation events, and to record relevant parameters (e.g. the quantity of available food). In terms of computational time, the speed of simulation per time step is related to the number of individuals. Recent executions of the simulation produced approximately 20000 time steps in 90 days.

Population and Species. At almost every time step several prey and predator species co-exist. A species is a set of individuals with similar genomes (see 'collectives in design concepts' section for more details).

Entities, state variables, and scales

After perceiving its environment (including grass resources, predators, and sexual partner), the possible actions for a prey agent are: evasion (escape from predator), search for food (if there is not enough grass available in its cell, prey can move to another cell to find grass), socialization (moving to the closest prey in the vicinity, moving to the cell with strongest prey, moving to the cell with maximum total prey's strength, and moving to a cell with minimum total prey's strength), exploration, resting (to save energy), eating, and breeding. Predators also perceive the environment to gather information used to choose an action among: hunting (to catch a prey), moving to the cell with strongest prey, moving to the cell with minimum total prey's strength, moving to the cell with the weakest prey, search for food, socialization (moving to the closest predator in the vicinity, moving to the cell with strongest predator), exploration, resting, eating, and breeding. Every individual takes one action per time step then its energy level and its strength are adjusted. The age of all individuals are also increased by one unit at each time step. In addition, there are two environmental processes which are adjusted: the amount of grass and meat after all the individuals perform their actions.

At each time step, the value of the state variables of individuals and cells are updated. The overview and scheduling of every time step is as follows:

1. For prey individuals:
    - 1.1. Perception of the environment
    - 1.2. Computation of the next action
    - 1.3. Performing of their action and updating of their energy and strength
    - 1.4. Updating the list of prey
    - 1.5. Sorting prey based on the strength
    - 1.6. Updating prey species
2. For predator individuals:
    - 2.1. Perception of the environment
    - 2.2. Computation of the next action
    - 2.3. Performing of their action and updating of their energy and strength
    - 2.4. Updating the list of predators and prey
    - 2.5. Sorting predators based on the strength
    - 2.6. Updating predator species
3. For every cell in the world
    - 3.1 Updating of the grass level
    - 3.2 Updating of the meat level
4. Updating of the age of the individuals

The complexity of the simulation algorithm is mostly linear with respect to the number of individuals. If we consider that there are N_1 prey and N_2 predators and we exclude the sorting parts which have a complexity of $O(N_1 log N_1)$ and $O(N_2 log N_2)$ but are negligible in computational time, then the complexity of part 1 and part 2 of the above algorithm, including the clustering algorithm used for speciation, will be $O(N_1)$ and $O(N_2)$ respectively (Aspinall and Gras, 2010). This virtual world of the simulation has 1000×1000 cells, therefore the complexity of part 3 will be $O(k = 1000\times1000)$. The complexity of part 4 will be $O(N_1+N_2)$. As a result, the overall complexity of the algorithm is $O(2N_1+ 2N_2+ k)$, which is $O(N = 2N_1 +2N_2)$.

Design concepts

Basic principles

A FCM is the base for describing and computing the agents' behaviors [8]. Agents act based on their FCM to decide their next action. Their FCM is represented as part of their genome which is assigned to each individual at birth. A FCM is a directed graph containing nodes representing concepts and edges representing the influence of concepts on each other [18]. When a new offspring is created, it is given a genome which is a combination of the genomes of its parents with some possible mutations. The behavior model of each individual is therefore unique. Formally, a FCM is a graph which contains a set of nodes C (each node C_i is a concept) and a set of edges I (each edge I_{ij} representing the influence of the concept C_i on the concept C_j). A positive weight associated with the edge I_{ij} corresponds to an excitation of the concept C_j from the concept C_i, whereas a negative weight is related to an inhibition (a zero value indicates that there is no influence of C_i on C_j). The influence of the concepts in the FCM can be represented by a $n\times n$ matrix, L, in which n is the number of concepts and L_{ij} is the influence of the concept C_i on the concept C_j. If $L_{ij} = 0$, there is no edge between C_i and C_j.

Emergence

In each FCM, three kinds of concepts are defined: sensory (such as distance to foe or food, amount of energy, etc.), internal (fear, hunger, curiosity, satisfaction, etc.), and motor or action (evasion, socialization, exploration, breeding, etc.). The activation level of a sensory concept is computed by performing a fuzzification of the information the individual perceives in the environment. For an internal or motor concept *C*, the activation level is computed by applying the defuzzification function on the weighted sum of the current activation level of all the concepts having an edge directed toward *C*. Finally, the action of an individual is selected based on the maximum value of motor concepts' activation level. Activation levels of the motor concepts are used to determine the next action of the individual.

At the initiation of the simulation, prey and predators are scattered randomly all around the virtual world. Through the course of the simulation, distribution of the individuals in the world is changed drastically based on many different factors such as prey escaping from predators, individuals socializing to form groups, and individuals migrating to find food resources. The complex interactions between the individuals and their environment lead to emerging grouping patterns with spiral waves. Individuals' distribution forming spiral waves is one property of prey-predator models [19]. In addition, migration phenomena can be observed due to the combination of the predation pressure, and the search for resources and potential mates.

Adaptation

The FCM maximal length is fixed (663 genes for prey and 756 for predator), where each site corresponds to an edge between two concepts of the FCM. However, as many edges have an initial value of zero, only 117 edges for prey and 131 edges for predators exist at initialization. In addition to the FCM, every individual has physical traits (or physical genome) in order to describe its physical characteristics, each trait being coded by one gene. Maximum energy, maximum age, vision, maximum speed, and state of birth are common physical traits for prey and predator. Prey has also two more traits: defense, and cooperative defense, to be able to protect themselves of predators. The initial values for these two genes are zero. Every prey can have its own defense capability and also can participate in a cooperative defense with other prey against predators. When one individual participates in a defense position, it loses some amount of energy. Predators also have an energy penalty when it encounters a prey with defense ability or a group of prey with cooperative defense capability. It is even possible for a predator to be killed in this process. Step after step, as more individuals are created, changes in the FCM and physical genome occur due to the formation of new edges (with probability of 0.001), removal of existing edges (with probability of 0.0005), and changes in the weights associated to existing edges (with probability of 0.005). New genes may emerge from the initial pool of edges with a zero value. This emergence and disappearance of the genes in FCM is due to natural selection and genetic drift which lead to adaptability of individuals [20].

Fitness

A species' fitness is calculated as the average fitness of its individuals. The fitness of an individual is defined as the age of death of the individual plus the sum of the age of death of its direct offspring. Accordingly, the fitness value mirrors the individual's capability to survive longer and produce high number of strong adaptive offspring. There is no pre-defined explicit fitness-seeking process in the simulation, but rather it is a consequence of natural selection. Individuals which are more adapted to the environment live longer, have a higher level of energy, and therefore are able to have more offspring and can transfer efficient genomes to them.

Prediction

So far, there is no learning mechanism for individuals and they cannot predict the consequences of their decision. The only available information, for every individual to make decision with, is the information coming from their perceptions at the current time step and the value of the activation level of the internal and motor concepts at the previous time steps. The activation levels of the concepts of an individual are never reset during its life. As the previous time step activation level of a concept is involved in the computation of its next activation level, this means that the previous states of an individual participate in the computation of its current state. Therefore, an individual has a basic memory of its own past that will influence its future states. As the action undertaken by an individual at a given time step depends on the current activation level of the motor concepts, the global behavior of the individual depends on a complex combination of the individual's perception, the current internal states, and the past states it went through during its life.

Sensing

Every individual in EcoSim is able to sense the local environment inside of its vision range. Some of these sense abilities are common between prey and predator. For instance, both can perceive information about cells with food units and the number of likely mates within the vision range, current level of energy, age, and strength. In addition, both sense the strength of the strongest prey in the same cell, the sum of the strength of the prey in the local cell, and the strongest sum of the strength of the prey in the vision range cells. Moreover, predators can sense the closest prey and the strength of the strongest predator in the local cell.

Interaction

The only action that requires a coordinated decision of two individuals is reproduction. In order to have successful reproduction, the two parents need to be in the same cell, have enough energy, choose the reproduction action, and be genetically similar. The individuals cannot determine their genetic similarity with their potential partner. They try to mate and if the partner is too dissimilar, (the dissimilarity between the two genomes is greater than a threshold i.e. half of the speciation threshold), the reproduction fails.

Predator's hunting introduces another type of interaction in the simulation. For a predator to succeed in the hunting action, the target prey should be in the same cell as the predator is located.

Furthermore, there is a competition for prey and predators for food. For example, if in a given cell two agents choose the action of eating, the more powerful agent (in terms of strength) has more priority and acts first.

Stochasticity

To produce variability in the ecosystem simulation, several processes include stochasticity. For instance, at initialization time the amount of grass units is randomly determined for each cell (a value between 1 and *MaxGrass*). Moreover, the maximum age of an individual is determined randomly at birth from a uniform distribution centered at a value associated with its maximum value coming from the trait "maximum age" (*MaxAge*). Stochasticity is also included in several actions of the individuals; in evasion and socialization: if there is no predator or partner in the vision range of the individual, the direction of the movement would be random. Furthermore, the direction of the exploration action is always random.

Collectives

In EcoSim, the notion of species is implemented in a way that species emerge from the evolving population of agents. Species can become extinct if all of their members die. EcoSim implements a species based on the genotypic cluster definition [21] in which a species is a set of individuals sharing a high level of genomic similarity. In addition, in EcoSim, each species is associated with the average of the genetic characteristics of its members, called the 'species genome' or the 'species center'. The speciation mechanism implemented in EcoSim is based on the gradual divergence of individual genomes. The speciation method begins by finding the individual A in a species *S* with the greatest distance from the species center. The distance is the sum of the hamming distance between the physical genomes and between the FCM edges. Next, the individual B in S with the greatest distance to A is found. If this distance is greater than a predefined threshold for speciation, a 2-means clustering is performed [22], otherwise S stays unchanged.

To initialize the 2-means clustering process, one center is assigned to a random individual, denoted I_r, and the other center is assigned to the individual which is the most genetically different from I_r. After, eight cycles of the 2-means clustering algorithm, two new sister species are created to replace *S*.

Observation

EcoSim produces a large amount of data at every time step, including new and extinct species, geographical and internal characteristics of every individual, and status of the cells of the virtual world. Information regarding each individual includes position, level of energy, choice of action, species, parents, FCM, etc. Information about the individuals, species, and virtual world for every 100 time steps are stored in a file using HDF5 format [23] with an average size of 6 GB. Also there is a possibility to store all of the values of every variable in the current state of the simulation in a separate file, giving the possibility to restore the simulation from that state afterwards. The overall size of this file, which is only stored in every 100 time steps of the simulation, is a few GBs depending on the size of population and species. All the data is stored in a compact special format, to facilitate the storage and future analysis. There are also several program utilities which can be used to analyze the simulation outputs for example, to calculate the species and individuals fitness, to demonstrate the world snapshot for each time step of the simulation, generate the video of the world, and to draw the FCM of the individuals.

Initialization and input data

A parameter file is defined for EcoSim, which is used to assign the values for each state variable at initial time of the simulation. These parameters are as follows: width and height of the world, initial numbers of individuals, thresholds of genetic distance for prey/predator speciation, initial maximum age, energy, speed, vision range, and initial values of FCM for prey/predator. Any of these parameters can be changed for specific experiments and scenarios. An example of a list of most common user specified parameters for initially running the EcoSim are presented in Table 2.

Table 2. Values for user specified parameters.

User Specified Parameter	Used Value
Number of Prey	12000
Number of Predators	9000
Max Grass Quantity in each cell	1600
Prey Energy	650
Predator Energy	800
Prey Vision Range	13
Predator Vision Range	20

Submodels

At initialization, there is no meat in the world and the number of grass energy units is randomly determined for each cell. In this case, the initial number is generated uniformly between 1 and M*axGrass*. When a prey eats, the obtained energy is equal to *min*(*MaxEnergy* – *CurrentEnergy*, *GrassUnits*), which *GrassUnits* is the number of grass energy units, and then the amount of grass in the cell is decreased by this value. Predators have two modes of predation: hunting and scavenging. When a predator's hunting action succeeds, some amount of meat energy units, equal to the strength of the killed prey, is added to the cell. Afterward, the predator consumes the meat to gain required energy i.e. *min*(*MaxEnergy* – *CurrentEnergy*, *MeatUnits*), which *MeatUnits* is the number of meat energy units. The eventual remaining units of meat energy can be consumed by other predators. Prey have a defence capability as well as cooperative defence and use them in a battle against the predator [24]. Depending on the strength and defence ability of the attacked prey and the overall strength and cooperative defence ability of the other prey in the same cell, the predator may lose energy (See equation 3, A*P.D* and *AP.S* are defence and the strength of the attached prey. $CP_i.D$ and $CP_i.CD$ are the defence and cooperative defence ability of the prey *i* in the same cell).

$$P = AP.D * AP.S + \sum_i CP_i.D * CP_i.CD \qquad (3)$$

In addition, the prey which are involved in a cooperative defence also lose some amount of energy based on the strength of the predator (0.2 * *PredatorStrength*/ Number of defenders).

There are dynamic processes for the resources in each cell such as the amount of grass growth, grass diffusion, and variation in the amount of meat at each time step. The amount of meat in each cell increases by the strength of the dead prey in that cell. It also decreases at each time step, even if no meat has been eaten in this cell.

Each action also has its corresponding sub-model:

1. *Evasion* (for prey only). The evasion direction is the direction opposite to the barycenter of the five closest predators within the vision range of the prey, with respect to the current position of the prey. If no predator is within the vision range of the prey, the direction is chosen randomly. The current activation level of the *fear* concept is divided by two after evasion.
2. *Hunting* (for Predator only). The predator selects the closest cell (including its current cell) that contains at least one prey and moves toward that cell. If it reaches the corresponding cell based on its speed, the predator tries to kill a prey as explained before. When there are several prey in the destination cell, one of them is chosen randomly. If the speed of the predator is not enough to reach the prey, it moves at its speed toward this prey. If there is no prey in the current cell and in the vicinity hunting action is failed.
3. *Search for food*. The direction toward the closest food (grass or meat) within the vision range is computed. If the speed of the agent is high enough to reach the food, the agent is placed on the cell containing this food. Otherwise, the agent moves at its speed toward this food.
4. *Socialization*. The direction toward the closest possible mate within the vision range is computed. If the speed of the agent is high enough to reach the mate, the agent is placed on the cell containing this mate, and the current activation level of the *SearchPartner* concept is divided by three. Otherwise, the agent moves at its speed toward this mate. If no mate is within the vision range of the agent, the direction is chosen randomly.
5. *Exploration*. The direction is computed randomly. The agent moves at its speed in this direction. The activation level of the *curiosity* concept is divided by 1.5 after exploration action.
6. *Resting*. Nothing happens.
7. *Eating*. If the current amount of grass (of meat) is greater than 0, then this number is decreased by the required energy and the prey's (predator's) energy level is increased as discussed earlier. Its activation level for the *hunger* concept is divided by four.
8. *Breeding*. The process of generating a new offspring consists of the following steps. First, the edges' values in the FCM along with the values in physical genome from one randomly chosen parent are transmitted with possible mutations to the offspring. Then, the initial energy of the offspring is computed based on the parents *SOB* and the mutated *MaxEnergy*. To model the crossover mechanism, the edges are transmitted by block from one parent to the offspring. For each concept, its incident edges' values are transmitted together from the same randomly chosen parent. Finally, the energy level of the two parents is decreased by half of the energy transmitted to the offspring.
9. *MovetoStrongestIndividual*. The direction toward the strongest possible mate within the vision range is computed. If the speed of the agent is high enough to reach the mate, the agent is placed on the cell containing this mate, and the current activation level of *SearchPartner* is divided by three. Otherwise, the agent moves at its speed toward this mate. If no mate is within the vision range of the agent, the direction is chosen randomly.
10. *Move2StrongestPreyCell* (for prey only). This action follows the *MovetoStrongestIndividual* action's steps except that the direction of movement is toward the cell with the highest cumulative strength of prey individuals to allow prey to benefit from cooperative defence against predators.
11. *Move2WeakestPreyCell* (for prey only). This action is similar to *Move2StrongestPreyCell*, but the direction of movement is toward the cell with the lowest cumulative strength of prey individuals to allow prey to have higher chance in competition with other prey individuals for accessing to food.
12. *Move2StrongestPreyDistance* (for predator only). The predator moves toward the strongest prey individual to acquire more energy after possible hunting. If the speed of the agent is high enough to reach the prey, the agent is placed on the cell containing this prey, and the current activation level of *ChaseAway* is divided by two. If the speed of the predator is not enough to reach the prey, it moves at its speed toward this prey.
13. *Move2WeakestPrey* (for predator only). This action has the same steps of the *Move2StrongestPreyDistance* action with the exception of the direction of movement is toward the weakest prey individual for easy hunting in the next steps.
14. *Move2WeakestPreyCell* (for predator only). This action is similar to *Move2WeakestPrey*, but the direction of movement is toward the cell with the lowest cumulative strength of prey individuals to minimize the possible effect of cooperative defence by prey individuals.

For all movement actions *M* the speed is equal to *MaxSpeed**ActivationLevel(*M*).

Results and Discussion

Population and Species

Figure 1 shows the average population size for the prey and predators for 20000 time steps of five different runs of the simulation. As we expected, there is a dependency between prey and predator populations. At the beginning of the simulation, the number of prey is more than the number of predators. Therefore, they can reproduce and increase their population very fast. The increasing number of prey provides a good chance for the predators to have access to more food resulting in an increasing of their energy level and their reproduction rate. The resulting increase in hunting associated with a food resource shortage for prey decreases the prey population gradually and subsequently the predator population also declines. This cycle happens several times during the simulation with a time lag between the prey and predator population fluctuations. Both populations mostly stabilize with small fluctuations at the end of simulation, resulting in a prey population around 200000 and predator about 30000 individuals. The number of species for both prey and predators are positively correlated with the population size. An increase in the population size increases the variation in the gene pool and consequently increases the chance of the occurrence of a new species. This fact is shown in figure 2.

Physical Traits

With the current energy formula, individuals tend to increase their size (*MaxEnergy*) and their *MaxAge*. The individuals' visions also tend to decrease generally, but we observed that prey individuals prefer to have less vision range compared to predator. On the other hand, prey individuals have tendency to

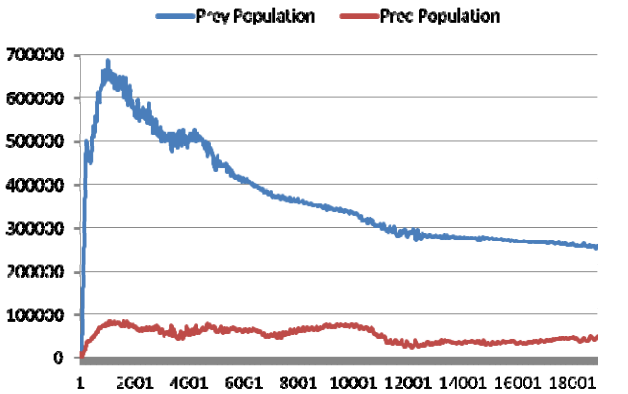


Figure 1 Average population size of 5 different runs for 20000 time steps

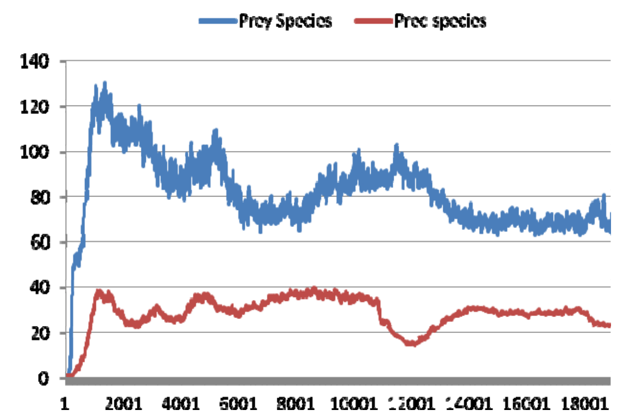


Figure 2 Average number of species of 5 different runs

increase their *MaxSpeed* to the maximum possible value while it stays almost fixed for predators (figure 3). While it is clear that the individuals try to become larger in order to be able to gain more energy and strength, it is less obvious why the *MaxAge* increases despite its cost in energy. There is no predefined fitness function giving preference to longer life expectancy and number of offspring, but it could represent a long term advantage for the species by increasing the overall birth ratio.

Defense and cooperative defense abilities of prey individuals, which are set to zero at initialization of the simulation, are also evolving. We observed that these abilities are used by the prey during some periods, but sometimes they decrease because of their associated energy penalty. However, the general trend for these abilities is increasing gradually.

Actions

We investigated the global behavior of different species in our system such as the average percentage of species' actions that can give insight into the decision-making processes of species to see if some separate, unique niches emerged. By monitoring the actions performed by predator individuals in different species, we can study how an individual or species responds to the distribution of resources and competitors, and how it consequently alters those same factors.

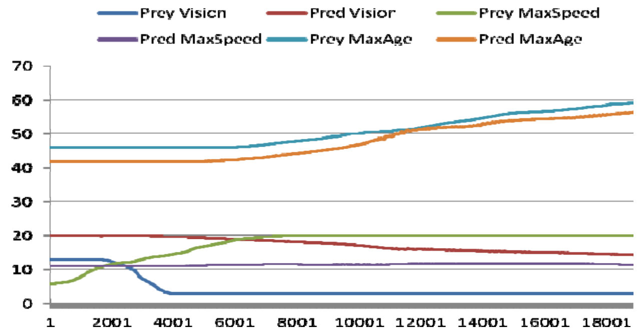
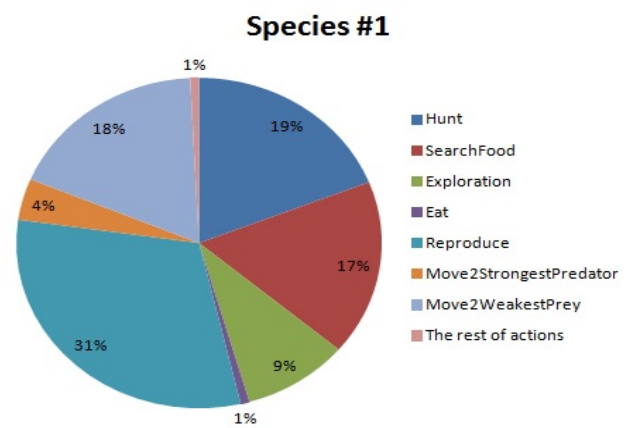
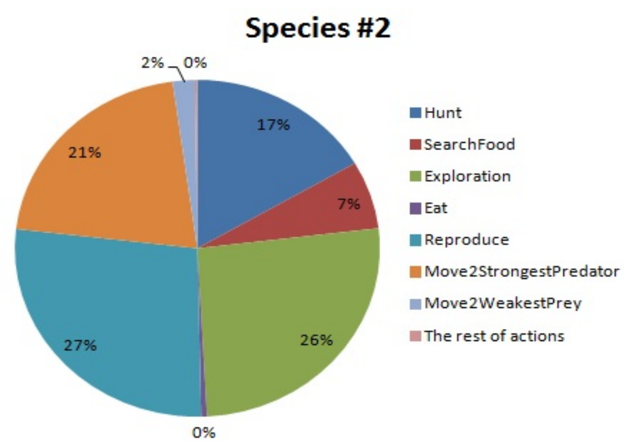


Figure 3 Evolution of some physical genome traits



(a)



(b)

Figure 4 Percentage of different actions for two different species.

Our results clearly show how natural selection drives competing species into different patterns of resource usage. Figure 4 shows the average amount of actions chosen by predator individuals of two different species. Aside from reproduction which is an important action in both species, the percentage of other actions is different. For example species #1 has high amount of movement toward the weakest prey in order to increase the chance of success in predation. It seems that this policy alongside high amount of search for food action works for this species in order to survive in the ecosystem. On the other hand, species #2 has a high amount of exploration and movement toward the strongest partner. These actions increase the ability of producing fit offspring for the next time steps.

Various physical traits evolve differently in these two species which is further evidence of niche adaptation. Some of these differences may be in direct relation with their difference in behavior (see figure 4 and figure 5). For example, species #1 has a lower *MaxEnergy* and consequently a lower strength than species #2 which can explain that they prefer scavenging (*SearchFood*) and selecting the weakest prey. Conversely, species #2 being more efficient in hunting can dedicate more of their energy to reproduction and selection of a strong mate.

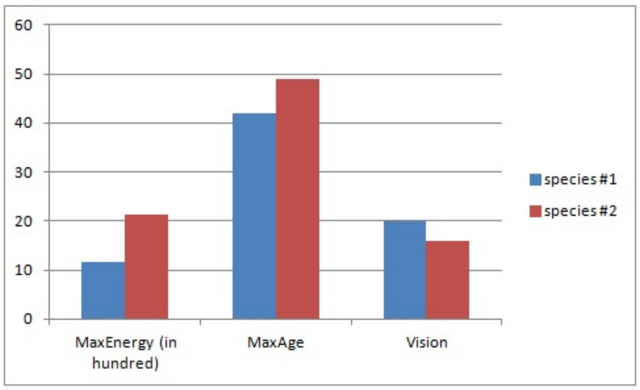


Figure 5 Physical trait values in two different species.

Conclusion

We added new sensing as well as new action concepts to the fuzzy cognitive map (FCM) of the individuals in EcoSim. In addition, new physical traits have been added to the behavioral genome allowing different niches to emerge. Our results underline the importance of ecological niches in evolution. Significantly, our study reveals insights into the genetic mechanisms of niche adaptation, advances our understanding of the evolution, and sheds more light on addressing more complicated biological questions. Being at the early stage of the analysis of the new version of EcoSim potentials, these preliminary results are promising and will lead to some more dedicated study on niche emergence.

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