Short Communication

Some steps forward in semi-quantitative networks modelling

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Abstract
System dynamics is an umbrella term for those approaches aiming to understand the behaviour of network-like systems over time. What makes system dynamics different from other methods about complex systems is the use of feedback loops, stocks and flows which allow to model how network-like systems can display strong nonlinear behaviours. Fuzzy Cognitive Maps (FCM) are semi-quantitative networks that can be regarded as a system dynamics method. Here I suggest 4 kinds of modifications to FCM: (1) if-then-else stop option; (2) piecewise option; (3) non-monotonicity option; (4) non-linearity option. These improvements to FCM might allow for fitter simulations of ecological and biological systems over time. I also present an applicative example to illustrate the proposed modifications.

Keywords semi-quantitative networks; fuzzy cognitive maps; if-then-else stops; non-linearity; non-monotonicity; piecewise model.

1 Introduction

Semi-quantitative networks are halfway between qualitative networks (e.g., loop analysis; Puccia and Levins, 1985) and quantitative ones (e.g., ecological network analysis; Ulanowicz, 1986).

Fuzzy cognitive maps (FCM; Kosko, 1986) are semi-quantitative networks which describe the behaviour of a system in terms of concepts (nodes); each concept represents a variable (e.g., species' abundances) or a characteristic of the system. Values of nodes change over time, and take values in the interval [0, 100]: a value of 0 means that the factor is absent, a value of 100 means that the factor is present to the maximum possible extent, while a value of 50 represents the actual level of system variables. The causal links between nodes are represented by directed weighted edges that illustrate how much one concept influences the interlinked concepts, and the causal weights of the interconnections belong to the [-1, +1] interval. The strength of the weight w_{ij} indicates the degree of influence between concept C_i and concept C_j. The value of each concept at every simulation step is calculated as follows:

$$A_j(t) = A_j(t-1) + \sum_i A_i(t-1) * w_{ij} \qquad (1)$$

where $A_j(t)$ is the value of concept C_j at time t, $A_j(t\text{-}1)$ is the value of concept C_j at time t-1, w_{ij} is the weight of the interconnection from concept C_i to concept C_j.

FCM are particularly useful for applications where relationships between concepts cannot be expressed in exact mathematical equations. Much human expert knowledge is expressed in natural language, which is characterised by this type of uncertainty and imprecision. Biological and environmental quantities and their causal interactions are often described in relative and vague terms. A large proportion of the ecological information is represented in this way, and cannot be used as an input to data-driven mathematical or statistical models. The main advantage of FCM relies in its ability to represent such fuzziness. Recent applications can be found in Kok (2009), Prigent et al. (2008), Ramsey and Veltman (2005).

2 An Example

Let's consider an environmental system with 4 interacting variables (e.g., 4 species in a plant community). The matrix below depicts the existing interactions among variables.

Fig. 1 shows the simulation results for the depicted system

Table 1 On the left, initial values. On the right interaction matrix among variables.

Initial values			
var A	var B	var C	var D
50	50	50	50

Variable interactions				
	var A	var B	var C	var D
var A	1	0.4	-0.6	0.1
var B	-0.8	1	0.3	0.7
var C	0.3	-0.2	1	-0.8
var D	0.4	-0.5	0.1	1

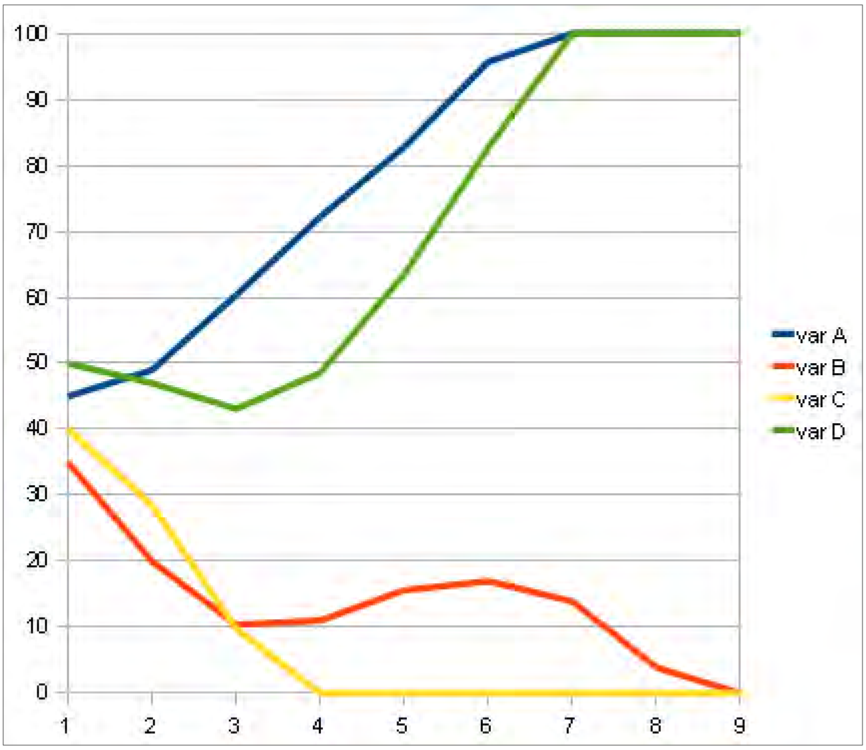

Fig. 1 Results of the application of FCM to the environmental system of Table 1.

There a 2 winning species (A and D) and 2 losers (B and C). While A and C respectively always increases and decreases, species B and D present a more complex behavior, sometimes increasing and sometimes decreasing. The system reaches a steady final state with B and C imploding to 0 (i.e. they disappear), while A and D reach their maximum possible extent (i.e., 100).

3 Some Steps Forward

The previous example shows how linear feedbacks can produce dynamics that are strongly non-linear. The ability to capture the effect of feedbacks and produce non-linear system changes is exactly where the strength of FCM lies. Nonetheless, I suggest here 4 kinds of modifications to FCM:

a) if-then-else stop option;
b) piecewise option;
c) non-monotonicity option;
d) non-linearity option.

3.1 If-then-else stops

Let's suppose that species B is important from a preservation viewpoint, and that management actions start when species B reaches about one-half (i.e. 25) its initial abundance in order to keep it almost constant. Hence, FCM should be able to incorporate an if-then-else stop condition (Fig. 2) so that system dynamics stop when species B reaches a value equal to about 25.

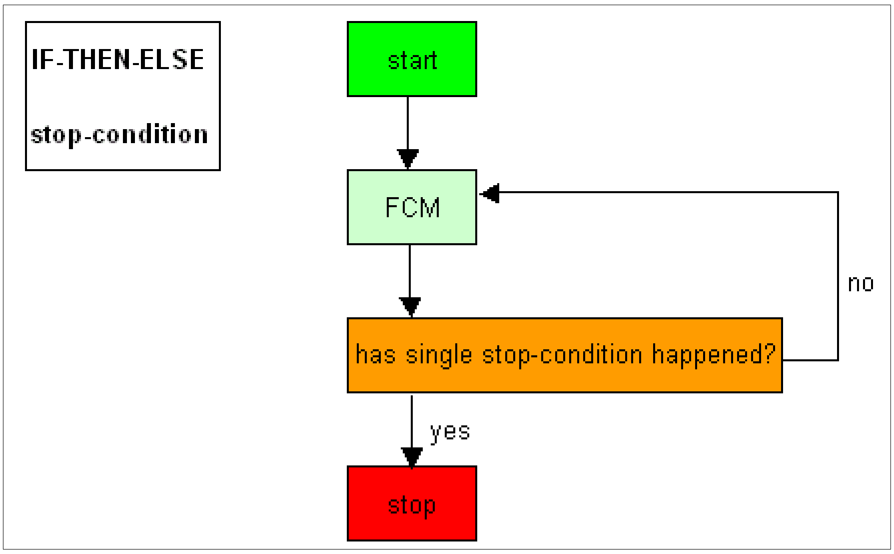

Fig. 2 Conceptual model of if-then-else stop option for FCM.

If applied to the starting example, the final (if-then-else stopped) state would be: A= 49; B= 20; C= 28, D= 47. We could consider that if-then-else stop may act on multiple conditions (Fig. 3), for instance that a stop condition happens when both species A and D are above 60 (i.e. 120% of the initial vales). In this case, the final (if-then-else stopped) state would be: A= 82; B= 15; C= 0, D= 63.

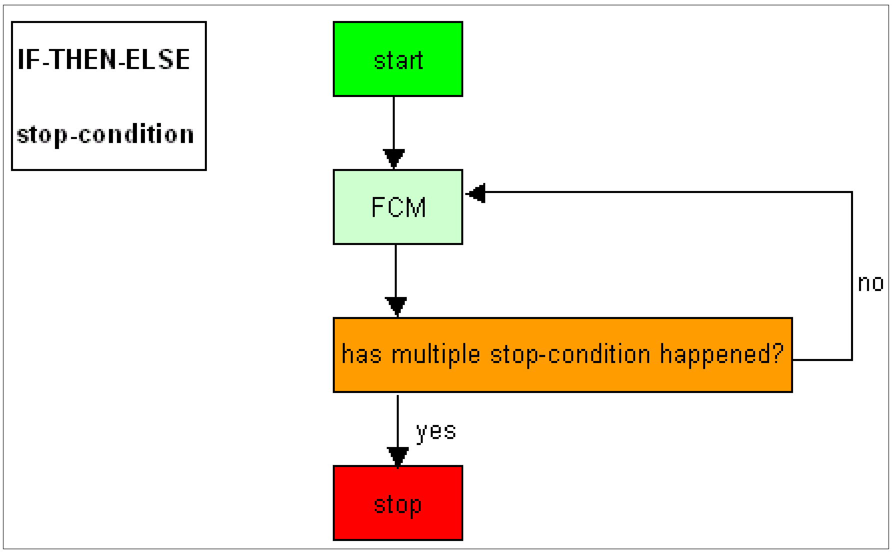

Fig. 3 Conceptual model of multiple if-then-else stops option for FCM.

3.2 Piecewise option

Piecewise option (Fig. 4) may simulate real-world events. For instance, the fishing pressure on a particular species might change depending on the abundance of the species itself. Also the hunting pressure on invasive species might change based on the abundance of such species. This often happens in the real world, where predator-prey interactions change over time depending on the abundance of both the prey and the predator. Let's consider that the negative effect of A on C decreases from -0.6 to -0.3 when C goes below 40 (i.e., 80% of its initial abundance).

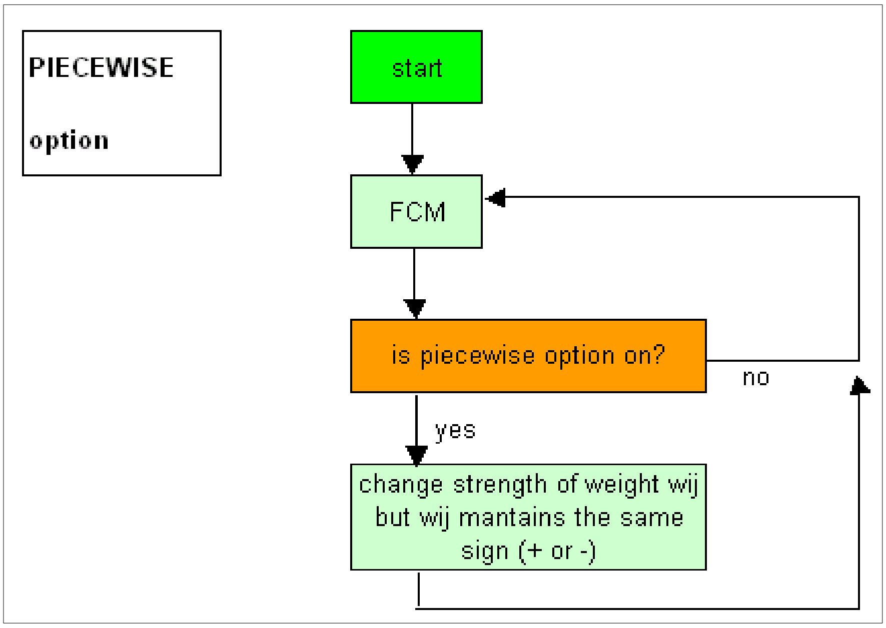

Fig. 4 Conceptual model of piecewise option for FCM.

If applied to the starting example, the system dynamics would be like in Fig. 5. Although the final state is the same as in Fig. 1, the intermediate states are very different.

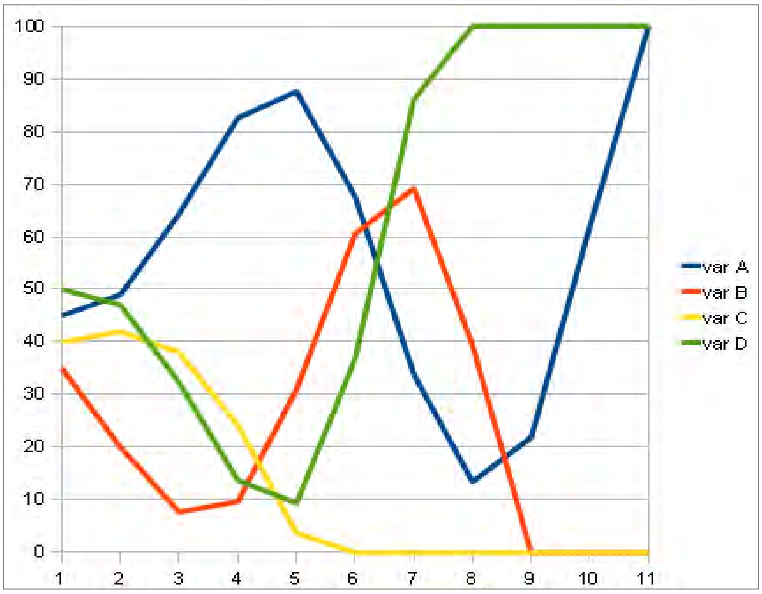

Fig. 5 Results of the application of a piecewise option to the environmental system of Table 1.

3.3 Non-monotonicity option

Non-monotonicity option for FCM (Fig. 6) is similar to piecewise one, but it's more drastic since it requires that the effect of a variable on another one changes during simulation time. For instance, let's suppose that the effect of species A on species C becomes positive (+0.2) as C goes below 40 (i.e., 80% of its initial abundance). If applied to the starting example, the system dynamics would be like in Fig. 7. Both the final and intermediate states are very different from Fig. 1.

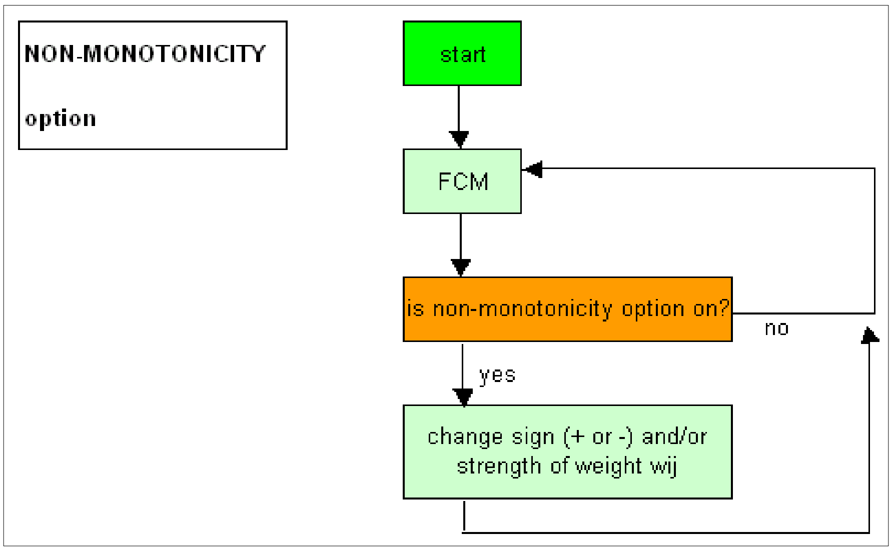

Fig. 6 Conceptual model of non-monotonicity option for FCM.

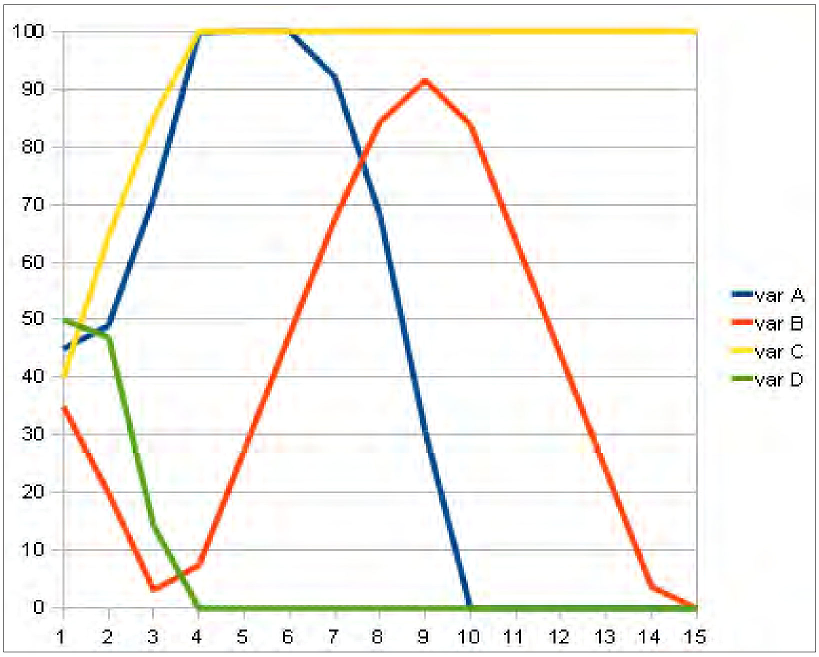

Fig. 7 Results of the application of a non-monotonicity option to the system of Table 1.

It's interesting to note that species B reaches high values (>90), but then it quickly decreases when species A disappears from the system.

3.4 Non-linearity option

Last, I conceive that the updating rule for one or more species may become non-linear (Fig. 8). For instance, let's simulate that the update of the positive effect of species A on species B may become quadratic after C goes below 10 (i.e., 20% of its initial abundance). If applied to the starting example, the system dynamics would be like in Fig. 9.

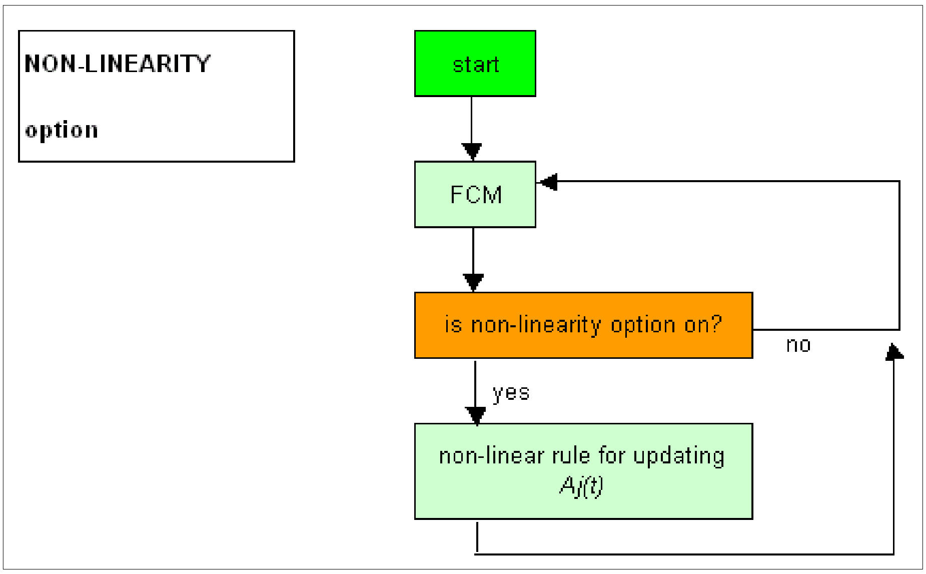

Fig. 8 Conceptual model of non-linearity option for FCM.

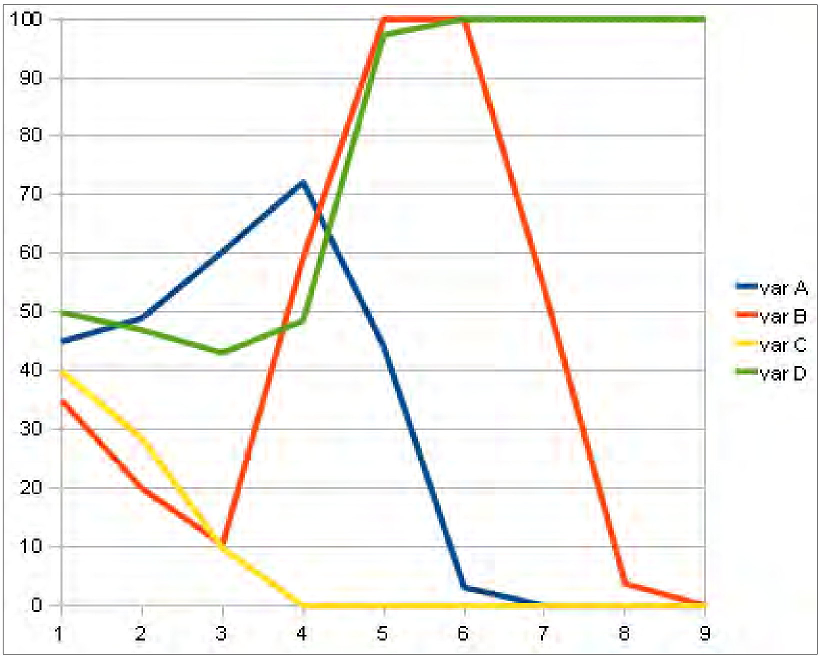

Fig. 9 Results of the application of a non-linearity option to the system of Table 1.

It's interesting to note that species B reaches its maximum possible value (100), but then it rapidly decreases when species A disappears from the system.

4 Discussion and Conclusions

FCM are a valuable tool for the simulation of biological and ecological systems over time. They: a) provide a lucid representation of complex systems, b) focus on indirect effects, c) force users to be explicit on relationship strengths, d) are reasonably parsimonious with regard to model building complexity, e) produce dynamics that are strongly non-linear.

Nonetheless, I have suggested here four improvements to FCM to fitter represent the complexity of real-world systems. I am aware that the proposed improvements make FCM less parsimonious, but I also claim that from a benefit-cost viewpoint the proposed improvements are rich in significance and implications.

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