P System Based Model of an Ecosystem of the Scavenger Birds

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Summary. The Bearded Vulture (*Gypaetus Barbatus*) is an endangered species in Europe that feeds almost exclusively on bone remains provided by wild and domestic ungulates. In [1], we presented a P system in order to study the evolution of these species in the Pyrenees (NE Spain). Here, we present a new model that overcomes some limitations of the previous work incorporating other scavenger species (predatory) and additional prey species that provide food for the scavenger intraguild and interact with the Bearded Vulture in the ecosystem. After the validation, the new model can be a useful tool for the study of the evolution and management of the ecosystem. P systems provide a high level computational modelling framework which integrates the structural and dynamical aspects of ecosystems in a compressive and relevant way. The inherent stochasticity and uncertainty in ecosystems is captured by using probabilistic strategies.

1 Introduction

Since nature is very complex, the perfect model that explain it will be complex too. A complex model is not practical or good to use, so we should obtain a simple model that keeps the most important natural factors and consequently will be useful.

The P system presented in [1] gives good results in order to study the evolution of the ecosystem based on the Bearded Vulture in the Catalan Pyrenees, but it does not take into account important factors such as the population density or the feeding limitations.

In the Catalan Pyrenees, in the North-east of Spain, three vulture species inhabits sharing the geographic space and the existent food resources so in this work, we present a P system for modelling an ecosystem based on three vulture species and the prey species present from which scavengers obtain their food. The present model improves the results presented in [1]. Apart from adding two new predator species (the Egyptian Vulture *Neophron percnopterus* and Eurasian Griffon Vulture *Gyps fulvus*), we introduce new prey species (making a total of 12 species) in the new model that provide feeding resources for the scavenger community. Besides, new rules are introduced to limit the maximum amount of animals that can be supported by the ecosystem as well as the amount of grass available for the herbivorous species.

For a good and efficient management of the ecosystems, it is necessary to know the quantity and the evolution of the biomass that reaches every species. One of the contributions the P system presents is the evolution of the quantity of annual biomass that is left by every species.

The paper is organized as follows: First, an ecosystem, which is located in the Catalan Pyrenees and is to be modelled, is described. Section 3 shows a formal framework to model ecosystems by means of probabilistic P systems, and a P system modelling the above mentioned ecosystem is presented. In Section 4, we discuss the results obtained and we compare the model presented in this paper to the one presented in [1], using a P-lingua simulator [4].

2 Modelling the Ecosystem

The ecosystem to be modelled is located in the Catalan Pyrenees (NE Spain). This area contains a total of 36 breeding territories of the Bearded Vulture, 65 of the Egyptian Vulture and 525 of the Eurasian Griffon Vulture.

In addition to the three vultures, the ecosystem to be modelled is also composed of 9 prey species: the Pyrenean Chamois (*Rupicapra pyrenaica*), the Red Deer (*Cervus elaphus*), the Fallow Deer (*Dama dama*), the Roe Deer (*Capreolus capreolus*), sheep (*Ovis aries*), the cow (*Bos taurus*), the horse (*Equus caballus*), the goat (*Capra hircus*) and the wild boar (*Sus scrofa*). Prey species remains constitutes the basic feeding source for the vultures in the area under study.

The three vultures are cliff-nesting and long-lived species characterized by their low fecundity [3]. Concerning their diet, the Bearded Vulture is the only vertebrate that feeds almost exclusively on bone remains of medium size ungulates (see reviews in [6], [5]), whereas the Egyptian vulture feeds on dead small animals and the Eurasian Griffon vultures on medium and large sized animals [3].

The Bearded Vulture has a mind lifespan in wild birds of 21 years [2]. The mean age of first breeding is 8 years. The number of decedents for breeding is one chick. The female's annual fertility rate in Catalonia in the last years is estimated to be around 38%.

The Egyptian Vulture and the Griffon Vulture has a mind lifespan in wild birds of 25 years. The mean age of first breeding is 5 years. The number of descendants per breeding is one chick. The female's annual fertility rate in Catalonia in the last years is estimated to be around 59% for the Egyptian Vulture and 75% for the Griffon Vulture ([3],[5]).

It is accepted that there is the same proportion of females than males in the three types of vultures.

The ecosystem modelled in [1] is characterized by the presence of the domestic species, sheep. We considered that species stay all year in the mountain and thus, the bones they left when they die is available for the vultures. The real situation is that there are some domestic animals which live permanently in the mountain whereas others only spend the summer season there. This fact is assumed in the present paper.

Taking all this background information into consideration, the following data are required for each species:

- I_1: age at which adult size is reached. Age at which the animal eats like an adult animal does. Moreover, at this age it will have surpassed the critical early phase during which the mortality rate is high;
- I_2: age at which it starts to be fertile;
- I_3: age at which it stops being fertile;
- I_4: average life expectancy;
- I_5: fertility ratio (number of descendants by 100 fertile female);
- I_6: mortality ratio in the first years, $age < I_1$ (per cent);
- I_7: mortality ratio in adult animals, $age \geq I_1$ (per cent);
- I_8: ratio of females in the population (per cent).
- I_9: amount of bones from young animals when they die (kg)
- I_{10}: amount of bones from adult animals when they die (kg)
- I_{11}: amount of meet from young animals when they die (kg)
- I_{12}: amount of meet from adult animals when they die (kg)
- I_{13}: amount of bones necessary per year and animal (kg)
- I_{14}: amount of meet necessary per year and adult animal (kg)
- I_{15}: amount of grass necessary per year and adult animal (kg)

The required information about each species is shown in Table 4 (see Appendix).

3 A formal framework: A P System Based Model of the Ecosystem

In this section, we present a model of the ecosystem described in Section 2 by means of probabilistic P systems. We will study the behaviour of this ecosystem under different initial conditions.

First, we define the P systems based framework (probabilistic P systems), where additional features such as electrical charges which describe specific properties in a better way, are used.

Definition 1. *A probabilistic P system of degree q is a tuple*

$$\Pi = (\Gamma, \mu, \mathcal{M}_1, \dots, \mathcal{M}_q, R, \{c_r\}_{r \in R})$$

where:

- Γ *is the alphabet (finite and nonempty) of objects (the working alphabet);*
- μ *is a membrane structure (a rooted tree), consisting of* q *membranes, labelled* $1, 2, \dots, q$*. The skin membrane is labelled by 1. We also associate electrical charges with membranes from the set* $\{0, +, -\}$*, neutral and positive;*
- $\mathcal{M}_1, \dots, \mathcal{M}_q$ *are strings over* Γ*, describing the multisets of objects initially placed in the* n *regions of* μ*;*
- R *is a finite set of evolution rules. An evolution rule associated with the membrane labelled by* i *is of the form*

  $$r: \; u[\; v \;]_i^{\alpha} \xrightarrow{c_r} u'[\; v' \;]_i^{\alpha'}$$

  where u, v, u', v' *are multisets over* Γ*,* $\alpha, \alpha' \in \{0, +, -\}$*, and* c_r *is a real number between 0 and 1. Besides, for each* $u, v \in M(\Gamma)$*,* $i \in \{1, 2, \dots, q\}$ *and* $\alpha \in \{0, +, -\}$*, it must verify* $\sum_{j=1}^{t} c_{r_j} = 1$*, being* $r_1, \dots, r_t$ *the rules whose left-hand side is* $u[\; v \;]_i^{\alpha}$*.*

We denote by $[\; v \to v' \;]_i^{\alpha}$ the rule $u[\; v \;]_i^{\alpha} \to u'[\; v' \;]_i^{\alpha'}$ in the case $u = u' = \lambda$, and $\alpha = \alpha'$.

We assume that a global clock exists, marking the time for the whole system (for all compartments of the system); that is, all membranes and the application of all the rules are synchronized.

The multisets of objects present at any moment in the n *regions* of the system constitutes the *configuration* of the system at that moment. Particularly, tuple $(\mathcal{M}_1, \dots, \mathcal{M}_q)$ is the initial configuration of the system.

The P system can pass from one configuration to another one by using the rules from R as follows:

- A rule $u[\; v \;]_i^{\alpha} \xrightarrow{c_r} u'[\; v' \;]_i^{\alpha'}$ is applicable (with a probability c_r) to a membrane labelled by i, and with α as electrical charge, when the multiset u is contained in the father of membrane i, and the multiset v is contained in membrane i. When rule $u[\ v\ ]_i^{\alpha} \xrightarrow{c_r} u'[\ v'\ ]_i^{\alpha'}$ is applied, multiset u (resp. v) in the father of membrane i (resp. membrane i) is removed of that membrane and multiset u' (resp. v') is produced in that membrane.

- The rules are applied in a *maximal consistent parallelism*, that is, all those rules of type $u_1[\ v_1\ ]_i^{\alpha} \rightarrow u_1'[\ v_1'\ ]_i^{\alpha'}$ and $u_2[\ v_2\ ]_i^{\alpha} \rightarrow u_2'[\ v_2'\ ]_i^{\alpha'}$ might be applied simultaneously in a maximal way.
- The constants c_r associated with the rules indicate the affinity of the above mentioned rule for its application.

3.1 The model

The model proposed consists in the following probabilistic P system of degree 2 with two electrical charges (neutral and positive):

$$\Pi = (\Gamma, \mu, \mathcal{M}_1, \mathcal{M}_2, R, \{c_r\}_{r \in R})$$

where:

- $\Gamma = \{X_{ij},\ Y_{ij},\ V_{ij},\ Z_{ij} :\ 1 \le i \le n,\ 0 \le j \le g_{i,7}\} \cup \{b_{0i},\ b_i :\ 1 \le i \le n\} \cup \{B,\ G,\ M,\ B',\ G',\ M',\ C,\ C'\} \cup \{H_i,\ H_i',\ F_i,\ F_i',\ T_i,\ d_i,\ a_i :\ 1 \le i \le n\}$ is the working alphabet.

  In our model, $n = 17$ represents the different types of animals (according to the management) of the 12 species which compose the ecosystem under study. Symbols X, Y, V and Z represent the same animal but in different states. Index i is associated with the species and index j is associated with their age. It also contains the auxiliary symbols $B,\ B'$, which represent 0.5 kg of bones, $M,\ M'$, which represent 0.5 kg of meet and $G,\ G'$, which represent 0.5 kg of grass. Objects $H_i,\ H_i'$ represent 0.5 kg of biomass of bones, and objects $F_i,\ F_i'$ represent 0.5 kg of biomass meet left by specie i in different states. T_i is an object that is used for counting the existing animals of species i. If a species overcomes the maximum density, values will be regulated. At the moment when a regulation takes place, object a_i allows us to eliminate the number of animals of species i that exceed the maximum density. Object d_i is used to put under control domestic animals that are withdrawn from the ecosystem for their marketing.
- $\mu = [\ [\ ]_2\ ]_1$ is the membrane structure. We represent two regions, the skin and an inner membrane. The first is important to check the densities of every species do not overcome the threshold of the ecosystem. Animals reproduce, feed and die in the inner membrane. For the sake of simplicity, neutral polarization will be omitted.
- $\mathcal{M}_1$ and $\mathcal{M}_2$ are strings over Γ, describing the multisets of objects initially placed in the regions of μ (encoding the initial population and the initial food);

– $\mathcal{M}_1 = \{b_{0i},\ X_{ij}^{q_{ij}} : 1 \leq i \leq n,\ 0 \leq j \leq g_{i,7}\}$, where the multiplicity q_{ij} indicates the number of animals of species i whose age is j that are initially present in the ecosystem;
– $\mathcal{M}_2 = \{C\}$,

- The set R of evolution rules consists of:

$r_0 \equiv [C \rightarrow G'^{\beta} C']_2^0.$

$r_1 \equiv [b_{0,i} \rightarrow b_i]_1^0.$

– Reproduction-rules.

· Adult males:

$r_2 \equiv [X_{ij} \xrightarrow{(1-k_{i,1})\cdot(1-k_{i,4})} Y_{ij}]_1^0,\ 1 \leq i \leq n,\ g_{i,5} \leq j \leq g_{i,7}.$

· Adult females that reproduce:

$r_3 \equiv [X_{ij} \xrightarrow{k_{i,2}\cdot k_{i,1}\cdot(1-k_{i,4})} Y_{ij} Y_{i0}^{k_{i,3}}]_1^0,\ 1 \leq i \leq n,\ i \neq 5,\ g_{i,5} \leq j < g_{i,6}.$

$r_4 \equiv [X_{5j} \xrightarrow{0.5\cdot k_{5,1}} Y_{5j} Y_{50}^{k_{i,3}}]_1^0,\ g_{5,5} \leq j < g_{5,6}.$

$r_5 \equiv [X_{5j} \xrightarrow{0.5\cdot k_{5,1}} Y_{5j} Y_{60}^{k_{i,3}}]_1^0,\ g_{5,5} \leq j < g_{5,6}.$

· Adult females that do not reproduce:

$r_6 \equiv [X_{ij} \xrightarrow{(1-k_{i,2})\cdot k_{i,1}\cdot(1-k_{i,4})} Y_{ij}]_1^0,\ 1 \leq i \leq n,\ g_{i,5} \leq j < g_{i,6}.$

$r_7 \equiv [X_{ij} \xrightarrow{k_{i,1}\cdot(1-k_{i,4})} Y_{ij}]_1^0,\ 1 \leq i \leq n,\ g_{i,6} \leq j \leq g_{i,7}.$

· Young animals that do not reproduce:

$r_8 \equiv [X_{ij} \xrightarrow{1-k_{i,4}} Y_{ij}]_1^0,\ 1 \leq i \leq n,\ 1 \leq j < g_{i,5}.$

– Growth rules.

$r_9 \equiv [X_{ij} \xrightarrow{k_{i,5}\cdot k_{i,4}} Y_{i(g_{i,5}-1)} Y_{ij}]_1^0,\ 1 \leq i \leq n,\ g_{i,5} \leq j \leq g_{i,7}.$

$r_{10} \equiv [X_{ij} \xrightarrow{(1-k_{i,5})\cdot k_{i,4}} Y_{ij}]_1^0,\ 1 \leq i \leq n,\ g_{i,5} \leq j \leq g_{i,7}.$

– Mortality rules.

$r_{11} \equiv b_i[\ ]_2^0 \rightarrow [b_i a_i^{g_{i,8}}]_2^+ :\ 1 \leq i \leq n.$

· Young animals that survive:

$r_{12} \equiv Y_{ij}[\ ]_2^0 \xrightarrow{1-m_{i,1}-m_{i,3}} [V_{ij} T_i]_2^+ :\ 1 \leq i \leq n,\ 0 \leq j < g_{i,4}.$

· Young animals that die:

$r_{13} \equiv Y_{ij}[\ ]_2^0 \xrightarrow{m_{i,1}} [H_i'^{f_{i,1}\cdot g_{i,3}} F_i'^{f_{i,2}\cdot g_{i,3}} B'^{f_{i,1}\cdot g_{i,3}} M'^{f_{i,2}\cdot g_{i,3}}]_2^+ :\ 1 \leq i \leq n,\ 0 \leq j < g_{i,4}.$

- Young animals that are retired from the ecosystem:

  $r_{14} \equiv [Y_{ij} \xrightarrow{m_{i,3}} \lambda]_1^0 : \ 1 \leq i \leq n, \ 0 \leq j < g_{i,4}.$

- Adult animals that do not reach an average life expectancy and survive:

  $r_{15} \equiv Y_{ij}[\ ]_2^0 \xrightarrow{1-m_{i,2}} [V_{ij}T_i]_2^+ : \ 1 \leq i \leq n, \ g_{i,4} \leq j < g_{i,7}.$

- Adult animals that do not reach an average life expectancy and die:

  $r_{16} \equiv Y_{ij}[\,]_2^0 \xrightarrow{m_{i,2}} [H_i'^{f_{i,3} \cdot g_{i,3}} F_i'^{f_{i,4} \cdot g_{i,3}} B'^{f_{i,3} \cdot g_{i,3}} M'^{f_{i,4} \cdot g_{i,3}} V_{i,g_{i,5}-1}^{k_{i,4}} T_i^{k_{i,4}}]_2^+ :$ $1 \leq i \leq n, \ g_{i,4} \leq j < g_{i,7}.$

- Animals that reach an average life expectancy and die in the ecosystem:

  $r_{17} \equiv Y_{ig_{i,7}}[\,]_2^0 \xrightarrow{c_{17}} [H_i'^{f_{i,3} \cdot g_{i,3}} F_i'^{f_{i,4} \cdot g_{i,3}} B'^{f_{i,3} \cdot g_{i,3}} M'^{f_{i,4} \cdot g_{i,3}} V_{i,g_{i,5}-1}^{k_{i,4}} T_i^{k_{i,4}}]_2^+ :$ $1 \leq i \leq n$, being $c_{17} = k_{i,4} + (1 - k_{i,4}) \cdot (m_{i,4} + (1 - m_{i,4}) \cdot m_{i,2}).$

- Animals that reach an average life expectancy and retire from the ecosystem:

  $r_{18} \equiv [Y_{ig_{i,7}} \xrightarrow{(1-k_{i,4}) \cdot (1-m_{i,4}) \cdot (1-m_{i,2})} \lambda]_1 : \ 1 \leq i \leq n.$

– Regulation rules.

  $r_{19} \equiv [G' \to G]_2^+.$
  $r_{20} \equiv [B' \to B]_2^+.$
  $r_{21} \equiv [M' \to M]_2^+.$
  $r_{22} \equiv [C' \to C]_2^+.$
  $r_{23} \equiv [H_i' \to H_i]_2^+ : \ 1 \leq i \leq n.$
  $r_{24} \equiv [F_i' \to F_i]_2^+ : \ 1 \leq i \leq n.$

– Evaluation of the density of the different species in the ecosystem

  $r_{25} \equiv [T_i^{g_{i,8}} a_i^{g_{i,8}-g_{i,9}} \to \lambda]_2^+ : \ 1 \leq i \leq n.$

  $r_{26} \equiv [V_{ij} \to Z_{ij}]_2^+ : \ 1 \leq i \leq n, \ 0 \leq j < g_{i,7}.$

– Feeding rules.

  $r_{27} \equiv [Z_{ij} a_i B^{f_{i,5} \cdot g_{i,3}} G^{f_{i,6} \cdot g_{i,3}} M^{f_{i,7} \cdot g_{i,3}}]_2^+ \to X_{i(j+1)}[\ ]_2^0 : \ 1 \leq i \leq n, \ 0 \leq$ $j \leq g_{i,7}.$

– Balance rules. The purpose of these rules is to make a balance at the end of the year. That is, the leftover food is not useful for the next year, so it is necessary to eliminate it. But if the amount of food not is enough, some animals die.

- Elimination of the remaining bones, meet and grass:

  $r_{28} \equiv [B \to \lambda]_2^0.$

$r_{29} \equiv [G \rightarrow \lambda]_2^0.$

$r_{30} \equiv [M \rightarrow \lambda]_2^0.$

$r_{31} \equiv [T_i \rightarrow \lambda]_2^0 : \ 1 \leq i \leq n.$

$r_{32} \equiv [a_i \rightarrow \lambda]_2^0 : \ 1 \leq i \leq n.$

$r_{33} \equiv [b_i]_2^0 \rightarrow b_i[\ ]_2^0 : \ 1 \leq i \leq n.$

$r_{34} \equiv [H_i]_2^0 \rightarrow H_i[\ ]_2^0 : \ 1 \leq i \leq n.$

$r_{35} \equiv [F_i]_2^0 \rightarrow F_i[\ ]_2^0 : \ 1 \leq i \leq n.$

· Young animals mortality:

$r_{36} \equiv [Z_{ij} \xrightarrow{g_{i,1}} H_i'^{f_{i,1}} F_i'^{f_{i,2}} B'^{f_{i,1}} M'^{f_{i,2}}]_2^0 : \ 1 \leq i \leq n, \ 0 \leq j < g_{i,4}.$
$r_{37} \equiv [Z_{ij}]_2^0 \xrightarrow{1-g_{i,1}} d_i[\ ]_2^0 : \ 1 \leq i \leq n, \ 0 \leq j < g_{i,4}.$

· Adult animals mortality:

$r_{38} \equiv [Z_{ij} \xrightarrow{g_{i,1}} H_i'^{f_{i,3}} F_i'^{f_{i,4}} B'^{f_{i,3}} M'^{f_{i,4}}]_2^0 : \ 1 \leq i \leq n, \ g_{i,4} \leq j \leq g_{i,7}.$

$r_{39} \equiv [Z_{ij} \xrightarrow{1-g_{i,1}} \lambda]_2^0 : \ 1 \leq i \leq n, \ g_{i,4} \leq j \leq g_{i,7}.$

$r_{40} \equiv [H_i \rightarrow \lambda]_1^0 : \ 1 \leq i \leq n.$

$r_{41} \equiv [F_i \rightarrow \lambda]_1^0 : \ 1 \leq i \leq n.$

The constants associated with the rules have the following meaning:

- $g_{i,1}$: 1 for wild animals and 0 for domestic animals.
- $g_{i,2}$: 1 for carnivorous animals and 0 otherwise.
- $g_{i,3}$: proportion of time that they remain in the mountain during the year.
- $g_{i,4}$: age at which adult size is reached. This is the age at which the animal eats like and adult does, and at which if the animal dies, the amount of biomass it leaves is similar to the total one left by an adult. Moreover, at this age it will have surpassed the critical early phase during which the mortality rate is high.
- $g_{i,5}$: age at which it starts to be fertile.
- $g_{i,6}$: age at which it stops being fertile.
- $g_{i,7}$: average life expectancy in the ecosystem.
- $g_{i,8}$: maximum density of the ecosystem.
- $g_{i,9}$: number of animals that survive after reaching maximum density of the ecosystem.
- $k_{i,1}$: proportion of females in the population (per one).
- $k_{i,2}$: fertility ratio (proportion of fertile female that reproduce).
- $k_{i,3}$: number of descendants per each fertile female that reproduce.

- $k_{i,4}$: it is equal to 0 when the species go through a natural growth (animals which remain in the same territory throughout their lives) and it is equal to 1 when animals are nomadic (the Bearded Vulture moves from one place to another until it is 6–7 years old, when it settles down).
- $k_{i,5}$: population growth (per one).
- $m_{i,1}$: natural mortality ratio in first years, $age < g_{i,4}$ (per one).
- $m_{i,2}$: mortality ratio in adult animals, $age \geq g_{i,4}$ (per one).
- $m_{i,3}$: percentage of domestic animals withdrawn in the first ages of the not stabilized populations.
- $m_{i,4}$: is equal to 1 if the animal dies at the age of $g_{i,7}$ and it is not retired, and it is equal to 0 if the animal not dies at the age of $g_{i,7}$ but it is retired from the ecosystem.
- $f_{i,1}$: amount of bones from young animals when they die, $age < g_{i,4}$.
- $f_{i,2}$: amount of meet from young animals when they die, $age < g_{i,4}$.
- $f_{i,3}$: amount of bones from adult animals when they die, $age \geq g_{i,4}$.
- $f_{i,4}$: amount of meet from adult animals when they die, $age \geq g_{i,4}$.
- $f_{i,5}$: amount of bones necessary per year and animal (1 unit is equal 0.5 kg of bones).
- $f_{i,6}$: amount of grass necessary per year and animal.
- $f_{i,7}$: amount of meet necessary per year and animal.

The constants used in this work are the same than those of [1], except for those referring to the maximum density of the population, the meet or the grass. However, they have been renamed in this work in order to be able to group them according to their characteristics. Thus, general characteristics are now named with g, those of reproduction with k, those corresponding to mortality with m and those of feeding with f. See Appendix in table 5.

3.2 Structure of the P system running

The model presented in [1], shows some restrictions which produce undesired effects for the study of the ecosystem evolution. Thus, in the first version of the model, it was not born in mind the resources for the feeding of herbivorous species, that is, it was assumed that there was enough grass at the ecosystem for all the population. Similarly, the maximum density of certain species in some areas of the ecosystem was not taken into consideration. It has been experimentally proved that, when the number of animals of a species exceeds a threshold, a phenomenon of auto-regulation of the population takes place.

In this paper, we present a new model of the ecosystem that includes new ingredients with the aim to overcome the limitations previously described. More specifically, the modifications made are the following:

- It has been added new species which have active roles in the ecosystem under study, although their roles are perhaps less relevant that those of the first species studied. These species are the wild boar, the horse, the goat and the cow. Besides, it has been included greedy species such as the Egyptian Vulture and the Griffon Vulture which compete with the Bearded Vulture.
- A new module has been added in order to regulate the population density of the ecosystem.
- The mortality module has been modified in order to consider that after an animal dies, in addition to the bones it leaves at the ecosystem, its meet serves as food for other animals.
- The feeding module has also been modified because the feeding resources for the species at the ecosystem have been modelled in this new approach. For this reason, new objects have been introduced representing, apart from the bones, the amount of meet and grass available at the ecosystem.

In the model presented in Section 3.1, a new module devoted to control the density has been introduced. From the point of view of the execution of the system, the new module has been incorporated between the Mortality and the Feeding modules. These are depicted in Figure 1.

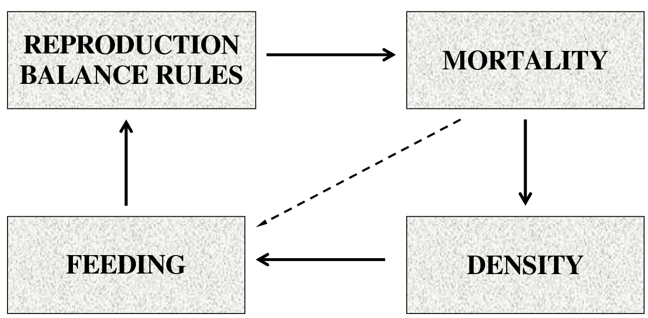


Fig. 1. Modules of the P systems

Let us recall that in the model presented in [1], objects X represent the different species along the execution of the reproduction module. Objects X evolve to objects Y when they pass to the mortality module, and these objects Y evolve to objects Z when they pass to the feeding module. Finally, the cycle is completed when objects Z evolve to objects X.

In order to keep the representation of the species at the different modules, we have used objects V to describe the species at the density module. For that purpose, objects Y (mortality module) evolve to objects V (density module), together with objects T which represent the number of individuals per each species. Then, objects V evolve to objects Z (feeding module). By the way, objects T will allow the activation of the process of auto–regulation of the ecosystem when the number of individuals of a species exceed the threshold of maximum density, which is codified by objects a.

When a cycle is produced, all objects which are not associated with species are eliminated, except the biomass generated by the animals that have died due to the process of regulation.

4 Results and discussions

The software tool used for the purposes of this paper is based on P-Lingua 2.0 [4], P-Lingua is a new programming language able to define P systems of different types (from now on, frameworks). For instance, P-Lingua can define any P system within the probabilistic framework mentioned in this paper.

Next, we describe how to implement in P–Lingua the applicability of the rules to a given configuration.

(a) Rules are classified into sets so that all the rules belonging to the same set have the same left–hand side.
(b) Let $\{r_1, \ldots, r_t\}$ be one of the said sets of rules. Let us suppose that the common left-hand side is $u\ [v]_i^\alpha$ and their respective probabilistic constants are $c_{r_1}, \ldots, c_{r_t}$. In order to determine how these rules are applied to a give configuration, we proceed as follows:
   - It is computed the greatest number N so that u^N appears in the father membrane of i and v^N appears in membrane i.
   - N random numbers x such that $0 \leq x < 1$ are generated.
   - For each k $(1 \leq k \leq t)$ let n_k be the amount of numbers generated belonging to interval $[\ \sum_{j=0}^{k-1} c_{r_j}\ ,\ \sum_{j=0}^{k} c_{r_j})$ (assuming that $c_{r_0} = 0$).
   - For each k $(1 \leq k \leq t)$, rule r_k is applied n_k times.

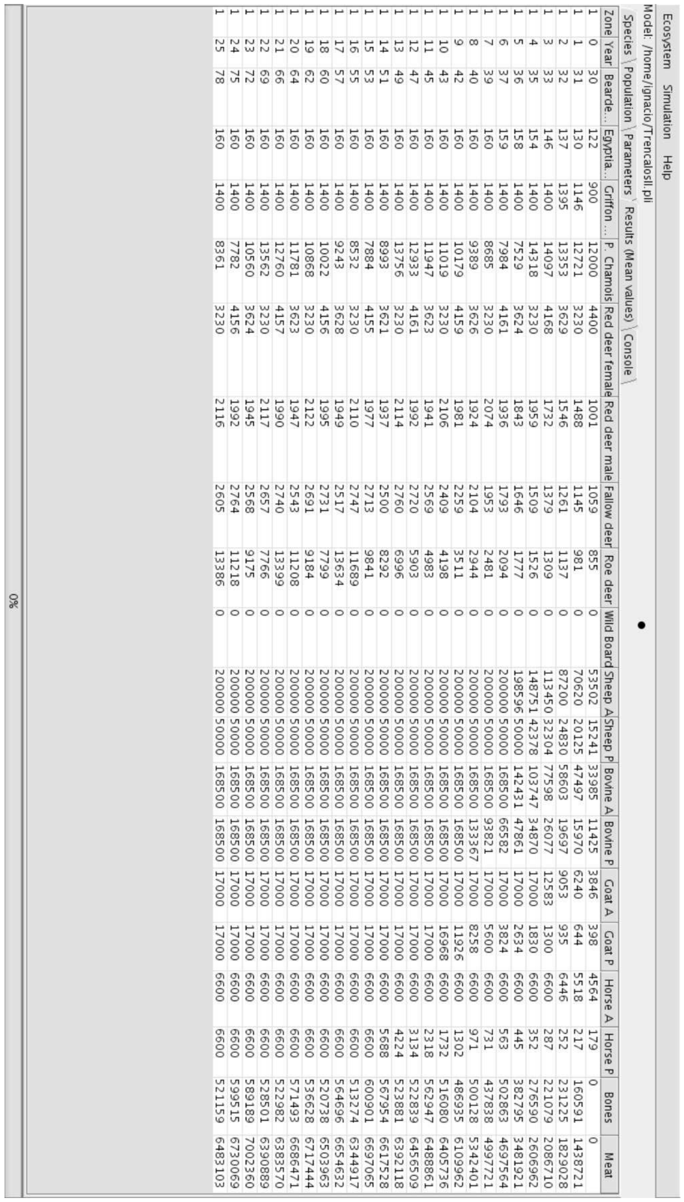
P-Lingua 2.0 provides a JAVA library that defines algorithms in order to simulate P system computations for each supported framework, so we are using a common algorithm for all P systems within the probabilistic framework.

By defining the ecosystem model by a P system written in P-Lingua, it is possible to check, validate and improve the model in a flexible way, instead of developing a new “ad hoc” simulator for each new model.

The application has a friendly user-interface, which sits on the P-Lingua JAVA library, allowing the user to change the initial parameters of the ecosystem in an easy way without special knowledge about the P system or the initial multisets. The main objective is to make virtual experiments over the ecosystem.

The current version of this software is a prototype GPL licensed [8].

In order to compare the model presented in this work to the one presented in [1], it has been used the P-lingua simulator [4]. We have simulated the evolution of the



Zone	Year	Bearde...	Egyptia...	Griffon ...	P. Chamois	Red deer female	Red deer male	Fallow deer	Roe deer	Wild Board	Sheep A	Sheep P	Bovine A	Bovine P	Goat A	Goat P	Horse A	Horse P	Bones	Meat
1	0	30	122	900	12000	4400	1001	1059	855	0	53502	15241	33985	11425	3846	398	4564	179	0	0
1	1	31	130	1146	12721	3230	1488	1145	981	0	70620	20125	47497	15970	6240	644	5518	217	160591	1438721
1	2	32	137	1395	13353	3629	1546	1261	1137	0	87200	24830	58603	19697	9053	935	6446	252	231225	1829028
1	3	33	146	1400	14097	4168	1732	1379	1309	0	113450	32304	77598	26077	12583	1300	6600	287	221079	2086710
1	4	35	154	1400	14318	3230	1959	1509	1526	0	148751	42378	103747	34870	17000	1830	6600	352	276590	2606962
1	5	36	158	1400	7529	3624	1843	1646	1777	0	198596	50000	142431	47861	17000	2634	6600	445	382795	3481921
1	6	37	159	1400	7984	4161	1936	1793	2094	0	200000	50000	168500	66582	17000	3824	6600	563	502863	4697564
1	7	39	160	1400	8685	3230	2074	1953	2481	0	200000	50000	168500	93821	17000	5600	6600	731	437838	4997721
1	8	40	160	1400	9389	3626	1924	2104	2944	0	200000	50000	168500	133367	17000	8258	6600	971	500128	5342401
1	9	42	160	1400	10179	4159	1981	2259	3511	0	200000	50000	168500	168500	17000	11926	6600	1302	486935	6109962
1	10	43	160	1400	11019	3230	2106	2409	4198	0	200000	50000	168500	168500	17000	16968	6600	1732	516080	6405736
1	11	45	160	1400	11947	3623	1941	2569	4983	0	200000	50000	168500	168500	17000	17000	6600	2318	562947	6488861
1	12	47	160	1400	12933	4161	1992	2720	5903	0	200000	50000	168500	168500	17000	17000	6600	3134	522839	6456509
1	13	49	160	1400	13756	3230	2114	2760	6996	0	200000	50000	168500	168500	17000	17000	6600	4224	523881	6392118
1	14	51	160	1400	8993	3621	1937	2500	8292	0	200000	50000	168500	168500	17000	17000	6600	5688	567954	6617528
1	15	53	160	1400	7884	4155	1977	2713	9841	0	200000	50000	168500	168500	17000	17000	6600	6600	600901	6697065
1	16	55	160	1400	8532	3230	2110	2747	11689	0	200000	50000	168500	168500	17000	17000	6600	6600	513274	6344917
1	17	57	160	1400	9243	3628	1949	2517	13634	0	200000	50000	168500	168500	17000	17000	6600	6600	564696	6654632
1	18	60	160	1400	10022	4156	1995	2731	7799	0	200000	50000	168500	168500	17000	17000	6600	6600	520738	6503963
1	19	62	160	1400	10868	3230	2122	2691	9184	0	200000	50000	168500	168500	17000	17000	6600	6600	536628	6717444
1	20	64	160	1400	11781	3623	1947	2543	11208	0	200000	50000	168500	168500	17000	17000	6600	6600	571493	6686471
1	21	66	160	1400	12760	4157	1990	2740	13399	0	200000	50000	168500	168500	17000	17000	6600	6600	522982	6383570
1	22	69	160	1400	13562	3230	2117	2657	7766	0	200000	50000	168500	168500	17000	17000	6600	6600	528501	6390889
1	23	72	160	1400	10560	3624	1945	2568	9175	0	200000	50000	168500	168500	17000	17000	6600	6600	589189	7002360
1	24	75	160	1400	7782	4156	1992	2764	11218	0	200000	50000	168500	168500	17000	17000	6600	6600	599515	6730069
1	25	78	160	1400	8361	3230	2116	2605	13386	0	200000	50000	168500	168500	17000	17000	6600	6600	521159	6483103

Fig. 2. A tool for simulating ecosystems

Bearded Vulture, Red Deer, Fallow Deer, Roe Deer and Pyrenean Chamois species, in a period of 25 years. The starting information is the population registered in the year 2008. Some of the results are shown in Figure 3.

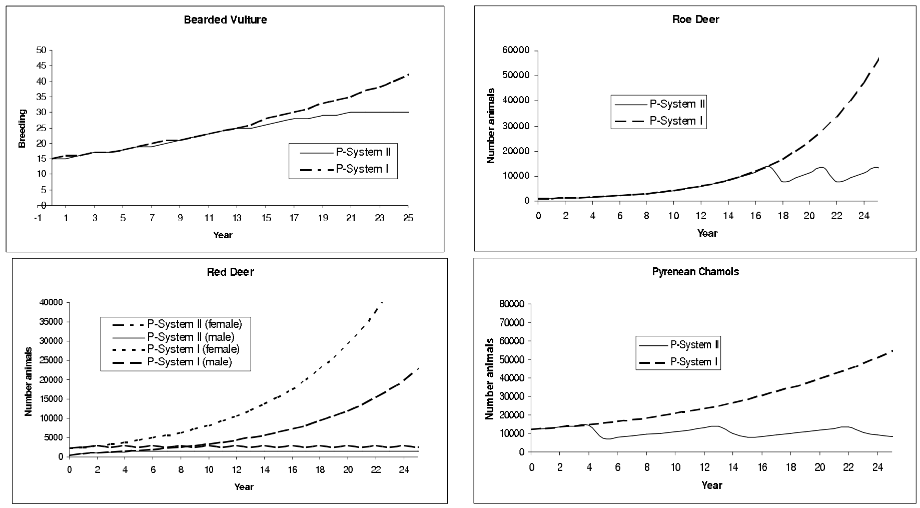


Fig. 3. Result of the simulation in 25 years time

It is observed that during the first years, the obtained values are almost equal. However, from a certain moment on, the population of the ecosystem experiments an exponential growth according to the P system [1] (P system I in the picture) whereas it maintains stable according to P systems II. The results of the new P system (P system II in the picture) are closer to the real situation.

The first step that will be taken is to validate the P system presented with real information, including all the proposed species with its specifications. When the model is validated, it will be able to apply it for the study of the evolution of an ecosystem under different situations. The model can be a useful tool for the management of the species.

In order to obtain a more realistic model, the following step should be to include possible movements of species among adjacent zones of the ecosystem.

5 Conclusions and Future works

A probabilistic P System which models an ecosystem related with Scavenger birds, and that is located in the Catalan Pyrenees, has been presented. By using this kind of P System, it has been possible to study the dynamics of the mentioned ecosystem adding new ingredients. That framework allows us to analyze how the ecosystem would evolve when different biological factors were modified either by nature or through human intervention, improving the results presented in [1].

A new JAVA software tool with a friendly user-interface sitting on the P-Lingua 2.0 JAVA library [4] has been developed in this paper. This application provides a flexible way to check, validate and improve computational models of ecosystem based on P systems instead of designing new software tools each time new ingredients are added to the models. Furthermore, it is possible to change the initial parameters of the modelled ecosystem in order to make the virtual experiments suggested by experts. These experiments will provide results that can be interpreted in terms of hypotheses. Finally, some of these hypotheses will be selected by the experts in order to be checked in real experiments.

In a future work, we will try to model neighbouring ecosystems with existing interactions among them, so it will be necessary to modify the scenario. Multi-environment P systems introduced in [7] could provides a friendly and flexible framework to get a new approach.

Acknowledgement

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References

1. M. Cardona, M. A. Colomer, M.J. Pérez–Jiménez, D. Sanuy, A. Margalida. Modelling ecosystems using P Systems: The Bearded Vulture, a case of study. *Lecture Notes in Computer Science*, **5391** (2009), 137–156.
2. C.J.Brown. Population dynamics of the Bearded Vulture Gypaetus barbatus in southern Africa. *African Journal of Ecology*, **35** (1997), 53–63.
3. J.A. Donázar. *Los buitres ibéricos: biología y conservación*. J.M. Reyero Editor, Madrid, Spain, 1993.
4. M. García–Quismondo, R. Gutiérrez–Escudero, I. Pérez–Hurtado. P–Lingua 2.0: added features and first applications. In this volume.
5. A. Margalida, J.Bertran, R. Heredia: Diet and food preferences of the endangered Bearded Vulture Gypaetus barbatus: a basis for their conservation. *Ibis* **151** (2009), 235–243.
6. A. Margalida, D. García, A. Cortés-Avizanda. Factors influencing the breeding density of Bearded Vultures, Egyptian Vultures and Eurasian Griffon Vultures in Catalonia (NE Spain): management implications. *Animal Biodiversity and Conservation*, **30**, 2 (2007), 189–200.
7. F.J. Romero, M.J. Pérez–Jiménez. A model of the Quorum Sensing System in Vibrio Fischeri using P systems. *Artificial Life*, 14, 1 (2008), 95-109.
8. GPL license: `http://www.gnu.org/copyleft/gpl.html`

Appendix

Species	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}	I_{12}	I_{13}	I_{14}	I_{15}
Bearded Vulture	1	8	20	21	38	6	12	50	0	0	0	0	460	0	0
Egyptian Vulture	1	5	24	25	59.3	21	25	50	0	0	0	0	0	166	0
Griffon Vulture	1	5	24	25	75	14	1	50	0	0	0	0	0	400	0
Pyrenean Chamois	1	2	18	18	75	60	6	55	3	6	4	24	0	0	275
Red Deer	1	2	17	17-20	75	34	6	50	10	20	15	90	0	1270	0
Fallow Deer	1	2	12	12	55	50	6	75	1	2	14	37	0	550	0
Roe Deer	1	1	10	10	100	58	6	67	0.5	1	4	19	0	300	0
Wild Board	1	1	4	11	3.5	62-79	30-40	50	4	12	6	60	0	365	0
Sheep	1	2	8	8	75	15	3	96	3.5	7	4	28	0	660	0
Bovine	2	2	9	14	90	5.7	0.45	90	10.5	6	59.5	519	0	5500	0
Goat	1	2	8	6	90	12	2	97	3.5	9.5	4	37.5	0	700	0
Horse	3	3	9	20	90	3.4	1.42	97	10.5	9	59.5	891	0	6000	0

Fig. 4. Natural constants used in the model

Species	i	$g_{i,1}$	$g_{i,2}$	$g_{i,3}$	$g_{i,4}$	$g_{i,5}$	$g_{i,6}$	$g_{i,7}$	$g_{i,8}$	$g_{i,9}$	$k_{i,1}$	$k_{i,2}$	$k_{i,3}$	$k_{i,4}$	$k_{i,5}$	$m_{i,1}$	$m_{i,2}$	$m_{i,3}$	$m_{i,4}$	$f_{i,1}$	$f_{i,2}$	$f_{i,3}$	$f_{i,4}$	$f_{i,5}$	$f_{i,6}$	$f_{i,7}$
Bearded Vulture	1	1	0	1	1	8	20	21	120	120	0.5	0.08	1	1	0.04	0.06	0.12	0	1	0	0	0	0	460	0	0
Egyptian Vulture	2	1	0	0.5	1	5	24	25	160	160	0.5	0.593	1	0	0	0.17	0.07	0	1	0	0	0	0	0	0	332
Griffon Vulture	3	1	0	1	1	5	24	25	1400	1400	0.5	0.75	1	0	0	0.03	0.01	0	1	0	0	0	0	0	0	800
P. chamois	4	1	0	1	1	2	18	18	15000	7500	0.55	0.75	1	0	0	0.6	0.06	0	1	6	8	12	48	0	550	0
Red deer female	5	1	0	1	1	2	17	17	4615	3230	1	0.75	1	0	0	0.34	0.06	0	1	15	26	30	120	0	2540	0
Red deer male	6	1	0	1	1	2	20	20	2885	2020	0	0	0	0	0	0.34	0.36	0	1	24	30	48	192	0	2540	0
Fallow deer	7	1	0	1	1	2	12	12	3000	2400	0.75	0.55	1	0	0	0.5	0.06	0	1	2	28	4	74	0	1100	0
Roe deer	8	1	0	1	1	1	10	10	15000	7500	0.67	1	1	0	0	0.58	0.06	0	1	1	8	2	38	0	600	0
Wild Board	9	1	0	1	1	1	4	11	200000	200000	0.5	0.035	3	0	0	0.705	0.035	0	0	8	12	24	120	0	730	0
Sheep A	10	0	0	1	1	2	8	8	200000	200000	0.96	0.75	1	0	0	0.15	0.030	0.59	0	7	8	14	56	0	1320	0
Sheep P	11	0	0	0.5	1	2	8	8	50000	50000	0.96	0.75	1	0	0	0.15	0.030	0.59	0	7	8	14	56	0	1320	0
Bovine A	12	0	0	1	2	2	9	14	168500	168500	0.9	0.9	1	0	0	0.057	0.045	0	0	21	119	12	1038	0	11000	0
Bovine P	13	0	0	0.5	2	2	9	14	168500	168500	0.9	0.9	1	0	0	0.057	0.045	0	0	21	119	12	1038	0	11000	0
Goat A	14	0	0	1	1	2	8	6	17000	17000	0.97	0.9	1	0	0	0.12	0.015	0.59	0	7	8	19	75	0	1400	0
Goat P	15	0	0	0.5	1	2	8	6	17000	17000	0.97	0.9	1	0	0	0.12	0.015	0.59	0	7	8	19	75	0	1400	0
Horse A	16	0	0	1	3	3	9	20	6600	6600	0.97	0.9	1	0	0	0.034	0.014	0	0	21	119	18	1782	0	12000	0
Horses P	17	0	0	0.5	3	3	9	20	6600	6600	0.97	0.9	1	0	0	0.034	0.014	0	0	21	119	18	1782	0	12000	0

Fig. 5. Constants used in the P system based model. Acronyms (A) and (P) mean *annual* and *periodical* respectively