Supplementary Information

Modelling the effects of sanitary policies on European vulture conservation

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Supplementary Materials and Methods

Study area

The study area was in northeastern Spain, where breeding sites occur for all four European vulture species, i.e., Eurasian griffon vulture (*Gyps fulvus*), cinereous vulture (*Aegypius monachus*), Egyptian vulture (*Neophron percnopterus*), and bearded vulture (*Gypaetus barbatus*). This region contains an important vulture population representative of southwestern Europe, which made it possible to test the potential effects of changes in food availability on European vulture population dynamics. An abundance of grazing livestock are found in this area, mainly sheep (*Ovis aries),* goats (*Capra hircus*), cattle (*Bos taurus*), and horses (*Equus caballus*) (see http://www.marm.es), while six wild ungulate species are also present, namely red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), fallow deer (*Dama dama*), mouflon (*Ovis musimon*), southern chamois (*Rupicapra pyrenaica*), and wild boar (*Sus scrofa*).

The study area was divided into 10 subareas of which detailed data censuses of avian scavengers and wild and domestic ungulates are available. Wild and domestic ungulates are herbivores (except the omnivorous wild boar) and their remains form the basic food source for the avian scavenger guild (>80% of the diet is based on these species [44]).

The study area contains a total of 19 feeding stations in which food is provided principally during the breeding season. Of these supplementary feeding stations, 10 are specific for bearded vultures (remains are principally sheep extremities; average amount of food provided by site/year 2598.2 ± SD = 1404.16 kg) and the rest for the remaining avian scavengers (carcasses and meat remains; average amount of food provided by site/year: 1531.8 ± SD = 1084.16 kg).

Since individuals can move from one area to another depending on the resources available, the ecosystem appears to function as a single set (overall ecosystem) composed of a network of 10 subsets according to specific data obtained in each area. In this way, whenever there is a lack of food in one of the subareas or the carrying capacity reaches its peak, the individuals will move to the nearest suitable area (Figure 3). Maximum carrying capacity for wild ungulates and avian scavengers (Table S1) has been established according to the data provided by the literature and estimates are based on the population growth observed during the previous 20 years and are used to adjust the variables of the model [24] .

The subarea in which the nest is located is considered the core area and the neighbouring subareas the potential home range from which each species will obtain their energetic requirements. Thus, in our model the individuals can move from one area to the other and the ecosystem's local carrying capacity has been limited to the appropriate areas and habitats for the different species as has the maximum density that can be reached (Table S1).

Censuses, dietary habits and demographic parameters

Data on the avian scavenger and wild ungulate populations were obtained through censuses carried out by technicians from the Departament de Medi Ambient i Habitatge of the Generalitat de Catalunya, literature and personal observations from 1994-2011.

Unlike in previous work [19, 24], the year has been divided into two periods: *winter*, from October to June and *summer*, from July to September. During the winter, the reproductive period of avian scavengers takes place, during which time egg-laying occurs between December and February (except for the Egyptian vulture in April) and fledging occurs between June and August coinciding with the presence of transhumant livestock in mountain areas. During the summer period, the number of livestock in the mountain areas increases significantly as a consequence of transhumant livestock. Thus, food availability differs among seasons being greater during the summer, whereas the energetic requirements of avian scavengers are higher during the breeding season (winter and spring). In addition to population fluctuations there are also some demographic (i.e., mortality) and biological (i.e., energetic requirements) parameters that vary between the summer and winter periods (Table S2).

With respect to interspecific differences in dietary habits, the diet of the bearded vulture is based on bone remains, whereas the diet of griffons, cinereous and Egyptian vultures is based on meat provided by wild and domestic ungulates and to a lesser degree small animal carcasses. In the case of cinereous, bearded and Egyptian vultures, small mammals are also important in the diet [45-48]. Thus, we established a minimum of 3600 kg of available biomass provided by small animal carcasses as a supplement to the diet of all avian scavengers. The remaining biomass is obtained from the food provided by the feeding stations.

Population Dynamic P System Model

This study of population dynamics used a variant of P systems, known as a *Population Dynamic P System* (PDP), i.e., a multi-environment probabilistic functional extended P system with active membranes of degree [m,q] [24, 45]. P systems are computational models that are based on the structure of biological cells and one of their key characteristics is their ability to work in parallel [21-24]. The way to model a problem using PDP models depends on the type of problem itself and the strategies used by the modeler. The costs grow by increasing the number of rules. PDPs are computational models that work with objects such that description is not simple and cannot be synthesized by analytical expressions as in classic models.

A cell in PDP models is represented by membranes within which objects are located. The objects evolve according to the characteristics of the medium generating a succession of configurations associated with the dynamics of the problem studied (Figure S1).

The main components of P systems are a *membrane structure*, which is made up of an external membrane that is often referred to as a skin membrane, and additional internal membranes that can also contain membranes. The entire series of membranes forms a structure that can be represented in a hierarchical manner, where the skin membrane constitutes the roots of the tree. The membranes are labelled (this number appears in the lower part) and they can possess a charge (this number appears in the upper part) with three possible values “0”, “+” , or “–“ (Figure S1). Objects are located in areas defined throughout the membrane structure, including existing objects associated with the input of the model (e.g., individuals) and objects necessary for the correct execution and synchronization of the model (Figure S1). The objects are described using symbols or chains of symbols known as *multisets of objects.* The *evolution rules* allow objects to evolve and move to different areas, or they can be transformed and dissolved. The evolution rules that can be applied in the regions formed by membranes in a variant PDP are of the following type:

$$u[v]_i^{\alpha} \xrightarrow{f_r} u'[v']_i^{\alpha'}.$$

If the area formed by membrane *i* with charge α contains object *v* and the outer part of the membrane contains object *u*, with a probabilityf_r, the rule will be applied to change the charge polarity of membrane *i* from α to α' and objects *u* and *v* will evolve to become *u*´and *v*´. If $f_r = 1$, it is omitted.

The rules that potentially can be applied will be applied in parallel and in a maximal way to consume all the objects involved. The application of the rules causes the P system to evolve and its configuration changes (Figure S1). A P system computation is made up of a sequence of configurations obtained from previous computations via transitions.

There are different environments (*q)* and communication is permitted between them. When an object passes through the skin membrane, it evolves in accordance with the rules in the new environment, which are of the following type:

$$(x)_{e_j} \xrightarrow{p(x,j,j_1 \cdots j_h)} (y_1)_{e_{j1}} \cdots (y_h)_{e_{jh}}.$$

If object *x* passes from environment $e_j$to environment $e_{j1} \cdots e_{jh}$it can be modified into object $y_1 \cdots y_h$, respectively.

Model used

The ecosystem modelled is composed of 10 environments, *E*, and 13 species of animals, *N*. The number of animals per species and environment as well as the biological parameters and the number of years to be simulated are the input of the model (Tables S2 and S3).

The output is formed by the number of animals of each species per year and the biomass (expressed in megacalories) that every species provides throughout the years simulated.

In order to model this ecosystem we use a PDP formed by five membranes and eleven environments, ten of which are associated with the established geographic area. The eleventh environment is used to facilitate the movement of animals between environments where resources are insufficient. This is a variant of P systems that reproduces the randomness of natural processes and assigns an environment to each of the areas studied. The polarization of the membranes is used to show environmental changes (i.e., time of year).

The membrane structure is $\mu = [[[\quad]_3]_1[[\quad]_4]_2]_0$

Objects that appear in the initial configuration in each of the membranes are:

- Membrane labelled with 0:

$$M_0 = \left\{X_{ij}^{q_{kij}}, XA_{ij}^{q_{kij}}, XS_{ij}^{qs_{kij}}, d_i, co_1\right\}, 1 \leq k \leq E, 1 \leq i \leq N, 1 \leq j \leq g_{i,5},$$

- Membrane labelled with 1 and 2: $M_j = \{R\}, 1 \leq j \leq 2$
- Membrane labelled with 3 and 4: $M_j = \{F0_k\}, 1 \leq k \leq E, 3 \leq j \leq 4.$

In the initial configuration (Figure S2), each wild animal of species *i* and age *j* exists as an object X_{ij}. In a similar way, an object XA_{ij} represents domestic animals that spend all year in the ecosystem whereas an object XS_{ij} represents domestic animals that spend only some time in the ecosystem, the superscripts indicate the number of each type of existing object. The object $co_1$is used to indicate the period (winter, co_2, or summer, co_1), FO_k is used to generate external contributions (i.e., supplementary feeding) and food provided by small animals present in the ecosystem, while object *R* (counter) allows the synchronisation of the model.

The objects evolve, by evolution rules, creating new objects, dissolving, moving between membranes, etc. The set of objects that will appear in different configurations form the working alphabet of the model and in the case of the proposed model is:

$$\Gamma = \left\{X_{i,j}, XA_{i,j}, XS_{i,j}, Z_{i,j}, ZS_{i,j}, Z'_{i,j}, Za'_{i,j}, Zm'_{i,j}, Z''_{4,j}, W_{i,j}, ZE_{i,j,c+2,k}, ZEa_{i,j,c+2,k}, ZEm_{i,j,c+2,k}, ZE'_{i,j,c+2,k}, ZEa'_{i,j,c+2,k}, ZEm'_{i,j,c+2,k}, W'_{i,j,c+2,k}, X'_{i,j,c+2}, 1 \leq i \leq N, 0 \leq j \leq g_{i,5}, 1 \leq c \leq 2, 1 \leq k \leq E\right\} \cup \left\{H_i, C_i, H'_i, C'_i, H''_{i,c+2}, 5 \leq i \leq N, 1 \leq c \leq 2\right\} \cup \left\{B, M, S, B'_{c+2}, BE_{c+2,k}, ME_k, SE_k, BE'_{c+2,k}, ME'_k, SE'_k, BM, 1 \leq c \leq 2, 1 \leq k \leq E\right\} \cup \{co_i, cop_i, 1 \leq i \leq 2\} \cup \{d_i, d'_i, D_i, a_i, a'_i, e_i, 1 \leq i \leq N\} \cup \{F0_k, F_k, b, 1 \leq k \leq E\} \cup \{R, R_i, 0 \leq i \leq N\}.$$

Objects $X_{i,j}, XA_{i,j}, XS_{i,j}, Z_{i,j}, ZS_{i,j}, Z'_{i,j}, Za'_{i,j}, Zm'_{i,j}, Z''_{4,j}, W_{i,j}, ZE_{i,j,c+2,k}, ZEa_{i,j,c+2,k}, ZEm_{i,j,c+2,k}, ZE'_{i,j,c+2,k}, ZEa'_{i,j,c+2,k}, ZEm'_{i,j,c+2,k}, W'_{i,j,c+2,k}, X'_{i,j,c+2}$ are objects associated with animals during the execution of the model and are related to the processes running. Index i is associated with the species, index j is associated with the age ($g_{i,5}$ is the average life expectancy), c is the simulated period and k the environment.

Objects $H_i, C_i, H'_i, C'_i, H''_{i,c+2}, B, M, S, B'_{c+2}, BE_{c+2,k}, ME_k, SE_k, BE'_{c+2,k}, ME'_k, SE'_k$ represent the biomass, the objects that include letters H or B are associated with bone biomass and C, M or S with meat biomass.

$F0_k$ and F_k are used to generate external contributions (i.e., supplementary feeding). D_i is an object used to count the existing animals of species i. If a species overcomes the maximum density values, it will be regulated. Objects d_i, a_i and $e_i$allow us to control the maximum number of animals per species in the ecosystem (i.e., carrying capacity). When a regulation takes place, object a_i allows us to eliminate the number of animals of species i that exceeds the maximum density. b is an object used to change the charge of the membrane. The objects co_i and cop_i indicate the period in which the model is working. At the end, object R and R_i are a counter that allow the synchronization of the P system.

Some objects go the environment as they leave the skin membrane (labelled with 0); all objects that appear in different configurations of the environment are the environment alphabet and in the case of the proposed model is:

$$\Sigma = \Big\{ZE_{i,j,c+2,k}, ZEa_{i,j,c+2,k}, ZEm_{i,j,c+2,k}, ZE'_{i,j,c+2,k}, ZEa'_{i,j,c+2,k}, ZEm'_{i,j,c+2,k}, W'_{i,j,c+2,k}, X'_{i,j,c+2}, 1 \leq i \leq N,\ 0 \leq j \leq g_{i,5}, 1 \leq c \leq 2, 1 \leq k \leq E\Big\} \cup \{BE_{c+2k}, ME_k, SE_k, BE'_{c+2k}, ME'_k, SE'_k, BM_{3,k}, 1 \leq c \leq 2, 1 \leq k \leq E\} \cup \{d_i, d'_i, a_i, e_i, 1 \leq i \leq N\}$$

The model has been structured in six modules (Figure 5) and is formed by 188 types of evolution rules that run within the membranes and 21 rules that are executed in the environment; all of these rules can be run in the 20 steps of the model, many of them applied in parallel. The following describes the 20 configurations involving a loop (Figure S2).

To summarize the description of the model composed of 209 rules, we only will describe the rules that correspond to the main processes.

The first rule that applies is

$$co_k[\quad]_k^0 \longrightarrow [co_k]_k^+, 1 \leq k \leq 2$$

that changes the polarization of membrane 1 (configuration 1) and activates the start of the model run.

After this step, the objects associated with animals $X_{ij}$and XS_{ij} enter the membrane labelled 1 with charge +; in the membrane skin we maintain copies of the objects associated with the populations of domestic animals controlled by man.

In step 3, the rules of reproduction are applied in parallel. A breeding female may or may not reproduce and if reproduction is successful new individuals are generated. The rules that allow the execution of this process are of the type:

$$\left[\mathrm{X}_{\mathrm{i,j}} \xrightarrow{1-\varphi(\mathrm{i,j})} \mathrm{Z}_{\mathrm{i,j}}\right]_1^0, \begin{cases} \mathrm{g}_{\mathrm{i},3} \leq \mathrm{j} < \mathrm{g}_{\mathrm{i},4}, \\ 1 \leq \mathrm{i} \leq \mathrm{N}. \end{cases} \quad \text{(males)}$$

$$\left[\mathrm{X}_{\mathrm{i,j}} \xrightarrow{\mathrm{k}_{\mathrm{i}2}\cdot\varphi(\mathrm{i,j})} \mathrm{Z}_{\mathrm{i,j}}\mathrm{Z}_{\mathrm{i}0}^{\mathrm{k}_{\mathrm{i}3}}\right]_1^0, \begin{cases} \mathrm{g}_{\mathrm{i},3} \leq \mathrm{j} < \mathrm{g}_{\mathrm{i},4}, \\ 1 \leq \mathrm{i} \leq \mathrm{N}. \end{cases} \quad \text{(breeding females)}$$

$$\left[\mathrm{X}_{\mathrm{i,j}} \xrightarrow{(1-\mathrm{k}_{\mathrm{i}2})\cdot\varphi(\mathrm{i,j})} \mathrm{Z}_{\mathrm{i,j}}\right]_1^0, \begin{cases} \mathrm{g}_{\mathrm{i},3} \leq \mathrm{j} < \mathrm{g}_{\mathrm{i},4}, \\ 1 \leq \mathrm{i} \leq \mathrm{N}. \end{cases} \quad \text{(non-breeding females)}$$

$\varphi(i,j)$ is the percentage of females of species i and age j. All objects of type X_{ij} evolved to object type Z_{ij} indicating that the process of reproduction has been carried out, while the objects associated with females that have reproduced create new objects of type Z_{i0}, the second subscript indicates the age is equal to 0.

In the same step are applied the rules that generates objects associated with annual food fixed contributions. Man makes contributions through the food provided in supplementary feeding sites (C_0 and H_0) and the ecosystem by small animals (S):

$$\left[\mathrm{F0}_{\mathrm{k}} \longrightarrow \mathrm{C}_0^{\beta_{\mathrm{k},1}}\mathrm{H}_0^{\alpha_{\mathrm{k},1}}\mathrm{M}^{\beta_{\mathrm{k},1}}\mathrm{B}^{\alpha_{\mathrm{k,c}}}\mathrm{S}^{\lambda\Gamma_{\mathrm{k},1}}\mathrm{F}_{\mathrm{k}}\right]_3^+ \ , 1 \leq \mathrm{k} \leq \mathrm{E}.$$

The subscripts associated with the objects are the contributions (expressed in kg) that are made in each period.

After the application of these rules we obtain the configuration 3. To this configuration the rules of natural mortality have been applied, removing the same objects of type Z_{ij} and ZS_{ij}, and those objects that are not removed enter the inner membrane (configuration 4). In the case of young animals, the mortality rules are of the type:

$$Z_{i,j}[\quad]_3^+ \xrightarrow{1-m_{i,1,1}} [Z_{i,j}]_3^+, \begin{cases} 0 \le j < g_{i,3}, \\ 1 \le i \le 4. \end{cases} \text{ (young animals that survive)}$$

$$Z_{i,j}[\quad]_3^+ \xrightarrow{m_{i,1,1}} [\quad]_3^+, \begin{cases} 0 \le j < g_{i,3}, \\ 1 \le i \le 4. \end{cases} \text{ (young animals that die)}$$

$m_{i,1,1}$ is the probability that a young animal of the species i will die during summer.

In the following two steps the feeding and control of the density rule are applied. In the first step all the scavengers eat except the griffon vulture ($i = 4$),

$$[Z_{i,j} a_i B^{f_{i,7}} M^{f_{i,8}} \rightarrow W_{i,j}]_3^+, \begin{cases} g_{i,3} \le j \le g_{i,5}, \\ 1 \le i \le 3. \end{cases}$$

$$\left[Z_{i,j} a_i B^{f_{i,7}} S^{f_{i,8}} \xrightarrow{g_{i,6}} W_{i,j}\right]_3^+, \begin{cases} g_{i,3} \le j \le g_{i,5}, \\ 1 \le i \le 3. \end{cases}$$

$$\left[Z_{4,j} \rightarrow Z''_{4,j}\right]_3^+, 0 \le j \le g_{i,5}.$$

$g_{i,6}$ is equal to 1 only for Egyptian vultures whose diet is mainly based on remains of small animals, whereas for the other the scavengers it is equal to 0.
f_{i7} and f_{i8} are respectively the amounts of biomass in kg of bones and meat required for each animal. f_{i7} is greater than 0 only for bearded vultures, because bones are not part of the diet of the other avian scavengers.
In the previous step the objects associated with the griffon vulture have evolved to Z''_{4j}. In the following step the griffon vulture eats if enough food is available.

$$[Z''_{4,j} a_i B^{f_{i,7}} M^{f_{i,8}} \rightarrow W_{i,j}]_3^+, g_{i,3} \le j \le g_{i,5}.$$

If there is an object a_i for an object $Z_{i,j}$ it means that this animal has sufficient physical space; if in addition the number of objects of type *B* and *M* that can be accessed are equivalent to the energy needs, the animal has sufficient resources and evolves.

In these rules, it is determined whether there is enough food and space. Objects Z_{ij} that do not evolve into objects W_{ij} correspond to animals that did not have enough resources (configuration 6).

The next step is to send to the environment all objects associated with animals that lacked resources and all resources that are left. In a first step these objects move out of the inner membrane labelled with 3, then enter the membrane labelled with 1 (configuration 7).

$$[\mathrm{Z}_{\mathrm{i,j}}]_3 \to \mathrm{Z'}_{\mathrm{i,j,3}}[\#]_3, \begin{cases} 0 \le \mathrm{j} \le g_{i,5}, \\ 1 \le \mathrm{i} \le 3. \end{cases}$$

It could be the case that there was insufficient space for some wild ungulates and therefore these animals died leaving food resources; the next step is to verify whether there are resources for avian scavengers who have not eaten (configuration 8). Subsequently, objects move to the skin membrane (configuration 9),

$$[\mathrm{Z'}_{\mathrm{i,j,3}}]_1 \to \mathrm{Z'}_{\mathrm{i,j,3}}[\#]_1, \begin{cases} 0 \le \mathrm{j} \le g_{i,5}, \\ 1 \le \mathrm{i} \le 3 \end{cases}$$

and finally these objects move to the environment (configuration 10).

$$[\mathrm{Z'}_{\mathrm{i,j,3}}]_0 \to \mathrm{Z'}_{\mathrm{i,j,3}}[\#]_0, \begin{cases} 0 \le \mathrm{j} \le g_{i,5}, \\ 1 \le \mathrm{i} \le 4. \end{cases}$$

Once in the environment, they must be moved to the environment e_{11}, not associated with geographical area (configuration 11).

$$(\mathrm{Z'}_{\mathrm{i,j,3}})_{\mathrm{ei}} \to (\mathrm{Z'}_{\mathrm{i,j,3}})_{\mathrm{e11}}, \begin{cases} 0 \le \mathrm{j} \le g_{i,5}, \\ 1 \le \mathrm{i} \le 4. \end{cases}$$

The following step is to enter membrane 0 (configurations 12) and then membrane 1 (configuration and 13), and to then check whether there are objects associated with resources available to the animals that had not evolved (configuration 14). The rules that apply are the type

$$\left[\mathrm{ZE}_{\mathrm{i,j,3,k}}\mathrm{aE}_{\mathrm{i},s}\, BE_{3,v}^{\mathrm{f}_{\mathrm{i},7}} ME_v^{\mathrm{f}_{\mathrm{i},8}}\right]_1^0 \xrightarrow{p_{TM_ikv} \cdot p_{TM_iks}} \mathrm{W'}_{\mathrm{i,j,3,s}}[\quad]_1^-, \begin{cases} \mathrm{g}_{\mathrm{i},3} \le \mathrm{j} \le \mathrm{g}_{\mathrm{i},5}, \\ 1 \le k \le E, \\ 1 \le s \le E, \\ 1 \le v \le E, \\ 1 \le i \le 4. \end{cases}$$

Associated with the rules, there is the probability that an animal from the environment k can access resources from s and v environments. In the rule shown, the animal finds food in the environment *v* and the accessible geographic space in the environment s $(aE_{i,s})$. Thus this animal leaves their original k environment to breed and lives in the environment *s*.

In the following configurations, objects move from the virtual environment, e_{11}, to the physical environment where the animal lives (4 steps, configurations 15-18) and restores their initial configuration (configuration 19). These 20 configurations encompass the entire summer season in the ecosystem. Another 20 configurations similar to the previous configurations are repeated with different parameters to simulate the passage of the winter period. Hence, one year involves 40 configurations and two consecutive executions of the loop shown (Figure S2).

Supplementary Table S1. Maximum carrying capacity considered in each subset of the study area. Avian scavengers are expressed as pairs (*n*) whereas the rest of the species are individuals (*n*).

	VA	**AR**	**PJ**	**PS**	**AU**	**C**	**R**	**B**	**S**	**N**
Gypaetus barbatus	7	10	14	14	14	3	5	5	5	6
Neophron percnopterus	1	11	22	7	15	2	5	9	10	14
Aegypius monachus	0	10	20	3	10	0	0	3	3	10
Gyps fulvus	15	180	360	100	300	20	60	60	70	210
Rupicapra pyrenaica	2000	2000	600	4000	650	850	4000	2000	650	50
Cervuselaphus	2750	70	1250	800	1000	200	250	1000	70	20
Dama dama	0	30	50	950	40	0	0	0	30	0
Capreolus capreolus	1700	250	1000	2000	850	850	650	1300	250	150
Ovis orientalis	0	0	0	600	100	50	500	0	50	0
Sus scrofa	4500	2500	5500	8750	7500	7500	10000	12500	22500	4250

Supplementary Table S2. Values of the parameters used in the model (for more details see Supplementary Table S3 and references 19 and 24).

	$g_{i,1}$	$g_{i,2}$	$g_{i,3}$	$g_{i,4}$	$g_{i,5}$	$g_{i,6}$	$k_{i,1}$	$k_{i,2}$	$k_{i,3}$	$m_{i,1,1}$	$m_{i,1,2}$	$m_{i,2,1}$	$m_{i,2,2}$	$ht_{i,1}$	$ht_{i,2}$	hp_i	$f_{i,1}$	$f_{i,2}$	$f_{i,3}$	$f_{i,4}$	$f_{i,5}$	$f_{i,6}$	$f_{i,7}$	$f_{i,8}$	$f_{i,9}$	$f_{i,10}$
Gypaetus barbatus	1	1	8	20	21	1	0.7	0.5	1	0.02	0.04	0.03	0.01	0	0	0	0	0	0	0	1	1	70	24	160	54
Neophron percnopterus	1	1	5	24	25	1	0.75	0.57	1	0.02	0.04	0.02	0.05	0	0	0	0	0	0	0	1	1	0	40	0	20
Aegypius monachus	1	1	5	24	25	1	0.7	0.55	1	0.02	0.04	0.02	0.05	0	0	0	0	0	0	0	1	1	0	132	0	272
Gyps fulvus	1	1	5	24	25	0	0.7	0.75	1	0.02	0.04	0.02	0.05	0	0	0	0	0	0	0	1	1	0	132	0	272
Rupicapra pyrenaica	1	1	2	18	18	0	0.55	0.75	1	0.2	0.4	0.02	0.04	0.3	0	0	3	4	6	24	0.5	0.5	0	0	0	0
Cervus elaphus	1	1	2	20	20	0	0.5	0.75	1	0.11	0.23	0.02	0.04	0.3	0	1	12	15	24	96	0.6	0.6	0	0	0	0
Dama dama	1	1	2	12	12	0	0.75	0.55	1	0.17	0.33	0.02	0.04	0	0	0	1	14	2	37	0.25	0.25	0	0	0	0
Capreolus capreolus	1	1	1	10	10	0	0.67	1	1	0.19	0.39	0.02	0.04	0	0	0	1	4	1	19	0.25	0.25	0	0	0	0
Ovis orientalis	1	1	2	12	12	0	0.5	0.9	2	0.2	0.4	0.02	0.04	0	0	0	3	4	6	22	0.6	0.6	0	0	0	0
Sus scrofa	1	1	1	4	6	0	0.5	0.55	4	0.05	0.09	0.03	0.07	0.32	0.32	0	4	6	12	60	0.25	0.25	0	0	0	0
*Ovis aries**	0	1	2	8	8	0	0.96	0.75	1	0.05	0.1	0.01	0.02	0	0	0	3	4	7	38	0.35	0.35	0	0	0	0
Bos taurus	0	2	2	9	9	0	0.9	0.9	1	0.02	0.04	0.02	0.03	0	0	0	10	60	6	518	0.025	0.3	0	0	0	0
Equus caballus	0	3	3	9	20	0	0.97	0.9	1	0.01	0.02	0	0.01	0	0	0	10	60	9	891	0.025	0.4	0	0	0	0

*Including individuals from *Capra hircus* populations

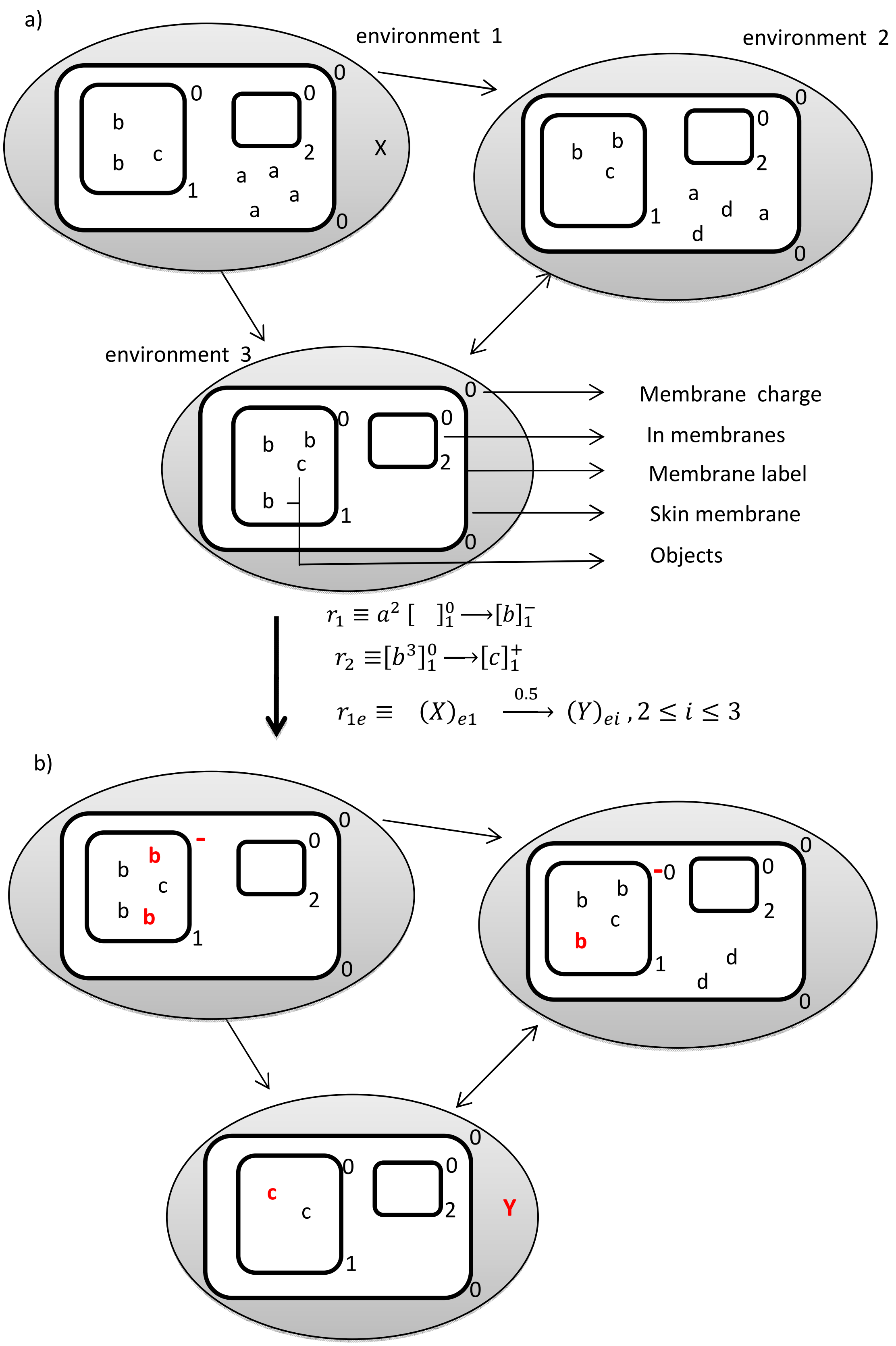
Supplementary Table S3. Description of the parameters used in the model.

Input		q_{kij}: Number of animals of species *i* and age *j* in the environment *k*. N: Number of years to simulate. N_R: Number of repetitions per year.
Parameters		$g_{i,1}$: 1 for wild species and 0 for domestic species. $g_{i,2}$: Age at which adult size is reached. This is the age at which the animal of species i consumes an adult diet with the same energetic requirements, and at which time, if the animal dies, the amount of biomass it leaves is similar to the total left by an adult. $g_{i,3}$: Age at which fertility begins in species *i*. $g_{i,4}$: Age at which fertility ends in species *i*. $g_{i,5}$: Average life expectancy of species *i* in the ecosystem. $g_{i,6}$: 1 when an important proportion of the diet of species *i* can be based on other small species (i.e. Carnivora, Leporidae) and 0 for the remainder.
		$k_{i,1}$: In the case of ungulates, percentage of females of the species *i* present in the population. For scavengers, percentage of pairs of the species *i* that can breed. For both scavengers and ungulates the sex-ratio at birth is considered as 1:1. $k_{i,2}$: Fertility ratio, proportion of fertile females that reproduce in the case of ungulates and proportion of pairs with successful breeding in the case of scavengers. $k_{i,3}$: Number of descendants of fertile females of species *i* that reproduce.
		$m_{i,1,c}$: Natural mortality ratio in first years of species *i* and period *c*, age$< g_{i,2}$ (per one). $m_{i,2,c}$: Mortality ratio in adult animals of species *i* and period *c*, age $< g_{i,2}$ (per one). $ht_{i,1}$: Percentage of males of the species *i* hunted. $\mathrm{ht}_{i,2}$: Percentage of females of the species *i* hunted. hp_i: 1 when after hunting the body of the animal of species *i* remains in the ecosystem and otherwise 0.

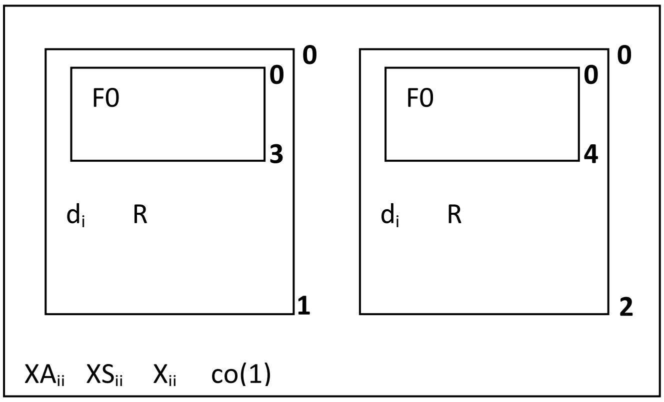
		$f_{i,1}$: Amount of bones (kg) provided by young animals of species *i* available, age $< g_{i,2}$. $f_{i,2}$: Amount of meat (kg) provided by young animals of species *i* available, age $< g_{i,2}$. $f_{i,3}$: Amount of bones (kg) provided by adult animals of species *i* available, age$\geq g_{i,2}$. $f_{i,4}$: Amount of meat (kg) provided by adult animals of species *i* available, age$\geq g_{i,2}$. $f_{i,5}$: Percentage of useful bones left by species *i*. $f_{i,6}$: Percentage of useful meat left by species *i*. $f_{i,7}$: Amount of bones (kg) necessary per year and pair of the species *i* according to the energetic requirements of the scavenger species in the summer period. $f_{i,8}$: Amount of meat (kg) necessary per year and pair of the species *i* according to the energetic requirements of the scavenger species in the summer period. $f_{i,9}$: Amount of bones (kg) necessary per year and pair of the species *i* according to the energetic requirements of the scavenger species in the winter period. $f_{i,10}$: Amount of meat (kg) necessary per year and pair of the species *i* according to the energetic requirements of the scavenger species in the winter period. $\beta_{k,c}$: Amount of bones delivered to supplementary feeding sites of the environment *k* during the period *c* (*c* =1 summer; *c* = 2 winter). $\alpha_{k,c}$: Amount of meat delivered to the feeding stations of the environment *k* during the period *c*. $\lambda_{k,c}$: Amount of meat provided by small animals delivered to the supplementary feeding sites of the environment *k* in the period *c*. $ff_{k,c,z}$: Percentage of food available for the avian scavengers in the peripheral zone *z*. The amount of food (kg) available is quantified with respect to the environment *k* in the period *c*.
		TM_i: Classification of the movements that can be made by the species *i* according to their foraging abilities. $P_{TM_i,k,v}$: Probability that species *i* will move from environment *k* to environment *v* when there is a lack of resources for the type of movement TM_i. $d_{i,k,1}$: Maximum density of species *i* in the environment *k*.
Output		$\overline{N_i}, \sigma_{Ni}$: Average and deviation of number of animals of species *i* for the year simulated. $\overline{B_i}, \sigma_{Bi}$, $\overline{M_i}, \sigma_{Mi}$: Average and deviation of amount of biomass, bones and meat, left for species and year simulated.

Supplementary Figure S1. Representation of the structure of the *Population Dynamic P System* model, which is formed by membranes, regions, and objects. a) Initial configuration of the model formed by five membranes all with a neutral charge. The type and amount of objects can vary between environments. In this example, a possible communication between environments exists. Concretely the environment 1 can communicate with the environment 2 and 3, and the environment 2 and 3 with each other. The rules r_1 and r_2 will be applied in parallel when possible. The rule r_1 is applied if membrane 1 has a neutral charge and in the region below membrane 0 there are two objects a. The rule r_2 will be applied if there are three objects b in membrane 3 with a neutral charge. In the case of the figure the rule r_1 is applied two times in environment 1 and one time in environment 2. The second rule is only applied one time in environment 3. r_e is an environment rule, as it satisfies the conditions that were applied randomly sending an object Y to environment 2 or 3 (environment 3 in Figure 3). The rules are applied in a maximal way and we obtain configuration b).

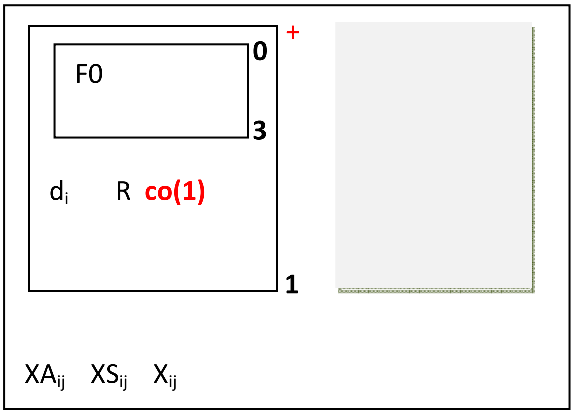
Figure S1.


a)
environment 1
environment 2
X
environment 3
Membrane charge
In membranes
Membrane label
Skin membrane
Objects
$r_1 \equiv a^2\,[\ \ ]_1^0 \longrightarrow [b]_1^-$
$r_2 \equiv [b^3]_1^0 \longrightarrow [c]_1^+$
$r_{1e} \equiv (X)_{e1} \xrightarrow{0.5} (Y)_{ei}, 2 \le i \le 3$
b)
Y

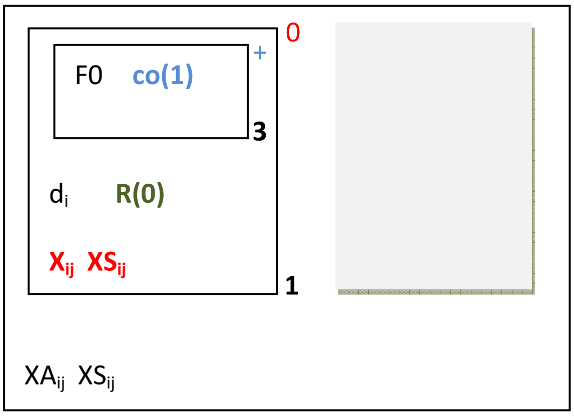
Supplementary Figure S2. PDP model proposed for the study of the dynamics of the avian scavengers is formed by six modules with 20 steps. The pass from one configuration to another is carried out by applying all possible evolution rules at each step.



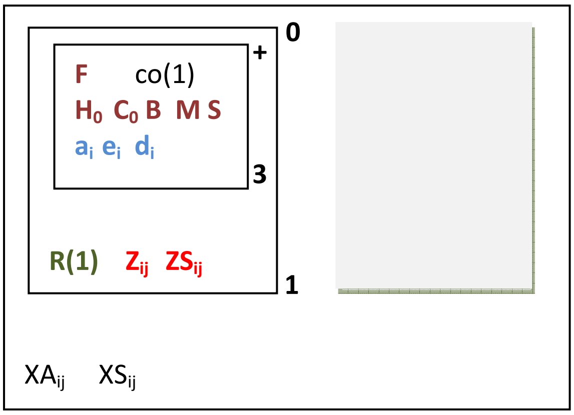
Configuration 0. X objects are associated with wild animals. XA objects with domestic animals living throughout the year in the ecosystem and the domestic *XS* nomads. The other objects were used to generate external inputs of food, control of animal densities and to synchronize the model. In membrane 1 and 3, summer processes are performed while in membrane 2 and 4 the winter processes are performed.



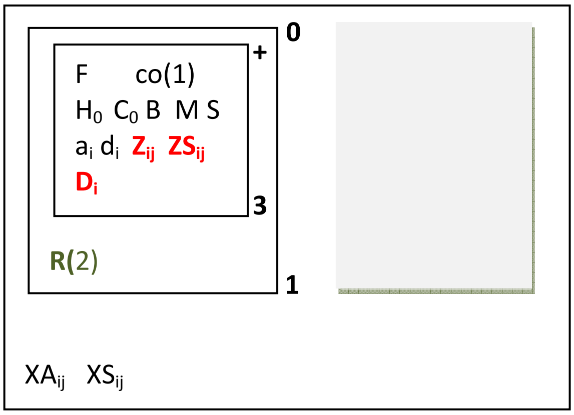
Configuration 1. The object co(1), which is in skin membrane. When entering membrane 1 changes the polarization of the membrane changes to positive. This activates the execution of the processes corresponding to the model summer period.



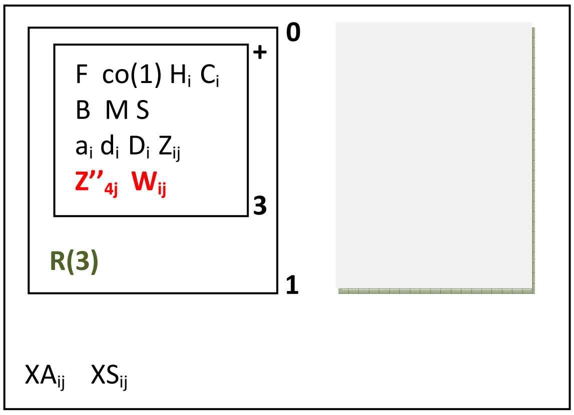
Configuration 2. The object co(1) which is in membrane 1 enters membrane 3 by changing the polarization of the membrane to positive. The objects associated with animals must enter membrane 1 so they can evolve according to the processes running in the summer period.
The R counter starts its evolution; this step ensures that the change of membrane charge 1 to neutral would not take place if there were no objects associated with animals



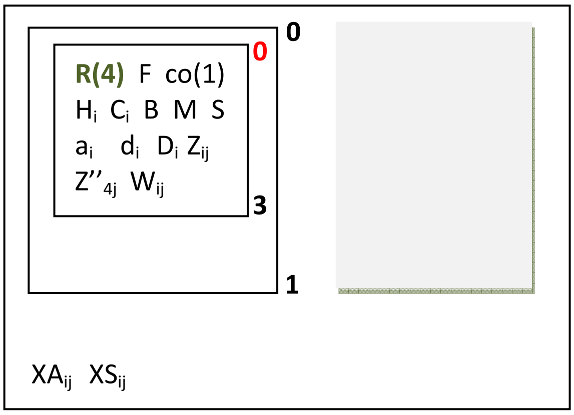
Configuration 3. The object $F0$ evolves as F object generating objects associated with food provided by humans and small animals. In the same step the object d_i enters membrane 3 generating new objects a_i and e_i that will allow control of population density of each species. In parallel runs the reproduction process evolving objects X_{ij} and XS_{ij} to Z_{ij} and ZS_{ij} respectively, generating new objects Z_{io} and ZS_{io}, corresponding to animals that are born.



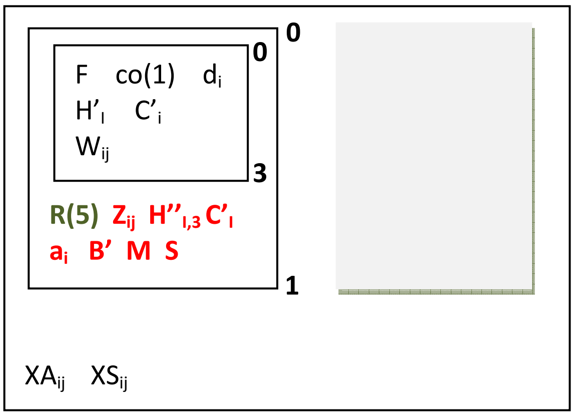
Configuration 4. In this step the rules that apply refer to mortality. These rules are applied randomly and according to the probability of death of each species. It eliminates a number of objects Z_{ij}, the rest enter membrane 3. An object D_i is created for each object Z_{ij} that enters membrane 3; the object is used to count the existing animals of species i .



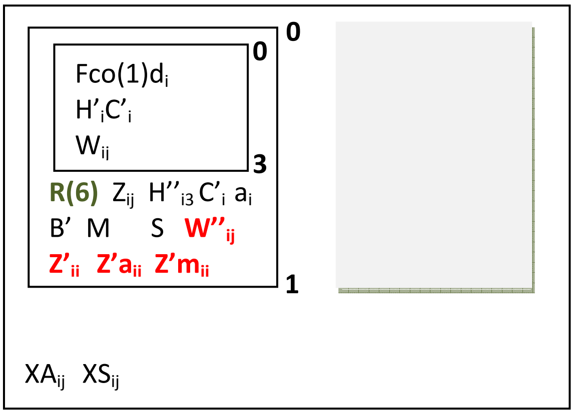
Configuration 5. If there are enough resources, food and space, animals will survive, so the objects are associated not dissolve, in this case Z_{ij} evolves to object W_{ij}. The species 4, griffon vulture, in the case of a lack of resources, are the last to eat, so the eat in the model in the next step which is achieved by making them evolve first. Z''_{4j}.



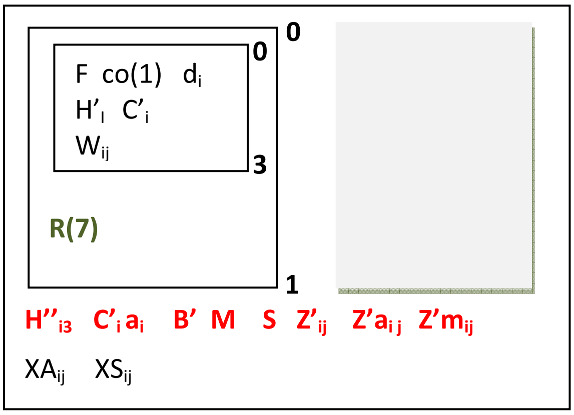
*Configuration 6***.** In this step the rules that apply are the feeding rules for the griffon vulture. By evolution of the counter R(3) to R(4) ensures the charge exchange of membrane 3.



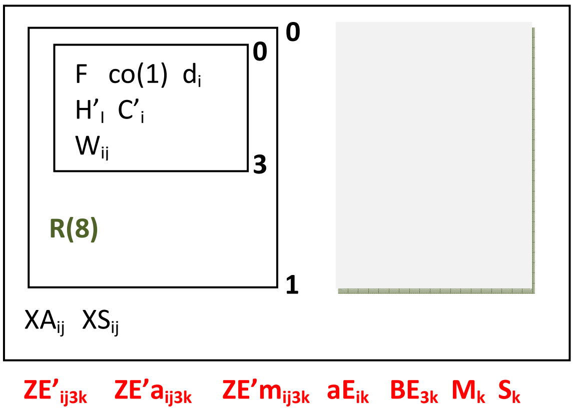
Configuration 7. If there is lack of resources, the objects Z_{ij} (associates to scavengers) do not evolve. If this object belongs to ungulates, it evolves to biomass objects and goes to membrane 1.



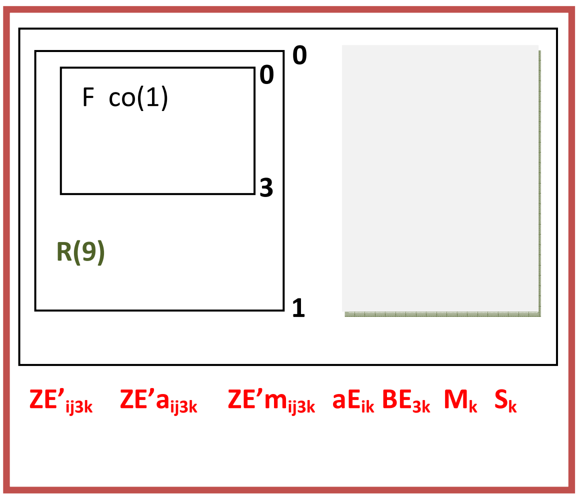
Configuration 8. Before to leave the objects Z_{ij} (membrane 1) it is checked what resource has been lacking. If the resource that is lacking is space Z'_{ij} evolves to $Z'm_{ij}$. In the case of a lack of food it evolves to $Z'a_{ij}$ and if both resources are lacking it evolves to W''_{ij}.



Configuration 9. In this step all objects associated with animals with a lack of resources and surplus resources exit to the membrane skin.

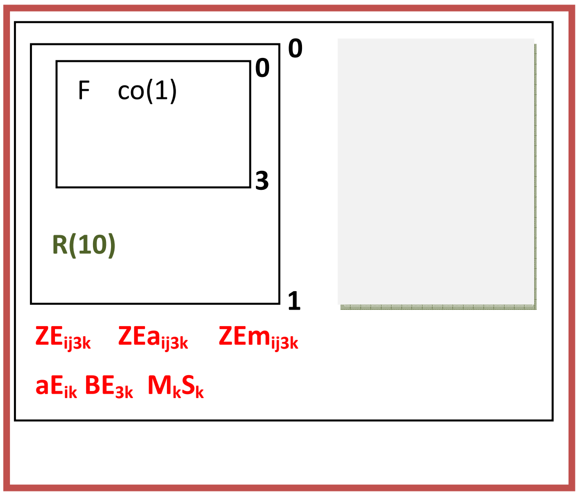


Configuration 10. In this step all objects associated with animals with a lack of resources and the objects associated with surplus resources go out to the environment. This objects keeping the environment from which they come (k) and the period of the year that is simulated (in this case 3 correspond to the summer period)

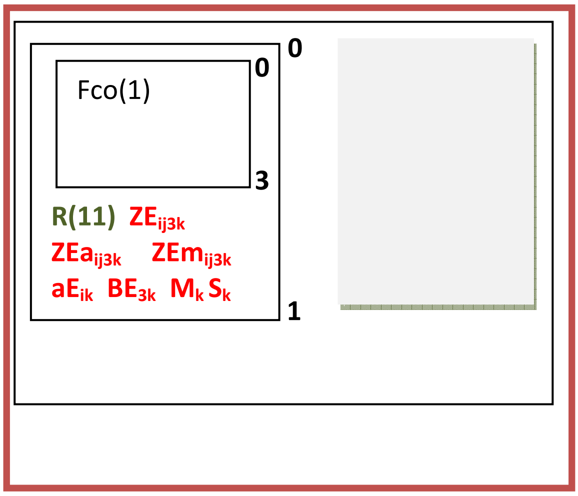


Environment e_{11}

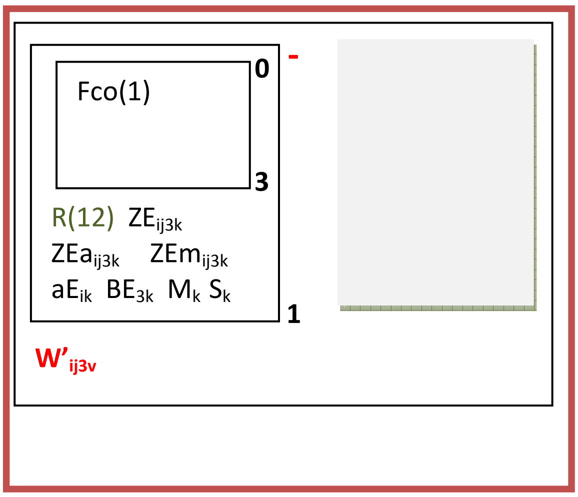
Configuration 11. In this step the objects that were in a physical environment pass to the virtual environment e_{11}. In the environment e_{11} objects associated with animals and food do not exist.



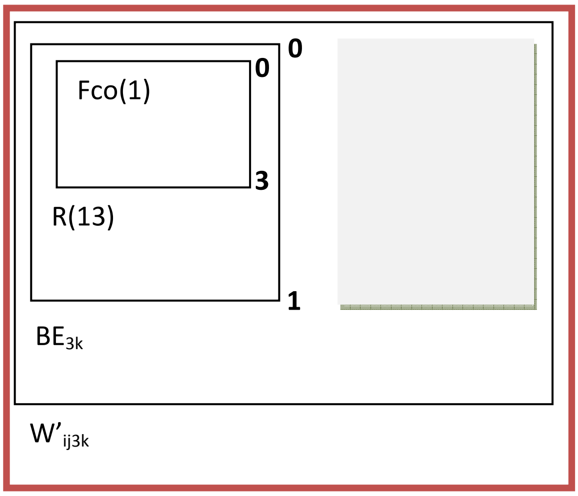
Configuration 12. The objects that are in the environment come into the skin membrane.



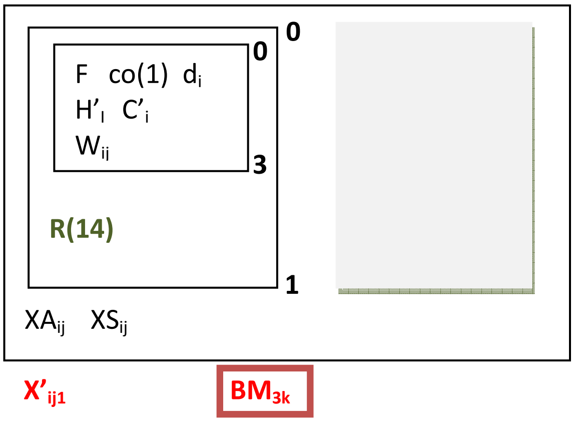
Configuration 13. In this step the objects pass to membrane 1.



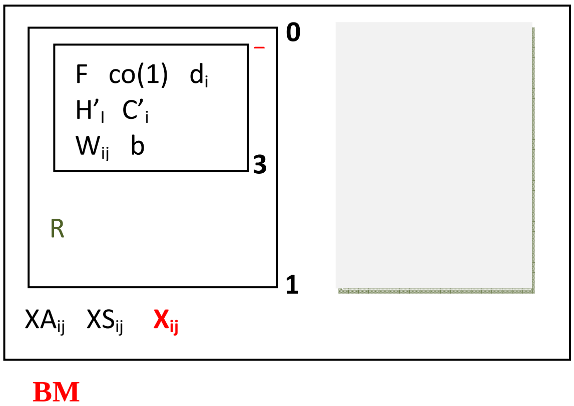
Configuration 14. In membrane 3, rules related to the existence of resources are applied. Not all animals have access to all resources, only those who belong to the area in which they can move. In the case that the animals have access to the necessary resources, the associated objects evolve to objects of type W'. In the same step they arrive at the skin membrane. The membrane labeled with 1 changes the polarization indicating that the process has been completed and will be able to dissolve the remaining objects (except parts of the bones).



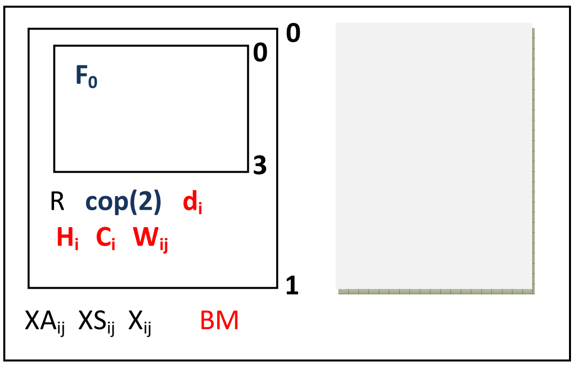
Configuration 15. The objects associated with animals that have enough resources must move to the environment in which they have physical space. The remaining objects, except part of the biomass in the form of bones, are dissolved. Some of the bones are covered by snow in the winter and serve as a food resource for Bearded vultures in the spring.



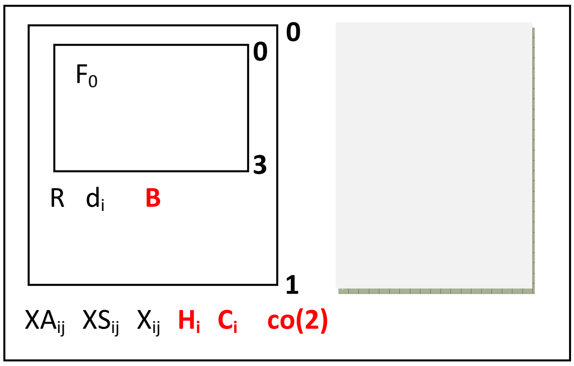
Configuration 16. In this step are the objects associated with uneaten bones found in e_{11} environment, while those associated with animals are already in the physical environment.



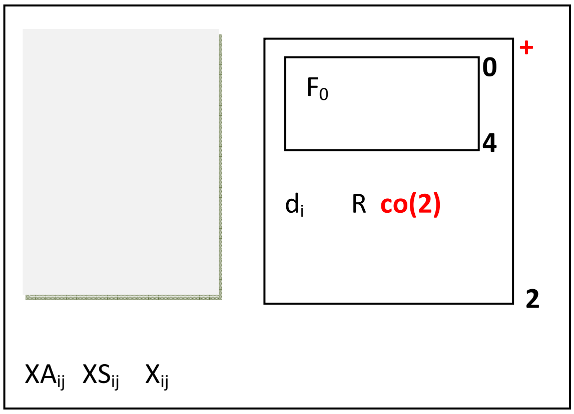
Configuration 17. This step begins the restoration of the initial configuration to start the Winter processes. The object X'_{ij} which is in the environment enters the skin membrane as X_{ij}. BM_{3k} moves to the environment e_k as BM.



Configuration 18. The object F evolves generating the object cop(2) indicating that the winter period should begin simulation. The objects W_{ij} must evolve to objects X_{ij} and move to the skin membrane. Objects H'_i and C'_i hold information on the amount of biomass that leaves each species in each period, and this information will be read in the membrane skin.



Configuration 19. In this configuration the initial configuration has been restored and therefore the next step in the process is initiated for the winter period.



Configuration 20. Start of the processes for the winter period.