A New P System to Model the Subalpine and Alpine Plant Communities

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Summary. In this work we present a P system based model of the ecosystem dynamics of plant communities. It is applied to four National Hunting Reservoirs in Catalan Pyrenees (Spain). In previous works several natural high- mountain- ecosystems and population dynamics were modeled, but in those works grass was considered unlimited and changes in plant communities were not taken into account. In our new model we take advantage of the modularity of P systems, adding the plant communities to an existing model on scavengers dynamics [6]. We introduce the plant community production and two possible changes or evolutions in communities: (1) due to less grazing pressure, and (2) due to recovering pastures with human management as for example fire or clearing.

1 Introduction

Everyday the knowledge on the functioning of biological processes and involved variables gain more importance. It is interesting to model this acquired knowledge through parallel independent work, defining a model as close to reality as possible, allowing to simulate behavioural processes in different possible scenarios.

Natural processes have a great complexity, because each biological process involves a large number of variables and their interactions, so that modelling ecosystems is not a simple task [5]. Classical models such as differential equations present several limitations. Most of all they cannot consider simultaneously multiple species and their interactions. The most frequently used models are viability models or multi-agent models, that do not allow the study of different species with their interactions. In the work at hand, we make use of bio-inspired models, called P systems, which could serve as an alternative to the multi-agent models, having in mind that in the case of the P systems the evolution rules cannot be expressed mathematically.

The use of P systems to model these natural processes has important advantages, such as the modularity (P systems can be composed of modules, which make it easier to modify and improve existing models). Another important characteristic of P systems is their ability to work parallel. Also, because strictly mathematical expressions are not required, there is no limitation to the number of variables. These characteristics make P systems very helpful for modelling complex ecosystems [6]. Their problem is, just like for every complex model, the necessity to hold an extensive set of experimental data to be successful. The more complex is the process to study, the more knowledge is needed. For this reason it is required to work with interdisciplinary teams of experts.

P systems are very useful to model natural ecosystems. Their properties make them very attractive for modelling complex ecosystems. Recently some works that model ecosystems using P Systems have been published [3, 4, 6]. In these works models focusing on animal population dynamics were presented. They model natural processes as feeding, grazing, reproduction and mortality. The food source is grass for ungulate species and meat or bones for avian scavengers.

In the present work, the amount of grass available for grazing is not a fixed value, as it was in previous ones. It depends of a large number of factors and furthermore of the existence of plant communities which evolve due to their management. The aim is to define new modules, which are incorporated into the model presented for the avian scavengers [6]. These modules operate parallel with the modules of the existent scavengers model.

We have developed a model in which different plant communities produce an amount of grass, in function on climate variables. In addition the plant communities can change and evolve over time due to changes in biotic or abiotic processes. Generally the abiotic processes occur in higher altitudes, and are not sufficiently known to be understood and to be modelled. The biotic processes play a more important role, causing changes in plant communities, in particular due to the grazing management.

2 Alpine and Subalpine Plant Communities

In the plant-geographic sense alpine life zone exclusively encompasses vegetation above the natural high altitude treeline [10]. In our work we also consider the subalpine life zone above the actual treeline. Both zones can be defined as man made pastures for summer grazing above the actual treeline.

The Phytosociology is the science that analyses and characterises the different levels of plant associations called formally "Plant Communities". These communities are divided into classes, these consist of orders, these of alliances and the latter of associations. The alliance level was chosen as the focus of this work, because of its better availability of information.

In high altitude zones the vegetation activity does not occur throughout the whole year, but is concentrated in the months in which the conditions are favourable. Thus, the growing season, is the part of the year when the vegetation is active and productive [10].

2.1 Communities production

Production is the amount of new biomass accumulation over a longer period of time.[10].

There are many methods to quantify the aerial net primary production (ANP) in grasslands; Singh et al. [15] provide in their work a list of exhaustive methods that have applied in the following several authors [8, 11]. In the present work we have chosen the method defined as peak standing crop of current live material plus recent dead, because it is the most commonly used and allows comparisons. This method includes the estimate of ANP, the peak community biomass (weight of the live vegetation) plus the weight of current season's growth which has reached the senescence before the date of peak live biomass [15].

2.2 Grassland dynamics. Plant Communities changes

This concept refers to changes over time of grassland structures and the replacement of some plant communities by others in relation to the variation of environmental factors, including animal grazing and human management [9]. Thus, grasslands are not static, but they evolve and transform over time due to abiotic and biotic factors. In our current work we analyse two changes in plant alliances: (1) the evolution due to less grazing pressure and, the inverse case, (2) the evolution due to recovering pastures with human management. However there are many other possible changes to treat. The observation and the study of these changes, some of which are still quite unknown [9], give the model wide possibilities for future research.

There are two different types of changes in plant communities: biotic and abiotic processes. The two situations taken into consideration in our work are located within the second group, inside the landscape changes due to anthropic management below 2000 meters.

Some plant communities, represented here by plant alliances, are not stable, but were created thanks to the use of these surfaces by cattle. Thus, very important ecological communities with a high degree of biodiversity have emerged. They increase the visual quality of landscape, without forgetting its significance for animal grazing, both domestic and wild. Therefore its protection, conservation and study are of importance.

Changes due to less grazing pressure are the most important ones that occur in our days in alpine and subalpine ecosystems, upper 1500 meters. Nowadays exist less domestic animals that exploit these grasslands, or in other words the currently carrying capacity is higher than the real number of animals.

In this case the grassland evolves first to a bush land and then to a coniferous forest (i.e. Class. *Vaccinio-Piceetea* Br.-Bl. in Br.-Bl., Sissingh & Vlieger

1939). In this first version of our work only the transformation from grassland (Al. *Bromion erecti* Koch 1926) to scrubland (Al. *Juniperion nanae* Br.-Bl. et al. 1939) is introduced into the model.

The alliance *Bromion erecti* can be defined as Pyrenean meso-xerophytic grassland; and *Juniperion nanae* as Alpine-Pyrenean dwarfed shrub and heaths of wind-swept places without long snow cover and sunny expositions [14].

The evolution of the vegetation due to human management to recover grasslands (e.g. fire, clearing) is the opposite of the previous case occurred due a low livestock pressure. In this processes the shrub *Juniperion nanae* evolve to the grassland *Bromion erecti*. The most likely cause is the controlled burning of these areas for grazing.

3 Materials and methods

The National Hunting Reserves of Catalonia (Spain) (NHR) are geographically defined territories, with special characteristics, declared to promote, preserve and protect native fauna species. They are located in mountainous areas with high ecological and landscape quality. In these areas exists a very important wildlife fauna, including some species of great significance for hunting. In this work we have chosen the four National hunting reserves placed in the Catalan Pyrenees: Alt Pallars-Aran (106.661 ha), Cerdanya-Alt Urgell (19.003 ha), Cadí (48.449 ha) and Freser-Setcases (20.200 ha) (data provided by [12], see figure 1). Over the centuries, these alpine and subalpine zones have been exploited by man to feed their herds, sheep, cows and mares and themselves, and their management has contributed to the landscape transformation. The Pyrenean orography presents altitudinal zones between 1000 and 3000 m but we use only the higher zones between 1500 and 3000 m, occupied mostly by grass.

In the Pyrenean region, the level of annual rainfall ranges from 800 to 1200 mm and the maximum average temperatures do not exceed 25 ℃ in summer and do not fall under 5 ℃ in winter. To characterise it, we provide a series of temperatures and precipitation obtained from different weather stations located in the study area provided by the Meteorological Service of Catalonia.

To model the high mountain ecosystem as correctly as possible, we have separated our range (from 1500 to 3000 meters) into three different zones in function of their height due to their different climatic and orographic characteristics, that define which plant communities are established in each range. As a result we have defined a low altitude zone (from 1500 to 2000 m), an intermediate zone (from 2000 to 2500 m) and an upper zone (more than 2500 m). The first and the second range zone can be considered as low and high subalpine zones, while the third is alpine altitudinal range. This distinction is related to different plant communities available in each range, their primary production and the different length of their seasonal growing periods, as the growing season in low ranges is longer than in the high one.

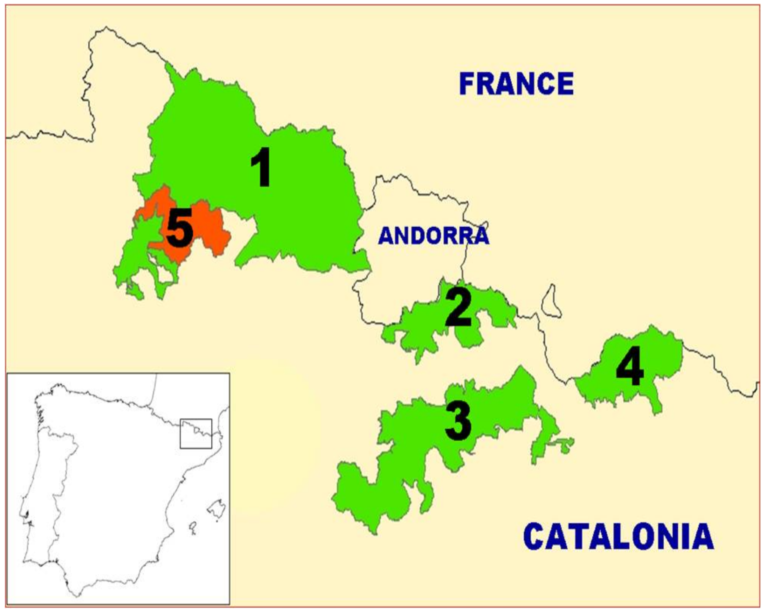

Fig. 1. Study area in the Catalan Pyrenees. Area 1: National Hunting Reservoir in l'Alt Pallars-Aran. Area 2: RNC Cerdanya-Alt Urgell. Area 3: RNC Cadí. Area 4 RNC: Freser-Setcases. Area 5: National Park, not include in the study.

Based on vegetation maps available [7], we defined the areas corresponding to the four National Hunting Reserves (RNC) and areas with an altitude below 1.500 meters were eliminated. As a result, we get the entire area bounded by the RNC situated above 1.500 meters, corresponding to the subalpine and alpine biogeographic regions.

In the present work we have identified a total of 26 different plant alliances (table 1). Each plant alliance is associated to an average production and a standard deviation [2, 1, 8, 11]. Each Natural Hunting Reservoir has a determinate surface at each altitude level, obtained from vegetation maps at scale 1:50000 [7].

The plant community production depends on:

- Type of plant community; in this work we focus on the alliance level.
- Weather, that determine the community production and the length of the growing season.
- Altitude, closely related to the previous concept. At higher altitudes, we have lower temperatures and shorter growing season.

An important variable is the length of the growing season. It is determined by climate and elevation. The beginning of the growing season is defined by means of the thermal integral, being the starting day of this period, for each altitudinal range, in which the sum of positive daily temperatures from the beginning of the year exceed 300 ℃. The end of the period is set from the consulted references [11].

Table 1. The 26 alpine and subalpine plant communities (at alliance level) defined in our model, their primary production ($g \cdot m^{-2} \cdot day^{-1}$) and their standard deviation [2, 1, 11] and their altitude range [9].* These alliances are assimilated to other similar alliances. ** Shrub community, not available for grazing.

Plant community	**Production**	**Standard deviation**	Altitude
Al.*Aphyllantion*	*	*	Low
Al.*Arabidion caeruleae*	*	*	Medium, High
Al.*Arrhenatherion-Bromion*	4,322	0,395	Low
Al.*Arrhenatherion 1*	7,253	0,662	Low
Al.*Arrhenatherion 2*	4,403	0,402	Low
Al.*Arrhenatherion 3*	3,529	0,322	Low
Al.*Bromion erecti*	4,026	0,368	Low, Medium
Al.*Bromion-Nardion*	4,026	0,410	Low, Medium
Al.*Caricion davallinae*	*	*	Low, Medium
Al.*Caricion nigrae*	2,966	0,271	Low, Medium
Al.*Cynosurion cristati*	2,292	0,209	Low
Al.*Elyonion myosuroidis*	1,750	0,160	Medium, High
Al.*Festuca panniculata*	3,895	0,356	Low, Medium
Al.*Festucion airoidis*	*	*	Medium, High
Al.*Festucion eskiae*	4,538	0,414	Low, Medium, High
Al.*Festucion scopariae*	0,967	0,088	Low, Medium, High
Al.*Juniperion nannae*	**	**	Low
Al.*Nardion strictae*	3,091	0,282	Low, Medium
Al.*Ononidion striatae*	4,028	0,368	Low, Medium
Al.*Polygonion avicularis*	3,266	0,298	Low, Medium
Al.*Primulion intricatae*	2,472	0,226	Low, Medium
Al.*Rumicion pseudoalpini*	3,26	0,298	Low, Medium
Al.*Salicion herbaceae*	1,292	0,118	Medium, High
Al.*Saponarion cespitosae*	*	*	Low, Medium, High
Cl.*Thlaspietea rotundifolii*	0,041	0,004	Low, Medium, High
Al.*Triseto-Polygonion*	2,795	0,255	Low, Medium

4 A P System Based modeling framework

In this section, we define a P system based framework where additional features, such as probabilistic functions and three electrical charges that better describe specific properties, are used.

A *skeleton of an extended P system* with active membranes of degree $q \leq 1$, $\Pi = (\Gamma, \mu, R)$, can be viewed as a set of (polarised) membranes hierarchised by a structure of membranes μ (a rooted tree) labeled by $0, 1, \ldots, q-1$. All membranes in μ are supposed to be (initially) neutral and they have associated with them R, a finite set of evolution rules of the form $u[v]_i^{\alpha} \rightarrow u'[v']_i^{\beta}$ that can modify their polarisation but not their label. Γ is an alphabet that represents the objects (i.e., animals, plant alliances, etc., see Fig. 3).

A probabilistic functional extended P system with active membranes of degree $q \leq 1$ taking T time units, $\Pi = (\Gamma, \mu, R, T, \{f_r : r \in R\}, M_0, \ldots, M_{q-1})$, can be viewed as a skeleton (Π, μ, R) with the membranes hierarchized by the structure μ labeled by $0, 1, \ldots, q-1$. T is a natural number that represents the simulation time of the system. For each rule $r \in R$ and a, $1 \leq a \leq T$, $f_r(a)$ is a whole number between 0 and 1, which represents a probabilistic constant associated with rule r at moment a. In a generic way, we denote $r : u[v]_i^{\alpha} \stackrel{f_r(a)}{\rightarrow} u'[v']_i^{\alpha'}$.

The tuple of multisets of objects present at any moment in the q regions of the system constitutes the configuration of the system at that moment. The tuple $(M_0, , \ldots, M_{q-1})$ is the initial configuration of Π.

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

- A rule $r : u[v]_i^{\alpha} \stackrel{f_r(a)}{\rightarrow} u'[v']_i^{\alpha'}$ is applicable to a membrane labeled by i, and with α as electrical charge if multiset u is contained in the membrane immediately outside of membrane i, it is to say membrane father of membrane i, and multiset v is contained in the membrane labeled by i having α as electrical charge. When that rule is applied, multiset u (respectively v) in the father of membrane i (respectively in membrane i) is removed from that membrane, and multiset u' (respectively v') is produced in that membrane, changing its electrical charge to α'.
- $M(\Gamma)$ is the set formed by the multisets of Γ. If $u, v \in M(\Gamma)$, $i \in \{0, \ldots, q-1\}$, $\alpha \in \{0, +, -\}$ and $r_1, \ldots r_z$ are the rules applicable whose left-hand side is $u[v]_i^{\alpha}$ at given moment a, then it should be verified that $f_{r1}(a) + \cdots + f_{rz}(a) = 1$, and the rules will be applied according to the corresponding probabilities $fr1(a), \ldots, f_{rz}(a)$.

A multienvironment functional probabilistic P system with active membranes of degree (q,m) with $q \geq 1$, $m \geq 1$, taking T time units $T \geq 1$.
$(G, \Gamma, \Sigma, R_E, \Pi, \{f_{r,j} : r \in R_{\Pi}, 1 \leq j \leq m\}, \{M_{i,j} : 0 \leq i \leq q-1, 1 \leq j \leq m\})$

can be viewed as a set of m environments $e-1, \ldots, e_m$ linked by the arcs from the directed graph G. Each environment e_j contains a probabilistic functional extended P system with active membranes of degree q, $\Pi = (\Gamma, \mu, R, T, \{f_{r,j} \in R_{\Pi}, 1 \leq j \leq m\}, M_{i,j} : 0 \leq i \leq q-1, 1 \leq j \leq m)$ each of them with the same skeleton, $\Pi = (\Gamma, \mu, R)$, and such that $M_{0j}, \ldots, M_{q-1j}$ describes their initial multisets. Σ is an alphabet that represents the objects of Γ that can be present in the different environments.

The communication rule between environments in R_E are of the form $r_e : (x)_{ej} \stackrel{p_{x,j,k}}{\rightarrow} (y)_{ek}$, and for each $x \in \Sigma, 1 \leq j \leq m, 1 \leq a \leq T$, it verifies $\sum P_{x,j,k}(a) = 1$. When a rule of this type is applied the object x moves from environment e_j to environment e_k converted into y, according to the probability $p_{j,k}$.

We assume that a global clock exists, marking the time for the whole system (for its compartments), that is, all membranes and the application of all rules are synchronized. In the P systems, a configuration consists of multisets of objects present in the m environments and at each of the regions of the P systems located in the environment.

The P system can pass from one configuration to another by using the rules from $R = R_E \cup \bigcup_{j=1}^{m}$ as follows: at each transition step, the rules to be applied are selected according to the probabilities assigned to them, and all applicable rules are simultaneously applied and all occurrences of the left-hand side of the rules are consumed, as usual.

5 Model

In order to model this ecosystem we use a *multienvironment functional probabilistic P system with active membranes* of degree (5,5) (five membranes and five environments), taking T time units (simulation years). We model the population dynamics of 13 animal species ($N = 13$) with 26 different plant communities ($NA = 26$) in 5 different environments ($E = 5$).

$(G, \Gamma, \Sigma, R_E, \Pi, \{f_{r,j} : r \in R_\Pi, 1 \leq j \leq 5\}, \{M_{i,j} : 0 \leq i \leq 4, 1 \leq j \leq 5\})$

We have 5 environments, 4 of them associated to a each National Hunting Reservoir and a fifth environment, in which occur the processes under a lack of resources.

Where:

1. The graph of the system is $G = (\phi)$ because, in this case, there are no animal movements between environments.
2. The membrane structure is

   $\mu = [[\ \ ]_1[\ \ ]_2[\ \ ]_3[\ \ ]_4]_0$

   The first three membranes are associated with the altitude: low, medium and high altitudinal ranges.

   The initial configuration is:

   $$\begin{array}{ll} Environment: \{T, R\} & \\ Membranes: & M_0 = \{P_0, d_{m,i} : 1 \leq m \leq 3, 1 \leq i \leq N\}, \\ & M_i = \{X_{ij}, A_v, U, \rho_0, \beta : 1 \leq i \leq N, 0 \leq j \leq g_{i,6}, 1 \leq v \leq NA\} \end{array}$$

3. The working alphabet of the P system is

$$\begin{aligned}
\Gamma = \{ & X_{ij}, Y_{ij}, Z_{ij}, Z'_{mij}, Z''_{kmij}, WN_{mij}, V_{kmij}, V'_{mij}, W'_{kmij} : \\
& 1 \le i \le N, 0 \le j \le g_{i,6}, 1 \le k \le E, 1 \le m \le 3\} \cup \\
& \{d_m i, a_i, e_i, e'_{mi}, a'_{mi}, a''_{kmi} : 1 \le i \le N, 1 \le m \le 3, 1 \le k \le E\} \cup \\
& \{A_v, G_v, G'_{mv}, G''_{kmv} : 1 \le v \le NA, 1 \le m \le 3, 1 \le k \le E\} \cup \{U, \beta, \gamma, \alpha\} \cup \\
& \{D_i, H_i, C_i : 1 \le i \le N\} \cup \\
& \{B, B'_m, B'_{km}, M, M'_m, M'_{km} : 1 \le m \le 3, 1 \le k \le E\} \cup \\
& \{P_i, \rho_i : 0 \le i \le 15\}
\end{aligned}$$

Objects X_{ij}, Y_{ij}, Z_{ij}, Z'_{mij}, Z''_{kmij}, WN_{mij}, V_{kmij}, V'_{mij}, W'_{kmij} represent the same animal but in different states. Objects B, B'_i, B''_{km} and H_i, represent bones, and M, M'_i, M''_{km} and C_i represent meat left by specie i. By the objects d_i, a_i, a'_{mi}, a'_{kmi}, e_i and e'_{mi} is controlled the maximum number of animals per species in the ecosystem. D_i is an object used to count the existing animals of specie i. If a species overcomes the maximum density values, it will be regulated. In all these objects index i is associated with the type of animal, index j is associated with the age, and $g_{i,6}$ is the average life expectancy, k is the environment and m the altitudinal range. A_v is a surface unit of the alliance v and G_v, G''_{vm}, G''_{kmv} is the amount of grass produced per hectare by alliance (A_v) in each altitudinal range m and environment k. U is an object used to control the carrying capacity, and objects β, α and γ are used to determine the grazing pressure level in the environment. At the end, objects P_i and ρ_i are counters that allow the synchronization of the P system. Necessary parameters introduced into the model to model the plant communities' dynamics, is given in table 2. The parameters related to animal dynamics can be consulted in Colomer et al. [6].

4. The environment alphabet is

$$\begin{aligned}
\Sigma = & \{R, T\} \cup \{T'_{k,j}, R'_{k,s}, N_{j,s} : 1 \le k \le E, 1 \le j \le 100, 1 \le s \le 100\} \cup \\
& \{G'_{m,v}, G''_{k,m,v} : 1 \le k \le E, 1 \le m \le 3, 1 \le v \le NA\} \cup \\
& \{B'_m, B''_{k,m}, M'_m, M''_{k,m} : 1 \le k \le E, 1 \le m \le 3\} \cup \\
& \{a'_{m,i}, a''_{k,m,i}, Z'_{m,i,j}, Z''_{k,m,i,j} : 1 \le k \le E, 1 \le m \le 3, 1 \le i \le N, 0 \le j \le g_{i,6}\}.
\end{aligned}$$

T and R are objects that include the climatic variability, T for the length of the growing season and R for the production of plant communities. The object N carries both information. All other objects belong to Γ and have been discussed in the respective sections.

5. The set R_E and R_Π is presented in the Appendix.

The model is structured in 8 modules, the scheme appears in the figure 2 and the details of rules in the Appendix. In the following the different modules are described.

5.1 Animal modules

The modules referring to the population dynamics (reproduction, mortality, feeding and density regulation and change in the environment module) were explained in detail in previous works [5, 6], therefore we only give a brief summary of all these modules in this work.

Table 2. Parameters that affect animals and plant communities dynamics (v animal specie, i plant community (alliance), m altitudinal range, k environment (NHR)).

Climatic variables	**Parameter**
Random numbers	$1 \leq NZ \leq 100$
Animals	**Parameter**
Equivalent weight	ew_v, $1 \leq v \leq 13$
Plant communities	**Parameter**
Amount of grass produced dairy (net primary production NPP)	μR_i, $1 \leq i \leq 26$
Standard deviation of plant net primary production	σR_i, $1 \leq i \leq 26$
Carrying capacity	Ca_k, $1 \leq k \leq 4$
Mean of the growing season length	μT_i, $1 \leq i \leq 26$
Standard deviation of growing season length	σT_i, $1 \leq i \leq 26$
Surface at low, medium and high altitude	as_i, $1 \leq as \leq 3$
Abandoned land evolution	ta
Fire evolution	fe
Fire evolution probabilities	fp
Ecosystem (plant community, altitude range, environment)	$\delta_{i,m,k}$, $1 \leq i \leq 26, 1 \leq m \leq 3, 1 \leq k \leq 4$

Reproduction module

At the beginning an object of type X is associated with each animal. When rules from the reproduction module are applied to objects of type X, they evolve into objects of type Y. Objects associated with females that reproduce create new objects Y at age 0 ($Y_{i,0}$) and evolve to the object Z with the same index. The rules applied in this module are of the type: $[X_{i,j}]_h^\alpha \xrightarrow{fr} [X_{i,j}, X_{i,0}]_h^\alpha$.

Mortality module

Two different mortality causes are considered, natural mortality and hunting mortality. When the domestic animals reach their life expectancy, they do not die, but they are removed from the ecosystem. when the animals die in the ecosystem and their bodies are not removed, they leave biomass, meat (C, M) and bones, (B, H). Mortality rules are of the form:

- When they leave biomass:

  $[Y_{i,j}]_h^\alpha \xrightarrow{fr} [H_i, C_i, B, M]_h^\alpha$.

- When they are removed from the ecosystem:

  $[Y_{i,g_{i,6}}]_h^\alpha \xrightarrow{fr} [\#]_h^{\alpha-}$.

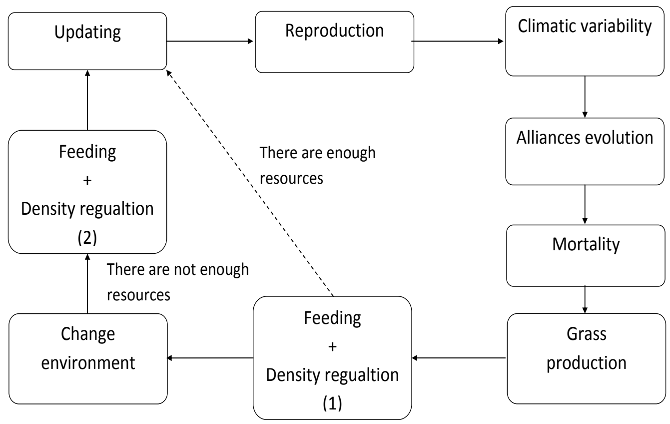

Fig. 2. Scheme model of the plant community and animal dynamics model.

Feeding and density regulation module

Whether or not the maximum carrying capacity of the ecosystem for each species has been reached, is determined by using objects a previously generated. Each altitudinal range of each environment and animal specie has associated its own carrying capacity.

Furthermore, objects Y evolve to objects Z to begin the feeding process. In the second step of this module, objects Z evolve to objects W if there is enough physical space and food.

If there are not enough resources for animals, objects Z leave the environment.

5.2 Plant community modules

The following modules have been added to improve and complete the modelling of the ecosystem presented by Colomer et al. [6]. It consists of three separate modules, the first one incorporates the production of grass that includes the grazing process, and the second which is dedicated to the changes and developments that occur in plant communities, in our ecosystem at alliance level. Finally we included also a preliminary module to introduce the climatic variability into the model.

Climate variability module

With the aim to introduce the climatic variability in the model, the objects T and R are used, whereat T includes the variability of the duration of the growing season, and R the production of communities. Previously, we created a set of 100 random numbers following a normal distribution with mean 0 and standard deviation 1. In the environment labeled as 1, T object evolves to four objects of type $T'_{k,j}$, and these are sent to their respective environments (2,3,4). The rest of T objects, placed in the environments 2, 3 and 4 disappear at the same moment. The same occurs with the object R. $T'_{k,j}$ and $R'_{k,s}$ evolve in each environment into a new object $N_{m,j,s}$, which contains the information of both objects T and R and enters into the membrane m $(1 \leq j \leq 100, 1 \leq s \leq 100, 1 \leq k \leq E, 1 \leq m \leq 3)$.

Plant communities production and grazing modules

The following rule produces an amount of grass, according to the information included into the object $N_{j,s,m}$. Thus, when the object $N_{j,s,m}$ and the object A_i (a surface unit of the alliance i) come together, they produce an amount of grass G_i available for herbivores.

Once food is produced, it serves as food for different species of ungulates present in the ecosystem. In this process it is possible to obtain two different scenarios: (1) the animal has enough available food and feeds, and (2) the animal cannot find food and goes to another high range. In the first one the animal (object Z) eats, and transforms itself into object Wn. In the second case the environmental module is applied as is explained in the following section.

Change environment module

When the animals cannot find enough resources, they leave their zone (membrane) with the following set of objects (G', a', B', M') and go to a membrane 4 of an environment 5. From there, objects that represent the animals can find resources and evolve into an object W' or evolve directly into an object V. These objects return to their environment and membrane and objects W' evolve into object WN, objects V evolve into V' and disappear later on creating objects of type B, M, C, H.

Plant communities evolution

Two different processes are introduced into the model encompassed into the evolution of the plant communities due to management: (1) less grazing pressure, and (2) recovering pastures with fire.

In the first case the object U controls the minimal carrying capacity required to maintain the type of grassland or plant community. If there is no abandonment, an object α is created, in the contrary case the β object evolves to gamma and changes the charge of the membrane to positive. When it occurs the alliance A_i can evolve into an alliance A_j with a stated probability.

When the surface of the alliance A_j scrubland exceeds a certain value, this plant community can evolve to grassland A_i with a stated probability due to human management (in this case fire).

Updating module

This module has the aim to restore the initial configuration in order to start a new simulation.

6 Final considerations

In this work we have presented a model to simulate the grassland dynamics, which allow to simulate behaviour in different scenarios. The next step is to define the simulator with MeCoSim [13] to validate the results. Afterwards we will improve the model by introducing new possible plant communities' evolutions.

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Appendix

Rules of the model.

- Counters
- In order to synchronize the model are needed objects that act as counters.

$$r_0 \equiv [\rho_i]_m^0 \rightarrow [\rho_{i+1}]_m^0, \quad \begin{cases} 0 \leq i \leq 11, \\ i <> 5, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_1 \equiv [\rho_i]_m^0 \rightarrow [\rho_{i+1}]_4^0, \quad \begin{cases} 0 \leq i \leq 12, \\ i <> 10. \end{cases}$$

$$r_2 \equiv [P_i]_0^0 \rightarrow [P_{i+1}]_0^0, \quad \begin{cases} 0 \leq i \leq 14. \end{cases}$$

- Density control.

$$r_3 \equiv [d_{m,i}]_0^0 \rightarrow d_{m,i}[\quad]_0^0, \quad \begin{cases} 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_4 \equiv d_{m,i}[\quad]_0^0 \rightarrow [d'_{m,i}, a_i'^{0.9 d_{i1mk}}, e_{m.i}'^{0.2 d_{i1mk}}]_0^0, \quad \begin{cases} 1 \leq j \leq 2, \\ 1 \leq i \leq N, \\ 1 \leq m \leq 3, \\ 1 \leq k \leq E. \end{cases}$$

$$r_5 \equiv d'_{m,i}[\quad]_m^- \rightarrow [d'_{m,i}]_m^0, \quad \begin{cases} 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_6 \equiv [d'_{m,i}]_m^- \rightarrow d_{m,i}[\quad]_m^0, \quad \begin{cases} 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

Reproduction module

- Males that do not reproduce.

$$r_7 \equiv [X_{i,j} \stackrel{(1-k_{i,1})}{\longrightarrow} Y_{i,j}]_m^0, \quad \begin{cases} 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

- Females at fertile age that reproduce.

$$r_8 \equiv [X_{i,j} \stackrel{k_{i,1} \cdot k_{i,2}}{\longrightarrow} Y_{i,j}, Y_{i,0}^{k_{i,3}}]_m^0, \quad \begin{cases} g_{i,3} \leq j < g_{i,4}, \\ 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

- Females at fertile age that do not reproduce.

$$r_9 \equiv [X_{i,j} \stackrel{k_{i,1} \cdot k_{i,2}}{\longrightarrow} Y_{i,j}]_m^0, \quad \begin{cases} g_{i,3} \leq j < g_{i,4}, \\ 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

- Adult non-fertile males and females.

$$r_{10} \equiv [X_{i,j} \rightarrow Y_{i,j}]_m^0, \quad \begin{cases} g_{i,4} \leq j \leq g_{i,5}, \\ 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

- Non-fertile young animals

$$r_{11} \equiv [X_{i,j} \rightarrow Y_{i,j}]_m^0, \quad \begin{cases} 0 \leq j < g_{i,3}, \\ 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{12} \equiv [X_{i,j} \rightarrow Y_{i,j}]_m^0, \quad \begin{cases} 0 \leq j < g_{i,3}, \\ 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

Climatic variability module

- Generate randomise climatic variables

$r_{e1} \equiv (T \overset{\frac{1}{100}}{\rightarrow} T'_{1,j}, T'_{2,j}, T'_{3,j}, T'_{4,j})_{e1}, \quad \{ 1 \leq j \leq 100,$

$r_{e2} \equiv (R \overset{\frac{1}{100}}{\rightarrow} R'_{1,s}, R'_{2,s}, R'_{3,s}, R'_{4,s})_{e1}, \quad \{ 1 \leq s \leq 100,$

$r_{e3} \equiv (T \rightarrow \#)_k, \quad \{ 2 \leq k \leq E,$

$r_{e4} \equiv (R \rightarrow \#)_k, \quad \{ 2 \leq k \leq E,$

Plant communities evolution module

Less grazing pressure

- If do not exist abandonment an object α is created.

$$r_{13} \equiv [\beta, U^{(Ca_{m,k} \cdot \delta_{m,k})}]^0_m \xrightarrow{a} [\alpha]^0_m, \quad \begin{cases} 1 \leq i \leq 13, \\ 1 \leq m \leq 3, \\ 1 \leq k \leq E. \end{cases}$$

- If the abandonment exist the object β evolve to γ.

$r_{14} \equiv [\beta]^-_m \rightarrow [\gamma]^0_m, \quad \{ 1 \leq m \leq 3.$

- The alliance evolve if during a time period has been abandoned.

$r_{15} \equiv [\alpha, \gamma]^0_m [\#]^0_m, \quad \{ 1 \leq m \leq 3.$

- If there are the conditions, the membrane charge change.

$r_{16} \equiv [\rho_{12}, \gamma \cdot Ca]^0_m \rightarrow [\rho_{12}]^+_m, \quad \{ 1 \leq m \leq 3.$

- The alliances evolve.

$$r_{17} \equiv [A_i]^+_m \xrightarrow{p_{i,j}} [A_j]^0_m, \quad \begin{cases} 1 \leq m \leq 3, \\ 1 \leq i \leq NA, \\ 1 \leq j \leq NA. \end{cases}$$

Human management

- When the surface of alliance i exceeds a certain value it evolves to the alliance j with a given probability.

$$r_{18} \equiv [A_i^{fe}]^0_m \xrightarrow{fp} [A_j^{fe}]^0_m, \quad \begin{cases} 1 \leq i \leq 26, \\ 1 \leq j \leq 26, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{19} \equiv [A_i^{fe}]^0_m \xrightarrow{1-fp} [A_i^{fe}]^0_m, \quad \begin{cases} 1 \leq i \leq 26, \\ 1 \leq m \leq 3. \end{cases}$$

Mortality module

- Young animals that survive.

$$r_{20} \equiv [Y_{i,j}]^0_l \xrightarrow{1-m_{i,1}-m_{i,3}} [Z_{i,j}, D_i]^0_l, \quad \begin{cases} 1 \leq l \leq 3, \\ 1 \leq i \leq N, \\ 0 \leq j \leq g_{i,2}. \end{cases}$$

- Young animals that die and leave biomass in the form of meat and bones.

$$r_{21} \equiv [Y_{i,j}]_l^0 \xrightarrow{m_{i,1}} [H_i^{(f_{i,1}f_{i,5}+0.5)}, C_i^{(f_{i,2}f_{i,6}+0.5)}, B^{(f_{i,1}f_{i,5}+0.5)}, M^{(f_{i,2}f_{i,6}+0.5)}]_l^0, \quad \begin{cases} 1 \le l \le 3, \\ 0 \le j < g_{i,2}, \\ 1 \le i \le N. \end{cases}$$

- Young animals removed from the ecosystem that do not leave biomass.

$$r_{22} \equiv [Y_{i,j}]_l^0 \xrightarrow{m_{i,3}} [\quad]_l^0, \quad \begin{cases} 1 \le l \le 3, \\ 0 \le j < g_{i,2}, \\ 1 \le i \le N. \end{cases}$$

- Adult animals that survive.

$$r_{23} \equiv [Y_{i,j}]_l^0 \xrightarrow{1-m_{i,2}} [Z_{i,j}, D_i]_l^0, \quad \begin{cases} 1 \le l \le 3, \\ g_{i,2} \le j < g_{i,5}, \\ 1 \le i \le N. \end{cases}$$

- Adult animals that die and leave biomass.

$$r_{24} \equiv [Y_{i,j}]_l^0 \xrightarrow{m_{i,2}} [H_i^{(f_{i,3}f_{i,5}+0.5)}, C_i^{(f_{i,4}f_{i,6}+0.5)}, B^{(f_{i,3}f_{i,5}+0.5)}, M^{(f_{i,4}f_{i,6}+0.5)}]_l^0, \quad \begin{cases} 1 \le l \le 3, \\ g_{i,2} \le j \le g_{i,5}, \\ 1 \le i \le N. \end{cases}$$

- Animals that die by hunter and can leave biomass or not

$$r_{25} \equiv [Y_{i,j}]_l^0 \xrightarrow{m_{i,2}} [H_i^{(f_{i,3}f_{i,5}hp_i+0.5)}, C_i^{(f_{i,4}f_{i,6}hp_i+0.5)}, B_i^{(f_{i,3}f_{i,5}hp_i+0.5)}, M_i^{(f_{i,4}f_{i,6}hp_i+0.5)}]_m^0,$$
$$where\ 1 \le l \le 3, 1 \le i \le N, g_{i,2} \le j \le g_{i,5}.$$

- Randomnes generation of the total amount of animals. The following rules are applied at the same time than mortality rules.

$$r_{26} \equiv a'_{m,i}[\quad]_m^0 \rightarrow [a_i]_m^0, \quad \begin{cases} 1 \le m \le 3, \\ 1 \le i \le N. \end{cases}$$

$$r_{27} \equiv e'_{m,i}[\quad]_m^0 \xrightarrow{0.5} [a_i]_m^0, \quad \begin{cases} 1 \le m \le 3, \\ 1 \le i \le N. \end{cases}$$

$$r_{28} \equiv e'_{m,i}[\quad]_m^0 \xrightarrow{0.5} [\#]_m^0, \quad \begin{cases} 1 \le m \le 3, \\ 1 \le i \le N. \end{cases}$$

- Seasonal growth and production randomness.

$$r_{e5} \equiv (T'_{k,j}, R'_{k,s})_{e1}(\quad)_{ek} \rightarrow (\quad)_{e1}(N_{j,s})_{ek}, \quad \begin{cases} 1 \le j \le 100, \\ 1 \le s \le 100, \\ 1 \le k \le E. \end{cases}$$

$$r_{e6} \equiv (T'_{1,j}, R'_{1,s})_{e1} \rightarrow (N_{j,s})_{e1}, \quad \begin{cases} 1 \le j \le 100, \\ 1 \le s \le 100, \\ 1 \le k \le E. \end{cases}$$

Alliance production

- Objects $N'_{j,s}$ associated with altitude are introduced into the membrane to produce grass.

$$r_{29} \equiv N_{j,s}[\quad]_0^0 \rightarrow [N'_{1,j,s}, N'_{2,j,s}, N'_{3,j,s}]_0^0, \quad \begin{cases} 1 \le i \le 4, \\ 1 \le j \le 100, \\ 1 \le s \le 100. \end{cases}$$

$$r_{30} \equiv N'_{m,j,s}[\quad]_m^0 \rightarrow [N_{j,s}]_m^0, \quad \begin{cases} 1 \le m \le 3, \\ 1 \le j \le 100, \\ 1 \le s \le 100, \\ 1 \le k \le 4. \end{cases}$$

- Animal density control.

$$r_{31} \equiv [D_i^{(d_{i,1,m,k})}, a_i^{(d_{i,1,m,k} - d_{i,2,m,k})} \rightarrow \#]_m^0, \quad \begin{cases} 1 \le k \le E, \\ 1 \le i \le N, \\ 1 \le m \le 3. \end{cases}$$

- Grass production.

$$r_{32} \equiv [N'_{j,s}, A_i \rightarrow G_i^{(NZ_j \sigma T_i + \mu T_i)(NZ_j \sigma R_i + \mu R_i)}, A_i]_m^0, \quad \begin{cases} 1 \le m \le 3, \\ 1 \le j \le 100, \\ 1 \le s \le 100, \\ 1 \le k \le 4. \end{cases}$$

Feeding and density regulation

- When the animal $Z_{i,j}$ into the membrane m and environment k finds grass G_i and has enough space a_i it eat and evolve to $WN_{m,i,j}$ and abandons the membrane.

$$r_{33} \equiv [Z_{i,j}, a_i, G_k^{fa_i}]_m^0 \xrightarrow{ft_{i,k}} WN_{m,i,j}[\quad]_m^-, \quad \begin{cases} 1 \le j \le g_{i,6}, \\ 1 \le i \le N, \\ 1 \le k \le NA, \\ 1 \le m \le 3. \end{cases}$$

- The following rules generate the membrane charge change.

$$r_{34} \equiv [\rho_5]_m^0 \rightarrow [\rho_6]_m^-, \quad \{1 \le m \le 3.$$

$$r_{35} \equiv [\rho_6]_m^- \rightarrow [\rho_7]_m^0, \quad 1 \le m \le 3.$$

Change environment module

- The animals that don't eat ($Z_{i,j}$), grass production (G_i), the biomass deposited in the ecosystem (B_m and M_m) and the density regulator object a abandon the membrane m.

$$r_{36} \equiv [Z_{i,j}]_m^- \rightarrow Z'_{m,i,j}[\quad]_m^0, \quad \begin{cases} 0 \leq j \leq g_{i,6}, \\ 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{37} \equiv [G_k]_m^- \rightarrow G'_{m,k}[\quad]_m^0, \quad \begin{cases} 1 \leq k \leq NA, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{38} \equiv [B]_m^- \rightarrow B'[\quad]_m^0, \quad 1 \leq m \leq 3.$$

$$r_{39} \equiv [M]_m^- \rightarrow M'[\quad]_m^0, \quad 1 \leq m \leq 3.$$

$$r_{40} \equiv [a_i]_m^- \rightarrow a'_{m,i}[\quad]_m^0, \quad \begin{cases} 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

- The same objects go out the skin membrane.

$$r_{41} \equiv [Z'_{m,i,j}]_0^0 \rightarrow Z'_{m,i,j}[\quad]_0^0, \quad \begin{cases} 1 \leq j \leq g_{i,6}, \\ 1 \leq i \leq N, \\ 1 \leq k \leq NA, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{42} \equiv [G'_{m,i}]_0^0 \rightarrow G'_{m,i}[\quad]_0^0, \quad \begin{cases} 1 \leq i \leq NA, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{43} \equiv [B'_m]_0^0 \rightarrow B'_m[\quad]_0^0, \quad 1 \leq m \leq 3.$$

$$r_{44} \equiv [M'_m]_0^0 \rightarrow M'_m[\quad]_0^0, \quad \{1 \leq m \leq 3.$$

$$r_{45} \equiv [a'_{m,i}]_0^0 \rightarrow a'_{m,i}[\quad]_0^0, \quad \begin{cases} 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

- Then the objects $Z''_{k,m,i,j}$, $G''_{k,m,i}$, $B''_{m,i}$, $M''_{m,i}$ and $a''_{k,m,i}$ abandon the environment k: $1 \leq k \leq 4$ and enter in environment 5.

$$r_{e7} \equiv (Z'_{m,i,j})_{ek}(\quad)_{e5} \rightarrow (\quad)_{ek}(Z''_{k,m,i,j})_{e5}, \quad \begin{cases} 1 \leq i \leq N, \\ 0 \leq j \leq g_{i,6}, \\ 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{e8} \equiv (G'_{m,i})_{ek}(\quad)_{e5} \rightarrow (\quad)_{ek}(G''_{k,m,i})_{e5}, \quad \begin{cases} 1 \leq i \leq NA, \\ 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{e9} \equiv (B'_m)_{ek}(\quad)_{e5} \rightarrow (\quad)_{ek}(B''_{k,m})_{e5}, \quad \begin{cases} 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{e10} \equiv (M'_m)_{ek}(\quad)_{e5} \rightarrow (\quad)_{ek}(M''_{k,m})_{e5}, \quad \begin{cases} 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{e11} \equiv (a'_{m,i})_{ek}(\quad)_{e5} \rightarrow (\quad)_{ek}(a''_{k,m,i})_{e5}, \quad \begin{cases} 1 \leq i \leq N, \\ 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{46} \equiv Z''_{k,m,i,j}[\quad]_0^0 \rightarrow [Z''_{k,m,i,j}]_0^0, \quad \begin{cases} 0 \leq j \leq g_{i,6}, \\ 1 \leq i \leq N, \\ 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{47} \equiv G''_{k,m,i}[\quad]_0^0 \rightarrow [G''_{k,m,i}]_0^0, \quad \begin{cases} 1 \leq k \leq E, \\ 1 \leq i \leq Na, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{48} \equiv B''_{k,m}[\quad]_0^0 \rightarrow [G''_{k,m}]_0^0, \quad \begin{cases} 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{49} \equiv M''_{k,m}[\quad]_0^0 \rightarrow [M''_{k,m}]_0^0, \quad \begin{cases} 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{50} \equiv a''_{k,m,i}[\quad]_0^0 \rightarrow [a''_{k,m,i}]_0^0, \quad \begin{cases} 1 \leq k \leq E, \\ 1 \leq i \leq N, \\ 1 \leq m \leq 3. \end{cases}$$

- These objects enter into a virtual environment ($e = 5$) and membrane $m = 4$.

$$r_{51} \equiv Z''_{k,m,i,j}[\quad]_4^0 \rightarrow [Z''_{k,m,i,j}]_4^0, \quad \begin{cases} 0 \leq j \leq g_{i,6}, \\ 1 \leq i \leq N, \\ 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{52} \equiv G''_{k,m,i}[\quad]_4^0 \rightarrow [G''_{k,m,i}]_4^0, \quad \begin{cases} 1 \leq i \leq Na, \\ 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{53} \equiv B''_{k,m}[\quad]_4^0 \rightarrow [B''_{k,m}]_4^0, \quad \begin{cases} 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{54} \equiv M''_{k,m}[\quad]_4^0 \rightarrow [M''_{k,m}]_4^0, \quad \begin{cases} 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{55} \equiv a''_{k,m,i}[\quad]_4^0 \rightarrow [a''_{k,m,i}]_4^0, \quad \begin{cases} 1 \leq i \leq N, \\ 1 \leq k \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

Feeding rules

$$r_{56} \equiv [Z''_{k,m,i,j}, a''_{v,m,i}, G''^{fa_i}_{v,m,s}]_4^0 \xrightarrow{ft_{i,s}p_{i,k,v}} W'_{v,m,i,j}[\quad]_4^-, \quad \begin{cases} 0 \leq j \leq g_{i,6}, \\ 1 \leq i \leq N, \\ 1 \leq s \leq Na, \\ 1 \leq k \leq E, \\ 1 \leq v \leq E, \\ 1 \leq m \leq 3. \end{cases}$$

$$r_{57} \equiv [\rho_{11}]_4^0 \rightarrow [\rho_{12}]_4^-$$

$r_{58} \equiv [\rho_{12}]_4^- \rightarrow [\rho_{13}]_4^0$

- When the charge of the membrane 5 changes to negative, the remaining $Z''k, m, i, j$ objects (aniamls that have not enough resources) transform to an object $V_{k,m,i,j}$ and it also abandons this membrane. The remaining objects $(G''_{k,m,i}, B''_{k,m}, M''_{k,m} and a''_{k,m,i})$ disappear. And the membrane change its polarity to null.

$$r_{59} \equiv [Z''_{k,m,i,j}]_4^- \rightarrow V_{k,m,i,j}[\quad]_4^0, \quad \begin{cases} 0 \le j \le g_{i,6}, \\ 1 \le i \le N, \\ 1 \le k \le E, \\ 1 \le m \le 3. \end{cases}$$

$$r_{60} \equiv [G''_{k,m,i}]_4^- \rightarrow [\#]_4^0, \quad \begin{cases} 1 \le i \le Na, \\ 1 \le k \le E, \\ 1 \le m \le 3. \end{cases}$$

$$r_{61} \equiv [B''_{k,m}]_4^- \rightarrow [\#]_4^0, \quad \begin{cases} 1 \le k \le E, \\ 1 \le m \le 3. \end{cases}$$

$$r_{62} \equiv [M''_{k,m}]_4^- \rightarrow [\#]_4^0, \quad \begin{cases} 1 \le k \le E, \\ 1 \le m \le 3. \end{cases}$$

$$r_{63} \equiv [a''_{k,m,i}]_4^- \rightarrow [\#]_4^0, \quad \begin{cases} 1 \le i \le N, \\ 1 \le k \le E, \\ 1 \le m \le 3. \end{cases}$$

- The objects associated to the animals move to their environment.

$$r_{64} \equiv [W'_{k,m,i,j}]_0^0 \rightarrow W'_{k,m,i,j}[\quad]_0^0, \quad \begin{cases} 0 \le j \le g_{i,6}, \\ 1 \le i \le N, \\ 1 \le k \le E, \\ 1 \le m \le 3. \end{cases}$$

$$r_{65} \equiv [V_{k,m,i,j}]_0^0 \rightarrow V_{k,m,i,j}[\quad]_0^0, \quad \begin{cases} 0 \le j \le g_{i,6}, \\ 1 \le i \le N, \\ 1 \le k \le E, \\ 1 \le m \le 3. \end{cases}$$

$$r_{e12} \equiv (W'_{k,m,i,j})_{e5}(\quad)_{ek} \rightarrow (\quad)_{e5}(WN_{m,i,j})_{ek}, \quad \begin{cases} 0 \le j \le g_{i,6}, \\ 1 \le i \le N, \\ 1 \le k \le E, \\ 1 \le m \le 3. \end{cases}$$

$$r_{e13} \equiv (V_{k,m,i,j})_{e5}(\quad)_{ek} \rightarrow (\quad)_{e5}(V'_{m,i,j})_{ek}, \quad \begin{cases} 0 \le j \le g_{i,6}, \\ 1 \le i \le N, \\ 1 \le k \le E, \\ 1 \le m \le 3. \end{cases}$$

$$r_{66} \equiv WN_{m,i,j}[\quad]_0^0 \rightarrow [WN_{m,i,j}]_0^0, \quad \begin{cases} 0 \le j \le g_{i,6}, \\ 1 \le i \le N, \\ 1 \le m \le 3. \end{cases}$$

$$r_{67} \equiv V'_{m,i,j}[\quad]_0^0 \rightarrow [V'_{m,i,j}]_0^0, \quad \begin{cases} 0 \le j \le g_{i,6}, \\ 1 \le i \le N, \\ 1 \le m \le 3. \end{cases}$$

Updating module

$$r_{68} \equiv [P_{14} \rightarrow F_1, F_2, F_3, P_{15}]_0^0$$

$$r_{69} \equiv F_m[\quad]_m^0 \rightarrow [\quad]_m^-, \quad 1 \le m \le 3.$$

$$r_{70} \equiv WN_{m,i,j}[\quad]_m^- \rightarrow [X_{i,j+1}]_m^0, \quad \begin{cases} 1 \le m \le 3, \\ 1 \le j < g_{i,5}, \\ 1 \le i \le N. \end{cases}$$

- The objects associated to animals that have not found resources, disappear leaving biomass.

$$r_{71} \equiv V'_{m,i,j}[\quad]_m^- \rightarrow [H_i^{(f_{i,1}f_{i,5}+0.5)}, C_i^{(f_{i,2}f_{i,6}+0.5)}, B_i^{(f_{i,1}f_{i,5}+0.5)}, M_i^{(f_{i,2}f_{i,6}+0.5)}]_m^0, \quad \begin{cases} 1 \le m \le 3, \\ 1 \le j < g_{i,5}, \\ 1 \le i \le N. \end{cases}$$

$$r_{72} \equiv V'_{m,i,j}[\quad]_m^- \rightarrow [H_i^{(f_{i,3}f_{i,5}hp_i+0.5)}, C_i^{(f_{i,4}f_{i,6}hp_i+0.5)}, B_i^{(f_{i,3}f_{i,5}hp_i+0.5)}, M_i^{(f_{i,4}f_{i,6}hp_i+0.5)}]_m^0,$$
$$\textit{where } 1 \le m \le 3, g_{i,2} \le j < g_{i,5}, 1 \le i \le N.$$

- The objects associated to animals that have reached their life expectancy transform into objects associated to biomass.

$$r_{73} \equiv WN_{m,i,g_{i,5}}[\quad]_m^- \rightarrow [H_i^{(f_{i,3}f_{i,5}hp_i+0.5)}, C_i^{(f_{i,4}f_{i,6}hp_i+0.5)}, B_i^{(f_{i,3}f_{i,5}hp_i+0.5)}, M_i^{(f_{i,4}f_{i,6}hp_i+0.5)}]_m^0,$$
$$\textit{where } 1 \le m \le 3, 1 \le i \le N.$$

$$r_{74} \equiv [P_{16}]_0^0 \rightarrow T, R[P_0]_0^0$$

$$r_{75} \equiv [\rho_{12}]_m^- \rightarrow [\rho_0]_m^0, \quad 1 \le m \le 3.$$

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