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SYSTEM DYNAMICS APPROACH IN MANAGING COMPLEX BIOLOGICAL RESOURCES

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ABSTRACT

This paper discusses an application of System Dynamics approach in managing renewable biological resources. In essence, a management of a biological resource can be regarded as a control to the size of the associated population of the resource subject to certain criteria. For example, in harvesting theory or in fishery industries the management is directed towards the finding of the best size of the population giving rise to an optimal harvest as the objective. In finding this best size one should incorporate both the biological concern (sustainability of the resources) and the economic concern (maximum profit). In this regards, the objective can also be stated in other words, i.e. we have to find the maximum level of harvest such that the long-term sustainability of the resource is warranted. Technically this level of harvest is often called as the Maximum Sustainable Yield (MSY). The paper is aimed to find the MSY for biological resources having a complex ecosystem structure. We will assume that the resource forms a meta-population and in each sub-population the intra-specific competition may vary according to low, moderate and high level of competition. The paper shows that a different harvesting strategy should be applied depending on the level of competition status in each sub-population.

Keywords: maximum sustainable yield, intraspecific competition, meta-population model.

1. INTRODUCTION

System dynamics (SD) is an approach to understand the behavior of a complex system with the respect to time. SD is introduced for the first time by Professor Jay Forrester from the Massachusetts Institute of Technology [1] and often characterized by the existence of internal feedback loops in the form of flows connecting among entities (stocks). The complexities sometime increases, e.g. by the presence of time delays in the response of an action at the previous time to the reaction at the current time [2, 3]. These complexities certainly affect the behavior of the whole system.

Conceptually SD has a sister which is called Dynamical System (DS) born earlier in the Newton's mechanic era, and is defined roughly as a concept in which a fixed rule describes the dependences of the position of a point in a geometric space to time. The rule often appears in the form of differential equation with the solution called trajectory or orbit [4, 5].

Principally, both SD and DS study the same object, i.e. the time series of a system. However, SD more emphasizes on the application of mathematical computation through the discretization of the system using computer modeling software like Dynamo, Stella, Vensim, and Powersim. Meanwhile, DS more emphasizes on the application of analytical/mathematical tools to uncover the behavior of the system under study represented by the qualitative behavior of the solution of its mathematical equation or model.

In this paper we combine the SD and DS approaches since basically they work in the same spirit. In section 2 of the paper we give the formulation for the basic model used in the subsequent sections.

2. SYSTEM DYNAMICS IN FISHERIES INDUSTRY

2.1 Basic model and notations

The following notations will be used to formulate the mathematical model in this section,

N = Number of population
t = Time (in continuous model)
n = Time (in discrete model)
r = Intrinsic growth rate
K = Carrying capacity
α = Intra-specific competition intensity
h = Harvest rate
h^* = Optimal harvest rate
E = Effort of harvesting
q = Catch-ability of harvesting
U = Catch per unit effort
E_n = Effort of harvesting at time n
$U(n)$ = Catch per unit effort at time n
$\overline{U}_n$ = Total catch per unit effort in year n

Management in a fisheries industry in some sense can be regarded as the management of the number of fish population. The basic system in this regard is the growth of the fish population. The growth in many cases is assumed to be logistic [6], although other sigmoid form is also common [7]. In this paper we will assume that the natural growth of the fish is logistic. It is well-known that the DS equation for the system is given by (1),

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$$\frac{dN}{dt} = rN\left(1-\frac{N}{K}\right). \tag{1}$$

In equation (1), $N=N(t)$ defines the number of population at time t. The equation is equivalent to the SD form of flow-stock diagram (Figure-1) and to the SD equations in Powersim format (Figure-2).

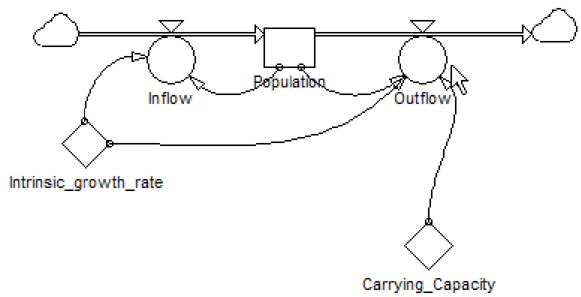

Figure-1. Representation of equation (1) in SD flow-stock diagram.

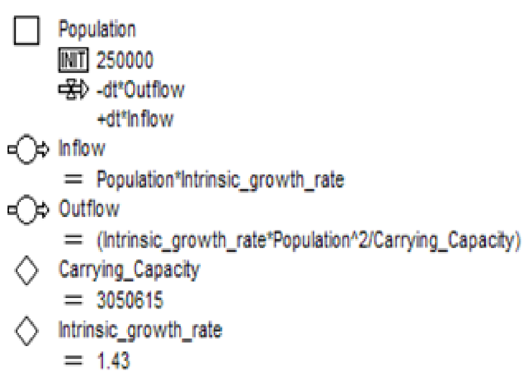

Figure-2. Representation of equation (1) in SD equations.

By referring to Figure-2 above, the initial value of the system is given by $N(0)$=250,000 at time t=0 with the known carrying capacity K and intrinsic growth rate r. Using Runge-Kutta scheme, the solution of the system from t=0 to t=6 is shown by Figure-3,

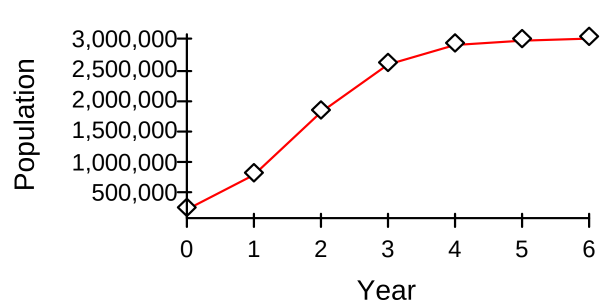

Figure-3. Time series solution of equation (1) with parameters in Figure-2.

2.2 MSY for the basic model

We assume that the commercial population governed by equation (1) is exploited with the constant harvesting rate h, such that the equation becomes

$$\frac{dN}{dt} = rN\left(1-\frac{N}{K}\right) - h. \tag{2}$$

The manager of the commercial population would like to maximize yield from the industry while keeping the population sustainable. Mathematically, sustainability can be achieved if the growth of the population is not negative. Without losing the generality, this is satisfied in the zero growth phase of the population. This condition is often used to find the maximum harvest h^* satisfying the sustainability of the population. The resulting harvest is called the Maximum Sustainable Yield (MSY) which can be obtained by noting that

$$h = h(N) = rN\left(1-\frac{N}{K}\right). \tag{3}$$

It is easy to show that at $N^* = K/2$ the harvest will be maximum given by $h^* = rK/4$. Harvesting the population at MSY level, theoretically, will guarantee that the industry will sustainable with the steady state of the fish population at the level of $N^* = K/2$. On the other hand, harvesting the population beyond that level may cause the industry collapse [8].

Furthermore, the author in [8] shows that if the exploitation is carried out at the level h (not necessarily at the MSY), then the steady state of the population is at the level of $N = (rK + \sqrt{r^2K^2 - 4rhK})/(2r)$. The results above tell us that knowing the values of r and K is very important in the fisheries industry. Figure-4 shows the effect of harvesting to the previous system illustrated in Figure-3 with MSY level given by $h^* = rK/4 =$ 1,090,595. In this Figure we assume that the first harvesting is carried out when the population is at its carrying capacity (i.e. after the sixth year shown in Figure-3) for the period of the remaining eight years onwards. Figure-4 is also the representation of the SD diagram in Figure-5.

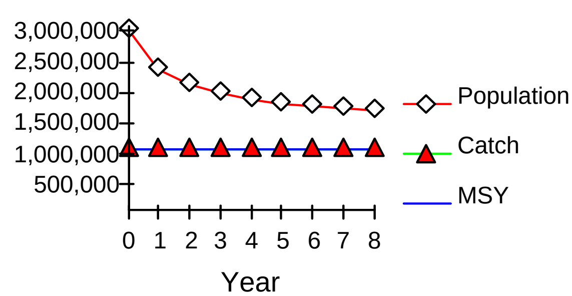

Figure-4. Harvesting of system in Figure-3 with the constant MSY.

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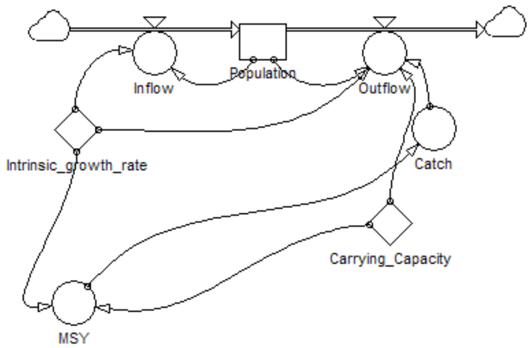

Figure-5. Representation of equation (2) in SD diagram.

Figure-4 above assumes that harvesting is done with a constant harvest of population. In this case at MSY level. In many cases harvesting is done with a constant effort rather than a constant harvest. In this case we can modified equation (2) as follows. Harvesting rate can be regarded as a function of the number of the existing population number (*N*) and the effort exerted to catch the population (*E*) with a certain catchability (*q*). Hence equation (2) becomes

$$\frac{dN}{dt} = rN\left(1-\frac{N}{K}\right) - qEN\,. \tag{4}$$

It can be shown easily that the optimal effort associated with the MSY level is $E^* = r/(2q)$. As in the case of the constant optimal harvest, the constant optimal effort also converge to a constant catch eventually (but see Figure-6 for comparison).

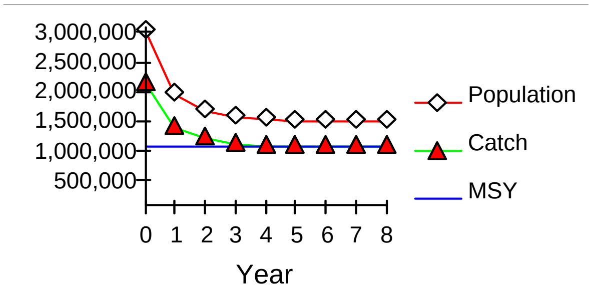

Figure-6. Harvesting of system in Figure-3 with a constant effort.

2.3 Parameter estimation for the basic model

Time series or trajectory as solution of equation (1) in Figure-3 above is obtained by assuming certain values for the parameters (*r* and *K*) of the model in the equation as illustrated by Figure-2. Hence the relevant question is how do we parameterize the model in equation (1) from available data? If for example we have a time series data as in Figure-3 then we can parameterize the model straight forward by regressing the equation to the data. But this kind of data is never existed. The only available data in a real application is the catch and effort data. To facilitate the parameterization we briefly summarize the method discussed in [9, 10] as follows.

To estimate the parameter in equation (1) we assume that the population depicted by the equation is harvested with a constant harvest *h*. As explained earlier harvesting rate can be regarded as a function of the number of the existing population number (*N*) and the effort exerted to catch the population (*E*) with certain catch ability (*q*). Using this assumption then equation (1) is equivalent to equation (4). Furthermore, [8, 9] defines *U as* catch per unit effort i.e. $U = h/E$, and hence $N = U/q$. Substituting this equation into equation (4), we have

$$\frac{dU}{qdt} = \frac{r}{q}U\left(1-\frac{U}{qK}\right) - EU \tag{5}$$

The authors in [9, 10] is able to develop the discrete version of equation (5) in the form of

$$\ln\left(\frac{\overline{U}(n+1)}{\overline{U}(n)}\right) = r - \frac{r}{2qK}(\overline{U}_{n+1} + \overline{U}_n) - \frac{q}{2}(\overline{E}_{n+1} + \overline{E}_n) \tag{6}$$

The last equation is a discrete analog of the continuous equation (1). Using this equation we are able to estimate the parameter *r* and *K* in equation (1) through the regression of equation (6) by an available catch-effort data. This method is often called the Schnute method, referring to the last name of the author in [10]. As an illustration of the application of equation (6), we use the catch-effort data presented in Table 1 of [9] giving rise to the values *K*=3,050,615, *r*=1.43, and *q*=0.000000913. For the subsequent discussion we will use these values unless stated otherwise.

3. NUMERICAL SIMULATION FOR COMPLEX MODELS

In this numerical simulation we consider two different source of complexity. The first one is the existence of different intensity of intra-specific competition and the second one is the presence of spatial heterogeneity in the system, where we assume that there is a metapopulation structure comprising of two different quality of patches.

3.1 Different intensity of intra-specific competition

Equation (1) assumes that the coefficient of intra-specific competition in the model is one. We may interpret this is a moderate situation of competition. In reality, the competition might be higher or lower than this moderate rate. In general if the intensity of the intra-specific competition is α then equation (1) becomes

$$\frac{dN}{dt} = rN\left(1-\frac{N^\alpha}{K}\right) \tag{7}$$

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By referring to [10], the MSY of the system in equation (7) is given by

$$h^* = r\left(\frac{K}{1+\alpha}\right)^{1/\alpha}\left(1-\frac{1}{1+\alpha}\right) \tag{8}$$

with the associated equilibrium population size given by

$$N^* = e^{\ln(K/(1+\alpha))/\alpha} \tag{9}$$

Next we use the catch-effort data in Table-1 of [9] for two different condition. The first condition is when the intensity of the intra-specific competition is low (α=0.90) and the second one is when the intra-specific competition is high (α=1.05). For both situation we will assume that the exploited population has parameters K=3,050,615, r=1.43, and q=1. The results of their respective MSY are shown in Figures-7 and 8.

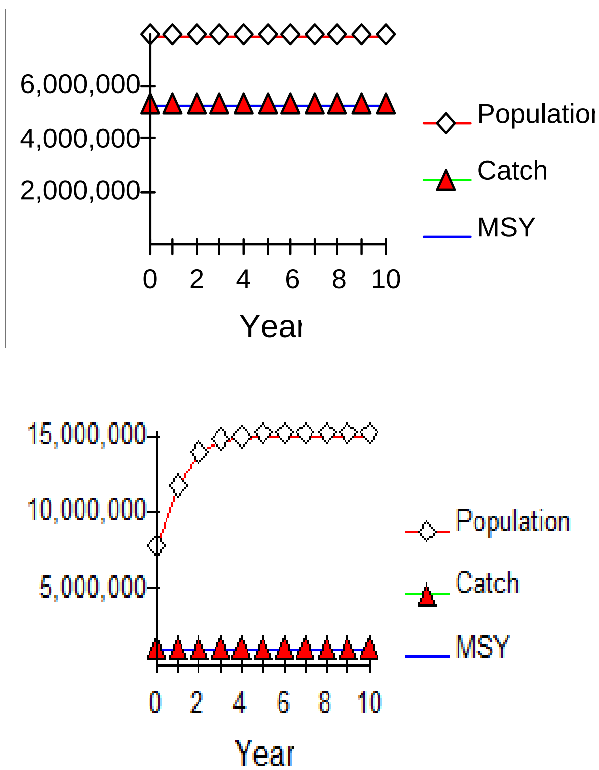

Figure-7. Equilibrium population size and MSY for correct management (top) and incorrect management (bottom) of the population. α=0.90 for both figures.

Figure-7 shows the case of low intensity of intra-specific competition. In this case, if we exploit the population correctly, then we have MSY=5,320,759 and the population equilibrium is at 7,855,045 with the graph of catch over time shown in Figure-7 (top). Meanwhile, if we exploit the population incorrectly, e.g. by ignoring the low intra-specific competition intensity, then we have MSY=1,090,595 and the population equilibrium is at 1,525,308 with the graph of catch over time shown in Figure-7 (bottom). Compared to the Figure (top), the catch predicted by Figure-7 (bottom) is lower than it is to be, indicating an underexploited situation.

Figure-8 shows the case of high intensity of intra-specific competition. In this case, if we exploit the population correctly, then we have MSY=553,949 and the population equilibrium is at 756,308 with the graph of catch over time shown in Figure-8 (top). Meanwhile, if we exploit the population incorrectly, e.g. by ignoring the high intra-specific competition intensity, then we have MSY=1,090,595 and the population equilibrium is at 1,525,308. If then we harvest the population at only 55% of the suggested MSY then the population goes extinct after the sixth year of exploitation (Figure-8 (bottom)). This clearly indicates that the resource is overexploited.

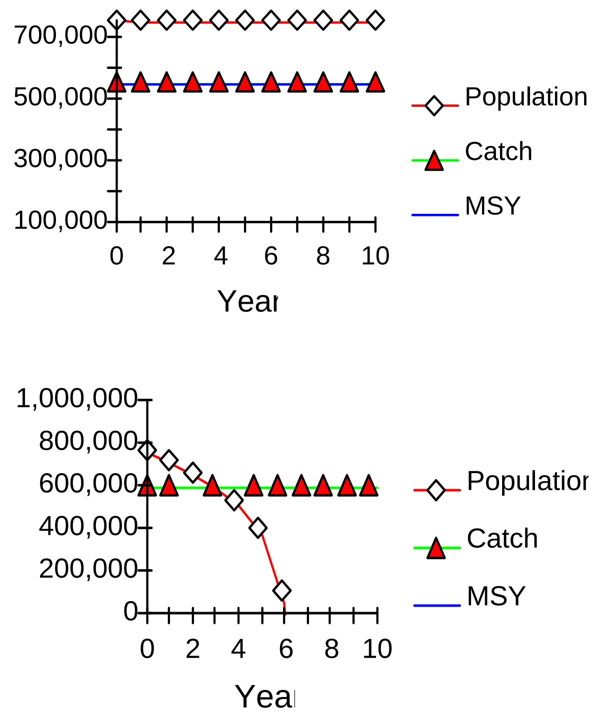

Figure-8. Equilibrium population size and MSY for correct management (top) and incorrect management (bottom) of the population. α=1.05 for both figures.

From Figures-7 and 8 we see that less intense intra-specific competition gives a higher MSY than more intense intra-specific competition, which is plausible. Table-1 shows this result for a more diverse of intra-specific competition. Every row in Table-1 is obtained from ordinary least square for linear regression of equation (6) using the data set in Table-1 of [9]. The only robust parameter is the catch ability parameter. Other parameters are sensitive to the change of the intra-specific competition intensity.

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Table-1. MSY and model parameters resulting from various assumption of the intra-specific competition intensity.

α.

α	R	q	K	MSY
0.10	7.366	7.45 x 10^{-7}	4.541	10,097,403
0.20	3.683	7.45 x 10^{-7}	20.62	5,048,701
0.30	2.455	7.45 x 10^{-7}	93.63	3,365,801
0.40	1.841	7.45 x 10^{-7}	425.1	2,524,350
0.50	1.473	7.45 x 10^{-7}	1,930	2,019,480
0.60	1.228	7.45 x 10^{-7}	8,765	1,682,900
0.70	1.052	7.45 x 10^{-7}	39,803	1,442,486
0.80	0.921	7.45 x 10^{-7}	180,736	1,262,175
0.95	0.775	7.45 x 10^{-7}	1,748,805	1,062,884
0.96	0.767	7.45 x 10^{-7}	2,034,485	1,051,812
0.97	0.759	7.45 x 10^{-7}	2,366,833	1,040,969
0.98	0.752	7.45 x 10^{-7}	2,753,472	1,030,347
0.99	0,744	7.45 x 10^{-7}	3,203,272	1,019,939
1.00	**0.737**	**7.45 x 10^{-7}**	**3,726,550**	**1,009,740**
1.01	0.729	7.45 x 10^{-7}	4,335,308	999,742
1.02	0.722	7.45 x 10^{-7}	5,043,512	989,941
1.03	0.715	7.45 x 10^{-7}	5,867,406	980,330
2.00	0.368	7.45 x 10^{-7}	1.389 x 10^{13}	504,870
3.00	0.246	7.45 x 10^{-7}	5.175 x 10^{19}	336,580
4.00	0.184	7.45 x 10^{-7}	1.929 x 10^{26}	252,435
5.00	0.147	7.45 x 10^{-7}	7.186 x 10^{32}	201,948

3.2 Heterogeneous intra-specific competition in two-patch connected population

Examples in Figures-7 and 8 show that if there are two separated populations with different level of intra-specific competition intensity, i.e. one with a low intensity of intra-specific competition (α=0.90) and the other one with a high intensity of intra-specific competition (α=1.05), then the total MSY extracted from these two populations is 5,874,708 (5,320,759 plus 553,949). In the next discussion we will assume that these populations belong to a meta-population. The populations live in different habitat but they are connected through the migration of individuals. We will use the data in Table 1 of [9] to facilitate the discussion and we will show that this complexity has a significant role in determining the level of the total MSY of the meta-population.

Considering there are two connected sub-populations in the system with known migration parameters, now we can modify equation (1) into the form as seen in [11]. In this example we assume that the migration parameter p12 = 0.5 and p21 = 0.4. In this case, the total MSY is not equal to the previous MSY of the separated populations, but given by only 3,000,000's (almost only a half of its original MSY for separated populations). Figure-9 shows the simulation of harvesting the two-patch meta-population for the situation above, with detail SD model given in Appendix 1. The figure shows that migration and exploitation have made the system fluctuate rapidly. This fluctuation is observed in both of sub-populations.

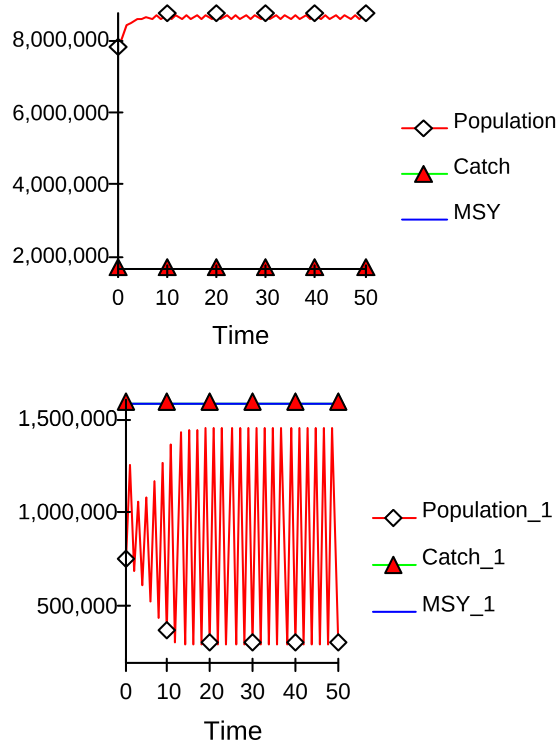

Figure-9. Equilibrium population size and the corresponding MSY for sub-population living in habitat 1 (top) and for sub-population living in habitat 2 (bottom). The migration parameters are p_{12}=0.5 and p_{21}=0.4 with the intra-specific competition α_1=0.90 and α_2=0.05. The resulting MSY are 1,695,760 for habitat 1 and 1,593,841 for habitat 2.

4. CONCLUSIONS

In this paper we give an example of the application of System Dynamics (SD) approach in the management of biological resources. SD is an appropriate approach to tackle problem in biological resource management, since most of problems in biological resource management is highly complex, hence mathematical tractability is often fail to delineate. In this case SD approach is a good alternative to thorough mathematical analysis of the problem. Via SD approach we can increase the realism of the model and obtain some insight of the model behavior relatively easy, which otherwise difficult to obtain from other approach.

The examples in the paper show that spasial heterogeneity and differential intra-specific competition intensity are vital in determining the appropriate maximum sustainable yield of the biological resources. Fail to recognise these two factors may lead to underexploitation or overexploitation of the resources depending on the values of parameters. In terms of parameter estimation of the model, the only robust parameter in the model is the catchability parameter. Other parameters are sensitive to the change of the intra-specific competition intensity. In this paper we have assumed that the value of the intra-specific competition intensity is known. In practice this value might be unknown and should also be estimated from the same available data. This is currently under investigation.

5. ACKNOWLEDGEMENTS

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APPENDIX-1 System Dynamics equations use in simulation to generate Figure-9.

```
init   Population = 7855045
flow   Population = -dt*Outflow
  +dt*Inflow
init   Population_1 = 756308
flow   Population_1 = -dt*Outflow_1
  +dt*Inflow_1
aux    Inflow =
  Population*Intrinsic_growth_rate+p_21*Population_1
aux    Inflow_1 =
  Population_1*Intrinsic_growth_rate_1+p_12*Population
aux    Outflow =
  (Intrinsic_growth_rate*Population^(1+Intra_spesific_co
  mpetition)/Carrying_Capacity)+Catch+p_12*Population
aux    Outflow_1 =
  (Intrinsic_growth_rate_1*Population_1^(1+Intra_spesifi
  c_competition_1)/Carrying_Capacity_1)+Catch_1+p_21
  *Population_1
aux    Catch = MSY
aux    Catch_1 = MSY_1
aux    Equil_pop_size =
  EXP(LN((Carrying_Capacity)/(1+Intra_spesific_competi
  tion))/Intra_spesific_competition)
aux    Equil_pop_size_1 =
  EXP(LN((Carrying_Capacity_1)/(1+Intra_spesific_comp
  etition_1))/Intra_spesific_competition_1)
aux    MSY =
  Intrinsic_growth_rate*(Carrying_Capacity/(1+Intra_spes
  ific_competition))^(1/Intra_spesific_competition)*(1-
  (1/(1+Intra_spesific_competition))) -
  p_12*(Carrying_Capacity/(1+Intra_spesific_competition
  ))^(1/Intra_spesific_competition) +
  p_21*(Carrying_Capacity_1/(1+Intra_spesific_competiti
  on_1))^(1/Intra_spesific_competition_1)
aux    MSY_1 =
  Intrinsic_growth_rate_1*(Carrying_Capacity_1/(1+Intra
  _spesific_competition_1))^(1/Intra_spesific_competition
  _1)*(1-(1/(1+Intra_spesific_competition_1))) -
  p_21*(Carrying_Capacity_1/(1+Intra_spesific_competiti
  on_1))^(1/Intra_spesific_competition) +
  p_12*(Carrying_Capacity/(1+Intra_spesific_competition
  ))^(1/Intra_spesific_competition)
const  Carrying_Capacity = 3050615
const  Carrying_Capacity_1 = 3050615
const  Intra_spesific_competition = 0.90
const  Intra_spesific_competition_1 = 1.05
const  Intrinsic_growth_rate = 1.43
const  Intrinsic_growth_rate_1 = 1.43
const  p_12 = 0.5
const  p_21 = 0.4
```