The Relevance of Fuzzy Cognitive Mapping Approaches for Assessing Adaptive Capacity and Resilience in Social–Ecological Systems

Frédéric Vanwindekens, Didier Stilmant, Philippe Baret

The Relevance of Fuzzy Cognitive Mapping Approaches for Assessing Adaptive Capacity and Resilience in Social–Ecological Systems

Frédéric M. Vanwindekens[1,2], Didier Stilmant[2], and Philippe V. Baret[1]

[1] Université catholique de Louvain – Earth and Life Institute – Agronomy, Agroecology
Croix du Sud 2 bte L7.05.14, B–1348 Louvain-la-Neuve, Belgium
{frederic.vanwindekens,philippe.baret}@uclouvain.be
[2] Walloon Agricultural Research Centre – Agriculture and Natural Environment Department – Farming Systems, Territory and Information Technologies Unit
Rue du Serpont 100, B–6800 Libramont, Belgium
{f.vanwindekens,stilmant}@cra.wallonie.be

Abstract. Social–Ecological Systems (SES) are complex due to uncertainty related to their nature and their functions. In these systems, decision-making processes and practices of managers are often value-laden and subjective, dominated by their world-views and their own knowledge. People's knowledge are central in building their adaptive capacity but are seldom taken into account by traditional decision-making approaches in modelling SES management. In this paper, we introduce a Fuzzy Cognitive Mapping approach to study the dynamic behaviour of managers' systems of practices. As a case study, we aim to assess farmers' forage management under different climatic scenarios. Results show that summer drought have varying consequences according to farmers' systems of practices. Fuzzy Cognitive Mapping approaches are particularly relevant in studying systems of practices in SES. Their utilisation is promising for the evaluation of adaptive capacity and resilience in SES at local scale (exploitation, community) and regional scale (ecological areas, country).

Keywords: Agriculture, Social–Ecological Systems, Systems of Practices, Fuzzy Cognitive Mapping, Resilience Assessment

1 Introduction

The management of Social–Ecological Systems (SES, [7]) is complex due to the intricacy of their components, to the uncertainty related to their nature and to the various societal, institutional, physical, ecological, economical processes involved in their functions [1]. Managers' strategies are largely influenced by their perceptions of the ecological, economical and social environments of SES [1]. These influences have been particularly pointed out and studied in the agricultural context [3, 4, 9]. In order to help farmers in managing their farm, Decision

Support Systems (DSS) have been developed by 'management scientists' [13]. But unexpectedly, farmers pay little attention to these DSS [1, 4, 13, 16].

Recent scientific approaches have been developed to cope with incorporation of human, social and institutional aspects in SES models by explicitly accommodating relations between the natural and human environment [1]. Fuzzy cognitive maps (FCM) are particularly relevant tools in modelling SES based on people explicit knowledge [16] as they can be considered as a model of a belief system [11] constituted by concepts, the key drivers of the system, and edges, causal relationships between concepts. They have been developed by Bart Kosko in 1986 [12] in introducing the notion of 'fuzziness' and 'fuzzy weigth' to relationships of Robert Axelrod's cognitive maps (CM) [2].

In the agricultural context (see [23]), CM and FCM have been successfully applied for (i) analysing people knowledge, beliefs [19] and decision-making on farm [10], (ii) studying adoption of agri-environment measures [15], (iii) modelling farmers perceptions of how their ecosystem works [5] and of the sustainability of farms [6], and (iv) predicting yield production [17, 18]. In order to study farmers' systems of practices (SOP) based on their own conceptions, we developed an approach for building cognitive maps by coding people's open-ended interviews. This approach was named CMASOP for 'Cognitive Mapping Approach for Analysing Actors' Systems of Practices' in SES. In a previous paper, we presented the core principles of CMASOP [23]. In this first publication, we applied CMASOP to the general description of farmers' SOP for managing grasslands in two Belgian agroecological areas [23]. In a second step, we developed complementary applications of CMASOP : a comparative one and a typological one. For comparing SOP between groups of managers defined *a priori*, we coupled CMASOP and descriptive statistical methods. For classifying SOP in *a posteriori* typological groups, we coupled CMASOP, clustering methods and statistical analysis. Results of the comparative and typological applications of CMASOP are being submitted [22].

In the present paper, we coupled CMASOP and auto-associative neural networks methods [16] for carrying out inferences about farmers' adaptations to climatic uncertainties. The objectives of this development is to model the dynamic behaviour of managers' SOP for assessing their adaptive capacity, and indirectly, the resilience of their SES. The aim of this paper is to present this new development of CMASOP and to demonstrate the relevance of using FCM approaches for assessing adaptive capacity of managers and resilience of their exploitation in social–ecological systems. The management of the second cut in grassland based livestock farming systems of southern Belgium is used as a case-study.

Resilience is defined by Folke *et al.* as the "*capacity of a system to absorb disturbance and reorganize [...]*" [7]. Adaptive capacity is defined as the "*capacity of actors in a system to influence resilience*" [7]. Different studies have used FCM for scenario analysis in SES [16, 11, 21, 26]. They rely on the possibility to compare the steady state calculation under various conditions : (i) current situation, (ii) evolution of some environmental variables (prices, rainfall) or (iii) implementation of different policy options (laws, tax). These concepts are closed to the concept of 'vulnerability' that has been analysed using FCM by Murungweni *et al.* (2011) in the study of livelihood [14].

2 Materials and Methods

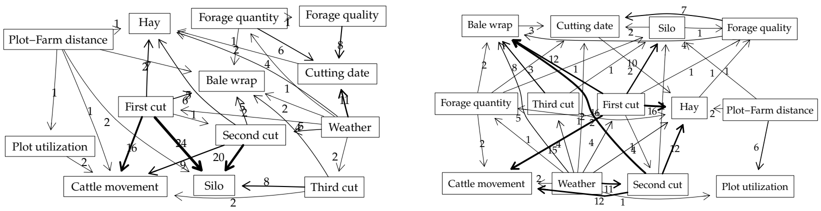
We studied farmers' Systems of practices (SOP) in Ardenne and Famenne, two grassland based agroecological areas in southern Belgium. We collected qualitative and quantitative data during forty-nine open-ended interviews on management of farms systems (structure, technical orientation, world views) and subsystems (forage, herd, grazing). We developed a cognitive mapping based approach for analysing systems of practices (CMASOP[3][23, 22]). We applied it for studying grass forage management in our surveyed area.

The core principles of CMASOP consists in coding open-ended interviews of managers in order to create individual cognitive maps (ICM). These ICM can then be used to build a social cognitive map (SCM). As open-ended interviews focus on managers practices in social-ecological systems (SES), the ICM and SCM are considered as inductive models of SOP based on people conceptions [23]. The SCM is *inter alia* constituted by thirteen highly related concepts classed in seven core hubs (First, Second and Third cuts, Silo, Bale wrap, Hay and Cattle movement) and six peripheral hubs (Plot utilization, Plot-Farm distance, Forage quality, Forage quantity, Cutting date and Weather). A quote-retrieving module has been implemented in order to permanently relate each relationships to managers' quotations.

We developed applications for using CMASOP in comparative and typological ways [22]. Differences in SOP between groups of managers can be highlighted in coupling CMASOP and descriptive statistical methods. Typology of systems of practices can be processed by coupling CMASOP, clustering methods and statistical analysis. These developments have been applied to our case study, grass forage management in farming systems. The clustering of SOP in these systems highlighted two contrasted groups of farmers based on the management of their second grass cut(figure 1). The first group of farmers (A, n=24, figure 1(a)) are more prone for silaging (20) than they are for bale wrapping (5) or haying (5). Conversely, the second group of farmers (B, n=25, figure 1(b)) are more prone for bale wrapping (16) and haying (12) than they are for silaging (1). As a result of previous works, the drought has been quoted by farmers as a typical risk in grassland management in Famenne. The potential drought mainly occurs during the summer and have damageable consequences on grass growth and, in parallel, on milk production and animal performances in general. In order to cope with drought, farmers' adaptations are contrasted : grazed area increase or supplementation in grazing plots.

The two SCM (figures 1) have been taken as patterns to build two synthetic FCM (figures 2) for studying systems resilience and farmers' adaptive capacity

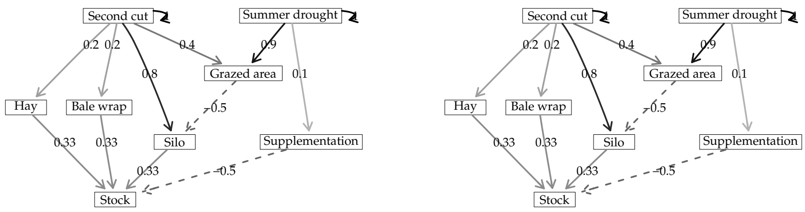
[3] CMASOP was developed in R [20]. Figures 1 and 2 were done using Rgraphviz [8]. Figures 3 and 4 were made using ggplot2 [25]



(a) Core of the social map of SOP A cluster, based on silaging

(b) Core of the social map of SOP B cluster, based on bale wrapping and haying

Fig. 1. The 49 farmers' Systems of Practices (SOP) have been classified in two groups using the clustering application of CMASOP [22]. Farmers of the first cluster (A) are specialized and have SOP based on silaging. Farmers of the second cluster (B) are more diversified and have SOP based on bale wrapping and haying. The social maps of two clusters of SOP have been used to build and calibrate two synthetic FCM used in the present study (figure 2)



(a) FCM of the SOP A cluster based on silage

(b) FCM of the SOP B cluster based on bale wrap and hay

Fig. 2. FCM of the two different Systems of Practices assessed. Weights of relationships are illustrated by the saturation of the gray : from white (i.e. invisible,0) to black (1). Signs of relationships are illustrated by the type of line : continuous (positive) or dashed (negative). Values of relationships weights are shown besides relationships.

linked with summer drought. These synthetic FCM show the grassland plots allocated for harvesting (Silo, Bale wrap, Hay) or for grazing (Grazed area). The weights of relationships between Second cut and these four concepts are proportional to their weights in the SCM of the two clusters (0.8, 0.2, 0.2 and 0.4 respectively in A and 0, 0.6, 0.4 and 0.4 in B). We considered that the products harvested on cutting plots constitute the Stock of forage (0.33 for Hay, Bale wrap and Silo in A ; 0.5 for Hay and Bale wrap in B). In case of Summer drought, two adaptations are simulated : the increase of Grazed area (0.9 for A, 0.1 for B) or the Supplementation of forage in grazed plots (0.1 in A, 0.9 in B). The increase of Grazed area involve a decrease of the harvested area (-0.5 for Silo in A and -0.25 for Bale wrap and Hay in B). Two self-reinforcing relationships have been added for the driver concepts Second cut and Summer drought.

Farmers are more prone to distribute forage conditioned in Bale wrap or in Hay, available in individual elements (bales), than to open a whole Silo done with the harvest of the first cut. Therefore, farmers of the cluster B have the possibility to supplement herd in grazing plots because their stock are mostly constituted by Bale wrap and Hay. For the simulations, we supposed that these farmers choose to cope with Summer drought in supplementing. Conversely, farmers of cluster A has only few Bale wrap and Hay in their Stock. For simulations, we supposed then that these farmers choose the other adaptation, in increasing of Grazed area. For the same reason, we supposed that the reduction of Grazed area for these farmers (A) only affect the most important conditioning, Silo.

The simulations have been processed using the auto-associative neural networks method described by Özesmi and Özesmi [16] in order to calculate the activation degrees of each concepts at all time steps till convergence. Activation degrees are semi-quantitative values of concepts that can only be interpreted relative to each other [11]. The two scenarios have been implemented in forcing the activation degree of Summer Drought to 0 ('No Summer Drought') or 1 ('Summer Drought').

3 Results

Figure 3 shows the comparisons of the scenarios 'No Summer Drought' and 'Summer Drought' for the two Systems of Practices (SOP) assessed. The evolution of the two driver concepts ('Second cut' and 'Summer drought') is logically not shown nor analysed.

For SOP A cluster based on silaging, (i) the activation degree of Grazed area strongly increase from 0.380 (No Summer Drought) to 0.862 (Summer Drought), (ii) the activation degree of Supplementation slightly increase from 0.000 to 0.100, (iii) the activation degrees of Silo and of Stock decrease from 0.544 and 0.300 respectively to 0.353 and 0.194 respectively (table 1).

For SOP B cluster based on bale wrapping and haying, (i) the activation degree of Supplementation strongly increase from 0.000 to 0.716 while (ii) the activation degree of Stock strongly decrease from 0.246 to -0.118, (iii) the acti-

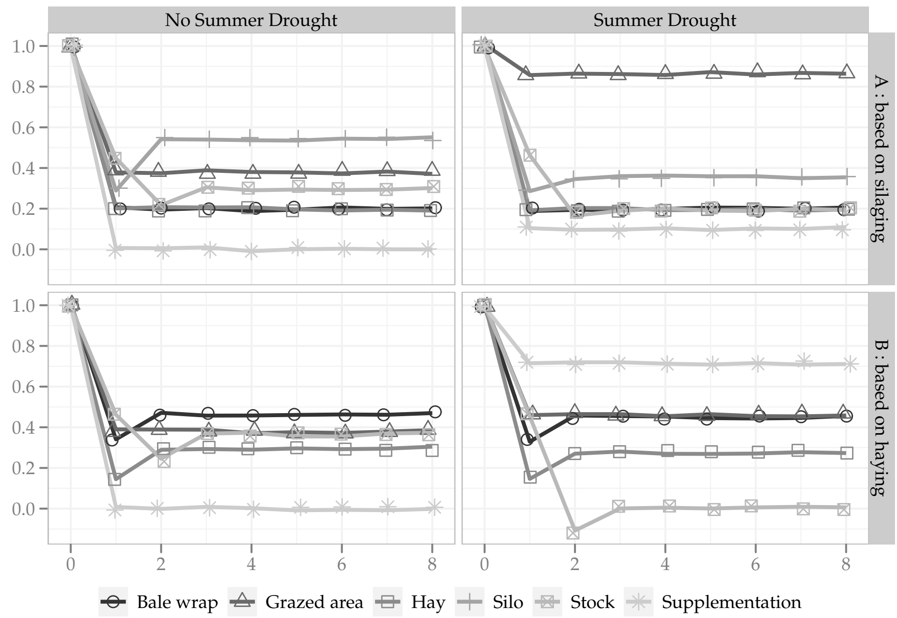


Fig. 3. Evolution of activations degrees of concepts in the four Fuzzy Cognitive Maps. Comparisons of the scenarios 'No Summer Drought' and 'Summer Drought' for the two Systems of Practices (SOP) assessed : A (SOP based on silaging) and B (SOP based on bale wrapping and haying). X-axis: iteration step, Y-axis: activation degree

vation degree of Grazed area increase from 0.380 to 0.462 and (iv) the activation degrees of Bale wrap and Hay slightly decrease from 0.466 and 0.296 respectively to 0.450 and 0.277 respectively (table 1).

The increases of Grazed area for SOP A cluster and of Supplementation for SOP B cluster are adaptations of each groups of farmers in case of Summer drought (figure 4). In the FCM of SOP A cluster, a direct consequence of increasing of Grazed area is the decrease of Silo and a subsequent decrease of Stock that is limited. In the case of SOP B cluster, as a direct consequence of the increase of Supplementation, FCM shows a decrease of the activation degree of Stock more important than for SOP A cluster (figure 4).

4 Discussion and conclusion

This article presents an original method for assessing managers' adaptive capacity under uncertain environmental conditions. This method gain in coherence and relevance through its integration in CMASOP, a complete Cognitive Mapping approach [23, 22]. The method is grounded on various kind of qualitative data collected during open-ended interviews. Its descriptive application allows

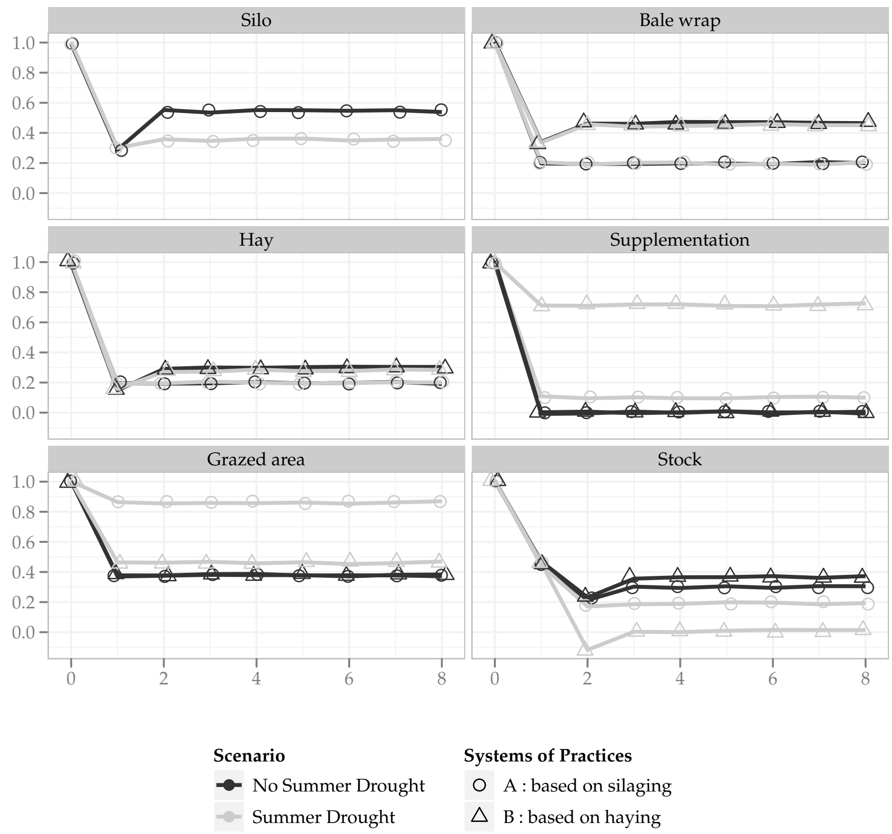


Fig. 4. Evolution of activations degrees of major concepts in the four Fuzzy Cognitive Maps. Comparisons of the adaptations of the two Systems of Practices (SOP) to cope with 'Summer Drought'. X-axis: iteration step, Y-axis: activation degree

to inductively model SOP of individual and groups of managers based on their own conceptions of their system. Its comparative and typological applications allow to objectively compare and cluster SOP. Finally, CMASOP allows to construct FCM of managers' SOP. In computing the steady states of FCM of various SOP under various environmental conditions, it is relevant in assessing adaptive capacity of managers in complex SES.

This paper present a first application of FCM for studying SOP in SES. The SOP we model are basic in terms of concepts and relations. As a consequence, the dynamic behaviours of the FCMs are elementary. Nevertheless, results confirm influences of farming practices on the whole functioning of the production system. They confirm also that various systems of practices have various effects on the system.

Beyond these results that could appear as relatively evident, results shows the possibility to model a wide variety of SOP in a simple way in order to assess them under various scenarios. The easy way of building model and simulating scenarios is a major advantage of the method presented. We illustrate it in processing further simulations in order to test two other SOP : C, based on a mixed sources of harvested forage (0.33 silo, 0.33 bale wrap and 0.33 hay) and D, whose stock is only constituted by purchased feed. Results are shown in table 1. Technically, our tool is easy-to-use for researchers or even for farmers : the relations and their weights are entered in a spreadsheet that is subsequently processed by an R program [20].

Table 1. Values of activations degrees of major concepts at steady states. Eight simulations are compared. Four Systems of Practices (SOP) : A, based on silageing ; B, based on haying ; C, based on mixed sources and D, feed purchasing. Two climatic scenarios : Normal (No Summer Drought) and Drought (Summer Drougth)

	SOP–A		**SOP–B**		**SOP–C**		**SOP–D**	
	Normal	Drought	Normal	Drought	Normal	Drought	Normal	Drought
Silo	0.544	0.353			0.259	0.205		
Bale wrap	0.197	0.197	0.466	0.450	0.259	0.205		
Hay	0.197	0.197	0.296	0.277	0.259	0.205		
Supplementation	0.000	0.100	0.000	0.716	0.000	0.462	0.000	0.462
Grazed area	0.380	0.862	0.380	0.462	0.380	0.716	0.762	0.762
Stock	0.300	0.194	0.364	0.005	0.251	−0.028	0.000	−0.432

Comparisons of two SOP in case of Summer drought showed differences in terms of Stock between farmers' FCM. These differences could also have significant consequences on concepts not modelled in the present study : feeding of herd during the winter (stocks are smaller), cows selling (stocks are insufficient) or feed purchase (for restoring stocks), treasury (due to purchasing) and, finally, resilience of the whole farms. Although these concepts are beyond the scope of our model, this reasoning illustrates how resilience of farms and adaptive capacity of farmers could be assessed using FCM approaches.

Most of previous studies of managers' practices in SES were conducted in a qualitative way by social scientists or modelled in reductionist DSS. The twofold nature of FCM (qualitative and quantitative) bring another advantage to our method. It allows building SOP model based on people's knowledge and processing simulations.

Further works could include developments of more elaborated FCM including various indicators of economic fields (e.g. production, profit), ecological sciences (e.g. environmental footprint) or social sciences and psychology (e.g. personal fulfilment, happiness). It has not escaped our notice that the broadening of the map could represent an opportunity of measuring resilience of social–ecological systems at local or regional scales.

As asserted by van Vliet *et al.* (2010, [24]), FCM could be a relevant communication and learning tools between managers and scientists. It would be very interesting to carry out qualitative surveys in order to discuss the results of FCM simulations and adaptive capacity assessment with managers of SES. The results of these surveys could also constitute relevant data for an inductive and qualitative evaluation of resilience and adaptive capacity.

Acknowledgements. The Walloon Agricultural Research Centre provided financial support for this work through the MIMOSA project. We would also like to thank two anonymous reviewers for their helpful comments.

References

1. Ascough, II, J.C., Maier, H.R., Ravalico, J.K., Strudley, M.W.: Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. Ecological Modelling 219(3-4, Sp. Iss. SI), 383–399 (2008)
2. Axelrod, R., Institute of public policy studies (Ann Arbor, M., Institute of international studies (Berkeley, C.: Structure of decision: The cognitive maps of political elites. Princeton University Press Princeton, NJ (1976)
3. Darré, J., Mathieu, A., Lasseur, J.: Le sens des pratiques. Conceptions d'agriculteurs et modèles d'agronomes. Science Update, INRA Editions (2004)
4. Edwards-Jones, G.: Modelling farmer decision-making: concepts, progress and challenges. Animal Science 82(Part 6), 783–790 (2006)
5. Fairweather, J.: Farmer models of socio-ecologic systems: Application of causal mapping across multiple locations. Ecological Modelling 221(3), 555–562 (2010)
6. Fairweather, J., Hunt, L.: Can farmers map their farm system? causal mapping and the sustainability of sheep/beef farms in new zealand. Agriculture and Human Values 28(1), 55–66 (2011)
7. Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T., Rockstrom, J.: Resilience thinking: Integrating resilience, adaptability and transformability. Ecology and Society 15(4) (2010)
8. Gentry, J., Long, L., Gentleman, R., Falcon, S., Hahne, F., Sarkar, D., Hansen, K.: Rgraphviz: Provides plotting capabilities for R graph objects (2010)
9. Ingram, J., Fry, P., Mathieu, A.: Revealing different understandings of soil held by scientists and farmers in the context of soil protection and management. Land Use Policy 27(1), 51 – 60 (2010)
10. Isaac, M., Dawoe, E., Sieciechowicz, K.: Assessing local knowledge use in agroforestry management with cognitive maps. Environmental Management 43(6), 1321–1329 (2009)
11. Kok, K.: The potential of fuzzy cognitive maps for semi-quantitative scenario development, with an example from brazil. Global Environmental Change 19(1), 122 – 133 (2009)
12. Kosko, B.: Fuzzy cognitive maps. International Journal of Man-Machine Studies 24(1), 65–75 (1986)
13. McCown, R.L.: Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. Agricultural Systems 74(1), 179–220 (2002)
14. Murungweni, C., van Wijk, M., Andersson, J., Smaling, E., Giller, K.: Application of fuzzy cognitive mapping in livelihood vulnerability analysis. Ecology and Society 16(4) (2011)

15. Ortolani, L., McRoberts, N., Dendoncker, N., Rounsevell, M.: Analysis of farmers' concepts of environmental management measures: An application of cognitive maps and cluster analysis in pursuit of modelling agents' behaviour. In: Glykas, M. (ed.) Fuzzy Cognitive Maps, Studies in Fuzziness and Soft Computing, vol. 247, pp. 363–381. Springer Berlin Heidelberg (2010)
16. Özesmi, U., Özesmi, S.L.: Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. Ecological Modelling 176(1-2), 43 – 64 (2004)
17. Papageorgiou, E., Markinos, A., Gemtos, T.: Fuzzy cognitive map based approach for predicting yield in cotton crop production as a basis for decision support system in precision agriculture application. Applied Soft Computing Journal 11(4), 3643–3657 (2011)
18. Papageorgiou, E., Aggelopoulou, K., Gemtos, T., Nanos, G.: Yield prediction in apples using fuzzy cognitive map learning approach. Computers and Electronics in Agriculture 91, 19–29 (2013)
19. Popper, R., Andino, K., Bustamante, M., Hernandez, B., Rodas, L.: Knowledge and beliefs regarding agricultural pesticides in rural guatemala. Environmental Management 20(2), 241–248 (1996)
20. R Development Core Team: R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing (2009)
21. Soler, L.S., Kok, K., Camara, G., Veldkamp, A.: Using fuzzy cognitive maps to describe current system dynamics and develop land cover scenarios: a case study in the brazilian amazon. Journal of Land Use Science iFirst(0), 1–27 (2011)
22. Vanwindekens, F.M., Baret, P.V., Stilmant, D.: Using a cognitive mapping approach for studying diversity of farmers' systems of practices in agricultural systems, working paper
23. Vanwindekens, F.M., Stilmant, D., Baret, P.V.: Development of a broadened cognitive mapping approach for analysing systems of practices in social–ecological systems. Ecological Modelling 250(0), 352 – 362 (2013)
24. van Vliet, M., Kok, K., Veldkamp, T.: Linking stakeholders and modellers in scenario studies: The use of fuzzy cognitive maps as a communication and learning tool. Futures 42(1), 1–14 (2010)
25. Wickham, H.: ggplot2: elegant graphics for data analysis (2009)
26. Wise, L., Murta, A., Carvalho, J., Mesquita, M.: Qualitative modelling of fishermen's behaviour in a pelagic fishery. Ecological Modelling 228, 112–122 (2012)