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# Decentralized control of ecological and biological networks through Evolutionary Network Control

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**Abstract**
Evolutionary Network Control (ENC) has been recently introduced to allow the control of any kind of ecological and biological networks, with an arbitrary number of nodes and links, acting from inside and/or outside. To date, ENC has been applied using a centralized approach where an arbitrary number of network nodes and links could be tamed. This approach has shown to be effective in the control of ecological and biological networks. However a decentralized control, where only one node and the correspondent input/output links are controlled, could be more economic from a computational viewpoint, in particular when the network is very large (i.e. big data). In this view, ENC is upgraded here to realize the decentralized control of ecological and biological nets.

**Keywords** centralized control; decentralized control; dynamical networks; genetic algorithms; Evolutionary Network Control; edge control; node control; network optimization; system dynamics.

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## 1 Introduction

Evolutionary Network Control (ENC) has been recently introduced to allow the control of any kind of ecological and biological networks, with an arbitrary number of nodes and links, from inside (Ferrarini, 2013) and from outside (Ferrarini, 2013b). The endogenous control requires that the network is optimized at the beginning of its dynamics so that it will inertially go to the desired state. The exogenous control requires that one or more exogenous controllers act upon the network at each time step.

ENC can be applied to both discrete-time (i.e., systems of difference equations) and continuous-time (i.e., systems of differential equations) networks. ENC opposes the common idea in the scientific literature that controllability of networks should be based on the identification of the set of driver nodes that can guide the system's dynamics, in other words on the choice of a subset of nodes that should be selected to be permanently controlled (Ferrarini, 2011).

ENC makes use of an integrated solution (system dynamics - genetic optimization - stochastic simulations) to compute uncertainty about network control (Ferrarini, 2013c) and to compute control success and feasibility (Ferrarini, 2013d). ENC employs intermediate control functions to locally (step-by-step) drive ecological and biological networks, so that also intermediate steps (not only the final state) are under its control (Ferrarini, 2014). ENC can also globally subdue nonlinear networks (Ferrarini, 2015), impose early or late stability to any kind of ecological and biological network (Ferrarini, 2015b) and locally control nonlinear networks (Ferrarini, 2016).

**Table 1** Evolutionary Network Control (ENC) and its developed variants.

| Reference | Goal |
|---|---|
| Ferrarini 2011 | Theoretical bases of Evolutionary Network Control |
| Ferrarini 2013 | Endogenous control of linear ecological and biological networks |
| Ferrarini 2013b | Exogenous control of linear ecological and biological networks |
| Ferrarini 2013c | Computing the uncertainty associated with network control |
| Ferrarini 2013d | Computing the degree of success and feasibility of network control |
| Ferrarini 2014 | Local control of linear ecological and biological networks |
| Ferrarini 2015 | Global control of nonlinear ecological and biological networks |
| Ferrarini 2015b | Imposing early/late stability to linear and nonlinear networks |
| Ferrarini 2016 | Local control of nonlinear ecological and biological networks |
| Ferrarini 2016b | Multipurpose control of ecological and biological networks |
| This work | Decentralized control of ecological and biological networks |

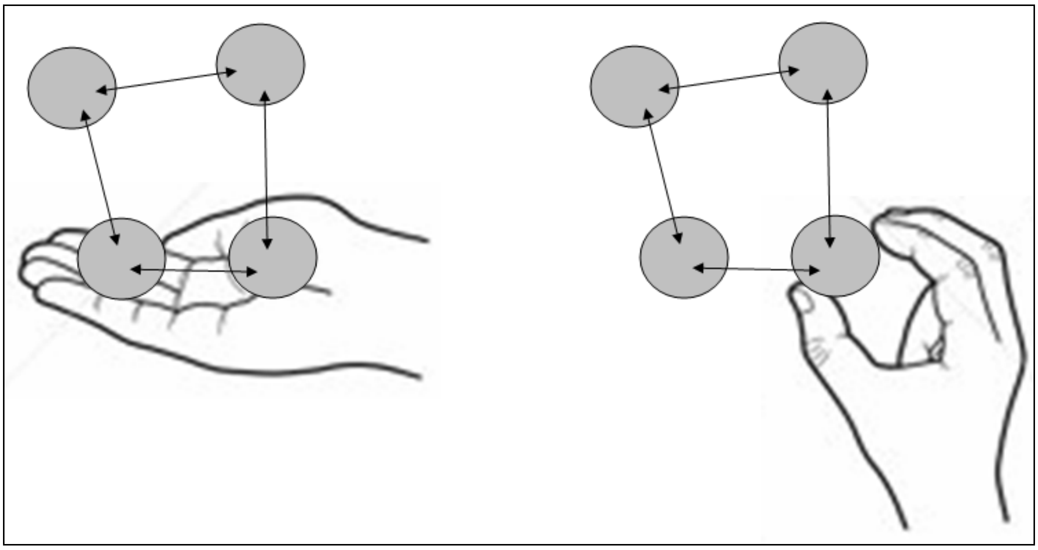

**Fig. 1** Conceptual difference between centralized (on the left) and decentralized (on the right) control of ecological and biological networks. In the former case, the control can be applied to any node and link. In the latter case, only one node and the correspondent links are controlled.

To date, ENC has been applied using a centralized approach where an arbitrary number of network nodes and links could be tamed. This approach has shown to be effective in the control of ecological and biological networks. However a decentralized control, where only one node and the correspondent input/output links are controlled, could be more economic from a computational viewpoint, in particular when the network is very large, like when dealing with big data. In this view, ENC is upgraded here to realize the decentralized control of ecological and biological nets.

## 2 Decentralized Evolutionary Network Control: Mathematical Formulation

An ecological (or biological) dynamical system of *n* interacting taxonomic resolutions (species, genera, family, etc.) or aggregated assemblages of taxa (e.g., phytoplankton) is as follows

$$\frac{d\mathbf{S}}{dt} = \gamma(\mathbf{S}(t)) \tag{1}$$

where $S_i$ is the number of individuals (or the total biomass) of the generic ***i-th*** taxonomic resolution (species, genera, family, or aggregated assemblages of taxa). If we also consider inputs (e.g. species reintroductions) and outputs (e.g. hunting) from outside, we must write:

$$\frac{d\mathbf{S}}{dt} = \gamma(\mathbf{S}(t)) + \mathbf{I}(t) + \mathbf{O}(t) \tag{2}$$

As noted by numerous authors (Luenberger 1979; Slotine and Li 1991) most real systems' dynamics can be modelled and simulated using a system of canonical, linear equations which represents a simplification of Eq. (2) as follows

$$\begin{cases} \frac{dS_1}{dt} = \alpha_{11}S_1 + ... + \alpha_{1n}S_n + I_1 + O_1 \\ ... \\ \frac{dS_n}{dt} = \alpha_{n1}S_1 + ... + \alpha_{nn}S_n + I_n + O_n \end{cases} \tag{3}$$

that can be written in the compact form

$$\frac{dS_i}{dt} = \underbrace{\alpha_{ii}S_i}_{\text{intra-specific}} + \underbrace{\sum_{j \neq i} \alpha_{ij}S_j}_{\text{inter-specific}} + \underbrace{\sum_k I_k + \sum_k O_k}_{\text{exogenous input-output}} \tag{4}$$

with initial values

$$\mathbf{S}_0 = <\mathrm{S}_1(0), \mathrm{S}_2(0)...\mathrm{S}_n(0)> \tag{5}$$

and co-domain limits

$$\begin{cases} \mathrm{S}_{1\min} \le S_1(t) \le \mathrm{S}_{1\max} \\ ... \\ \mathrm{S}_{n\min} \le S_n(t) \le \mathrm{S}_{n\max} \end{cases} \tag{6}$$

and where

$$A = \begin{pmatrix} a_{11} & \dots & a_{1n} \\ \dots & \dots & \dots \\ a_{n1} & \dots & a_{nn} \end{pmatrix} \quad (7)$$

is the matrix of the per unit time effect on $S_i$ due to unitary $S_j$. This system is inherently accelerated with acceleration equal to

$$\frac{d^2 S_i}{d^2 t} = \alpha_{ii} \frac{dS_i}{dt} + \sum_{j \neq i} \alpha_{ij} \frac{dS_j}{dt} + \sum_k \frac{dI_k}{dt} + \sum_k \frac{dO_k}{dt} \quad (8)$$

ENC solves the control of Eq. 3 using the following centralized approach (Ferrarini, 2013)

$$\begin{cases} \frac{dS_1}{dt} = a_{11*} S_1^* + \dots + a_{1n*} S_n^* + I_{1*} + O_{1*} \\ \dots \\ \frac{dS_n}{dt} = a_{n1*} S_1^* + \dots + a_{nn*} S_n^* + I_{n*} + O_{n*} \end{cases} \quad (9)$$

where any component (variable, parameter or coefficient) of Eq. 9 can be tamed, as denoted by the asterisk, to drive the network to the desired state. ENC makes use of genetic algorithms (GA; Holland, 1975; Goldberg, 1989) which consist of optimization procedures based on principles inspired by natural selection. GA involves ‘chromosomal’ representations of proposed problem solutions which undergo genetic operations such as selection, crossover and mutation.

ENC can also use an exogenous centralized control using an external controller $C_1$ (Ferrarini, 2013b)

$$\begin{cases} \frac{dS_1}{dt} = a_{11} S_1 + \dots + a_{1n} S_n + I_1 + O_1 + c_{11*} C_{1*} \\ \dots \\ \frac{dS_n}{dt} = a_{n1} S_1 + \dots + a_{nn} S_n + I_n + O_n + c_{n1*} C_{1*} \\ \frac{dC_1}{dt} = f_1 S_1 + \dots + f_n S_n \end{cases} \quad (10)$$

where asterisks stand for the genetic optimization of exogenous node’s edges (i.e., coefficients of interaction with the inner system) and exogenous node’s stock, i.e. the modification of such values at the beginning of network dynamics in order to get a certain goal (e.g., maximization of the final value of a certain variable). The controller $C_1$ that can also receive feedbacks from the network. that could be subject to control by taming $\langle f_1 \dots f_n \rangle$.

In case 1 controller is not enough, the model in (10) must be expanded to the following *k*-external-controllers model (Ferrarini, 2013b):

$$
\begin{cases}
\dfrac{dS_1}{dt} = a_{11}S_1 + ... + a_{1n}S_n + I_1 + O_1 + c_{11*}C_{1*} + ... + c_{1k*}C_{k*} \\
... \\
\dfrac{dS_n}{dt} = a_{n1}S_1 + ... + a_{nn}S_n + I_n + O_n + c_{n1*}C_{1*} + ... + c_{nk*}C_{k*} \\
\dfrac{dC_1}{dt} = f_{11}S_1 + ... + f_{1n}S_n \\
... \\
\dfrac{dC_k}{dt} = f_{k1}S_1 + ... + f_{kn}S_n
\end{cases}
\quad (11)
$$

However, many ecological (or biological) dynamical systems can be more properly described using difference (recurrent) equations rather than differential ones. This is true for many systems where dynamics happen on discrete time rather than on continuous one.

In this case, Eq. 3 becomes

$$
\begin{cases}
(S_1)_{t+1} = a_{11}(S_1)_t + ... + a_{1n}(S_n)_t + (I_1)_t + (O_1)_t \\
... \\
(S_n)_{t+1} = a_{n1}(S_1)_t + ... + a_{nn}(S_n)_t + (I_n)_t + (O_n)_t
\end{cases}
\quad (12)
$$

ENC solves the control of Eq. 12 using the following centralized approach

$$
\begin{cases}
(S_1)_{t+1} = a_{11*}(S_1)_t + ... + a_{1n*}(S_n)_t + (I_1)_{t*} + (O_1)_{t*} \\
... \\
(S_n)_{t+1} = a_{n1*}(S_1)_t + ... + a_{nn*}(S_n)_t + (I_n)_{t*} + (O_n)_{t*}
\end{cases}
\quad (13)
$$

where asterisks stand for the optimization of edges (i.e., coefficients of interaction among variables) or nodes (i.e., initial stocks), that is the modification of their values at the beginning of the network dynamics in order to get a certain goal (e.g., maximization of the final value of a certain variable).

In this centralized approach (i.e. Eqs. 9, 10, 11 and 13) an arbitrary number of network nodes and links can be tamed.

Instead, in decentralized ENC only one node and the correspondent input/output links are controlled, this being true for all the previous driver equations (Eqs. 9, 10, 11 and 13). In this sense, decentralized ENC can be considered a particular case, computationally very reasonable, of the more general approach used by centralized ENC.

## 3 An Applicative Example

Fig. 2 depicts an *in silico* simulation of a real ecological network. The goal is to preserve target species' occurrence (centre of the network) in the study area.

Greenish nodes represent positive actors or events for the increase or preservation of the target species. Reddish nodes represent ecological actors or events with negative impact on the target species. Bluish nodes represent resources needed by the target species. Stocks stand for the actual amounts of individuals or biomass. Updates stand for yearly internal dynamics (i.e., intra-specific gains due to births and/or immigration rates minus losses due to deaths and/or emigration rates). Minimum and maximum values stand for lowest and highest values of stock values. For the sake of simplicity, the maximum possible value for each actor has been set to 100. Hunters and poachers remain constant (i.e. 10) during the simulation.

The percent value associated to links represent the percentage of the receiver that is yearly consumed by the transmitter at the beginning of the network simulation. Traps mortality and re-introductions accounts for 19 and 10 individuals per year respectively. It should be noted that predators can also gain resources from outside, so their internal dynamics (updates) are not limited to the presence of the target species.

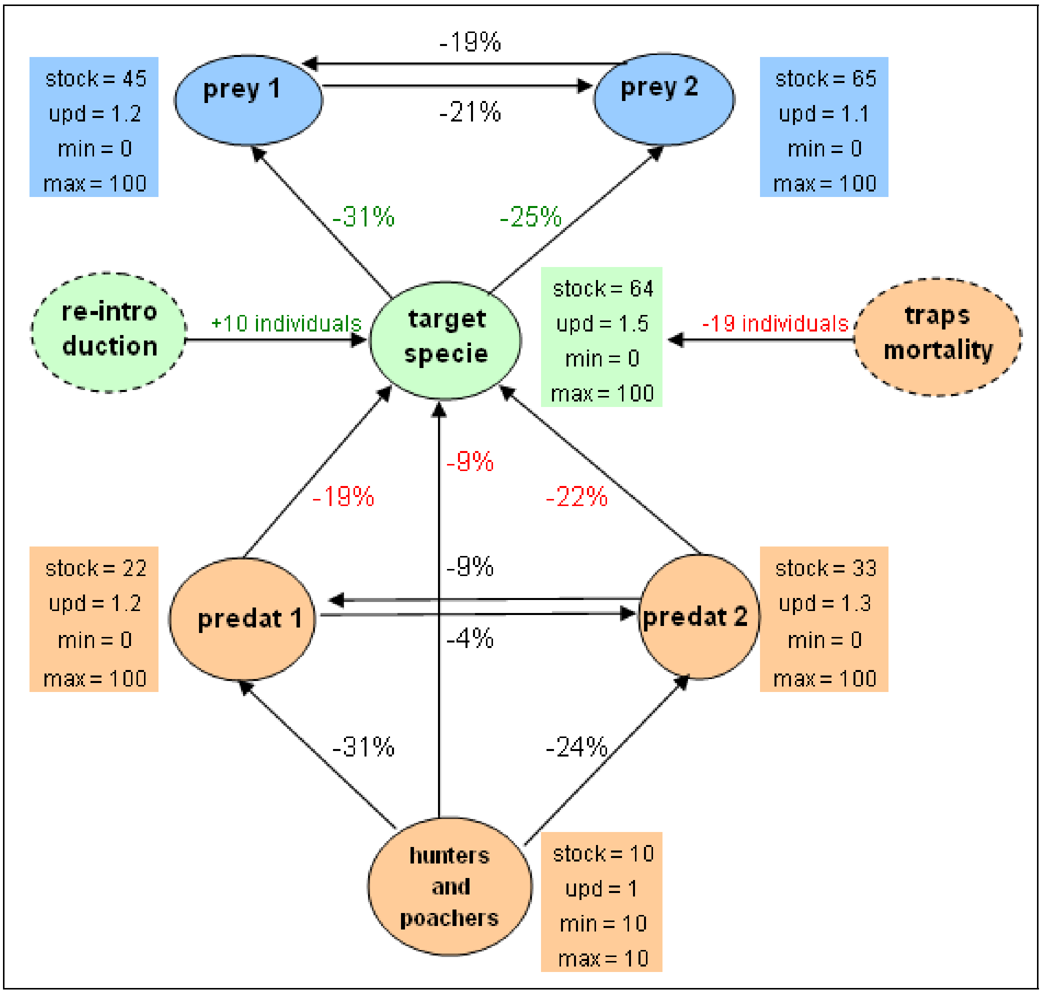


**Fig. 2** Initial conditions of the ecological network under study.

The previous ecological network has the following inertial dynamics (Fig. 3), with equilibrium time $E_T$ = 22 years and the *target species* (green line) disappearing in the studied system after 5 years. The final vector at $E_T$ = 22 is given by <*prey1*=100, *prey2*=0, *target*=0, *predat1*=0, *predat2*=100>.

**Table 1** Parameter declaration corresponding to the ecological network of Fig. 2, calculated using Control-Lab 6 (Ferrarini, 2015c).

| | INITIAL STOCK VALUES | | | | | |
|---|---|---|---|---|---|---|
| | prey1 | prey2 | target | predat1 | predat2 | hunters |
| initial stock | 45 | 65 | 64 | 22 | 33 | 10 |
| min | 0 | 0 | 0 | 0 | 0 | 10 |
| max | 100 | 100 | 100 | 100 | 100 | 10 |

| | INTERACTION MATRIX (yearly flows to receivers per unit of transmitters) | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Receivers | | | | | |
| | | prey1 | prey2 | target | predat1 | predat2 | hunters |
| Transmitters | prey1 | 1.2 | -0.303 | 0 | 0 | 0 | 0 |
| | prey2 | -0.131 | 1.1 | 0 | 0 | 0 | 0 |
| | target | -0.218 | -0.254 | 1.5 | 0 | 0 | 0 |
| | predat1 | 0 | 0 | -0.552 | 1.2 | -0.06 | 0 |
| | predat2 | 0 | 0 | -0.426 | -0.06 | 1.3 | 0 |
| | hunters | 0 | 0 | -0.576 | -0.682 | -0.792 | 1 |

| yearly constant flows | | | | | |
|---|---|---|---|---|---|
| Receivers | | | | | |
| prey1 | prey2 | target | predat1 | predat2 | hunters |
| 0 | 0 | -9 | 0 | 0 | 0 |

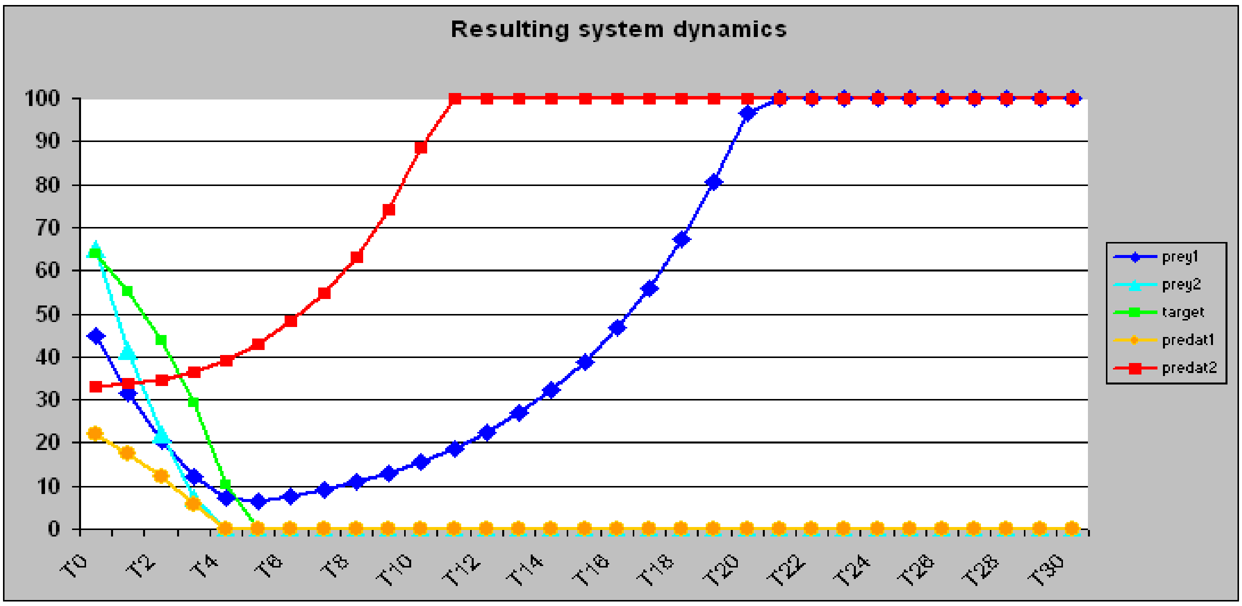


**Fig. 3** Resulting dynamics for the network of Fig. 2. X-axis measures time in years. Dynamics have been calculated using the software Control-Lab 6 (Ferrarini, 2015c).

Now let's suppose we want to safeguard the target species by acting only upon *predat2*. I'll use a decentralized control where only the node *predat2* and its links will be tamed in order to have the target species at its maximum (i.e. 100) once that system dynamics reach the equilibrium. To make the control more realistic, it's opportune that the optimization of the node *predat2* and its links is limited to small changes (e.g. no more than 10% or no more than 20%).

**Table 2** Ten solutions found by ENC to drive the system dynamics so that the target species reaches 100 at equilibrium. In this decentralized approach, ENC has only worked on node *predat2* and on its two links with the target species and with the other predator (*predat1*). The remaining network parameters were kept as in Tab. 1. Solutions have been detected using the software Control-Lab 6 (Ferrarini, 2015c).

| detected solution | stock value of predator2 | self coefficient of predator 2 | interaction upon predator1 | interaction upon target species | equilibrium value of target species | control achieved? |
|---|---|---|---|---|---|---|
| 1 | 31 | 1.22 | -0.07 | -0.36 | 100 | yes |
| 2 | 33 | 1.09 | -0.05 | -0.40 | 100 | yes |
| 3 | 32 | 1.12 | -0.04 | -0.33 | 100 | yes |
| 4 | 32 | 1.10 | -0.05 | -0.30 | 100 | yes |
| 5 | 30 | 1.16 | -0.08 | -0.42 | 100 | yes |
| 6 | 31 | 1.10 | -0.05 | -0.36 | 100 | yes |
| 7 | 32 | 1.17 | -0.08 | -0.39 | 100 | yes |
| 8 | 30 | 1.01 | -0.07 | -0.31 | 100 | yes |
| 9 | 30 | 1.15 | -0.05 | -0.33 | 100 | yes |
| 10 | 30 | 1.26 | -0.05 | -0.34 | 100 | yes |

ENC has found many possible solutions to the decentralized control of the ecological network presented in Fig. 2, ten of which are described in Table 2. All these solutions lead to the same result, i.e. the target species reaches 100 at equilibrium.

It is clear that the decentralized ENC can be applied to any other actor of the network. In addition, one could seek a decentralized solution so that the ecological network reaches the desired solution within a predetermined time interval. For instance, by acting only upon *predat2* we could seek the control of the ecological network of Fig. 2 so that the target species reaches 100 with equilibrium at $T$<10 years. One possible solution detected by decentralized ENC is depicted in Fig. 4.

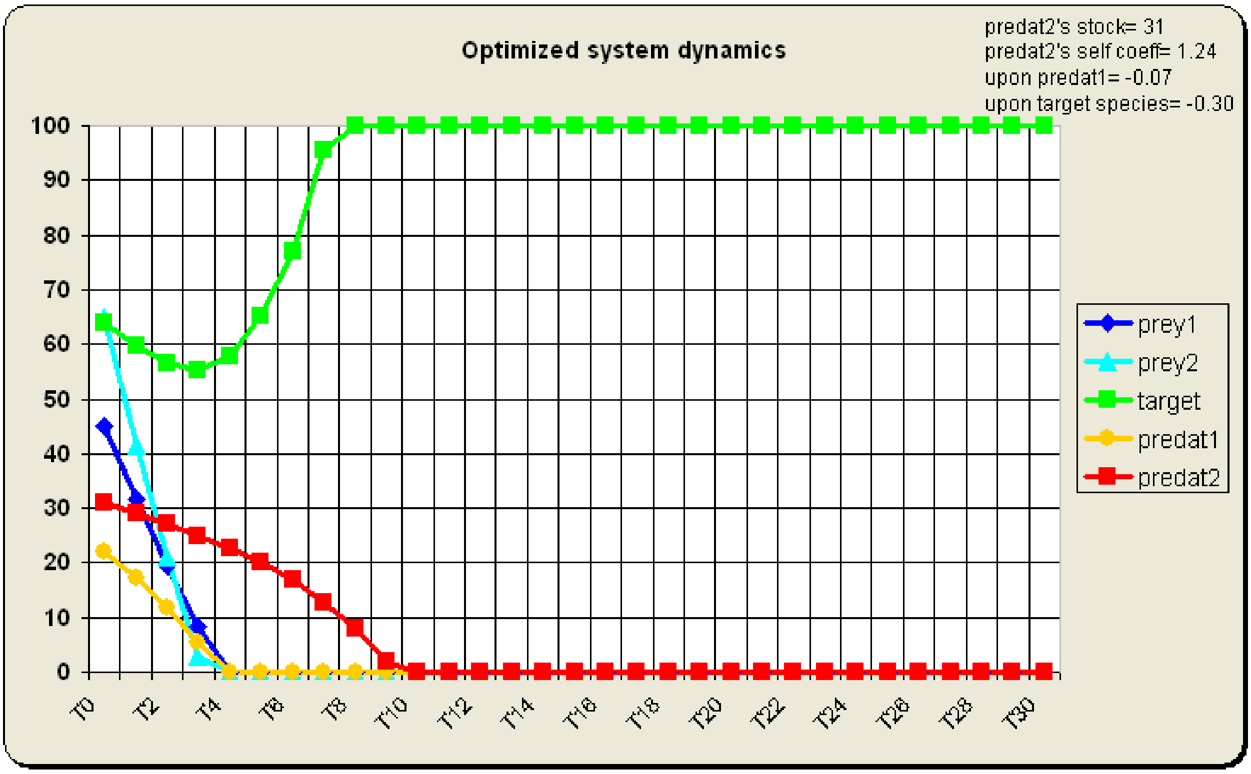


**Fig. 4** A solution detected by ENC to drive the system dynamics so that the target species reaches 100 with equilibrium at $T$<10. In this decentralized approach, ENC has only worked on node *predat2* and on its two links with the target species and with the other predator (*predat1*). The detected model parameters are described on the top right. Solutions have been detected using the software Control-Lab 6 (Ferrarini, 2015c).

The framework proposed here might also be applied to semi-quantitative networks (Ferrarini, 2011b). Decentralized ENC has been applied using the software Control-Lab 6 (Ferrarini, 2015c) written in Visual Basic (Balena, 2001; Pattison, 1998).

## 4 Conclusion

Evolutionary network control (ENC) has been introduced as a centralized methodology where an arbitrary number of network nodes and links could be tamed to drive the network dynamics towards the desired outputs. ENC has shown to be very effective in the control of ecological and biological networks. However a decentralized control, where only one node and the correspondent input/output links are controlled, could be more economic from a computational viewpoint, in particular when the network is very large. In this sense, decentralized ENC results very promising when applied to big data, the new frontier of network dynamics and control.

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