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The potential of Fuzzy Cognitive Maps for semi-quantitative scenario development, with an example from Brazil

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ABSTRACT

The main drawback of the Story-and-Simulation approach is the weak link between qualitative and quantitative scenarios. A semi-quantitative tool, Fuzzy Cognitive Mapping, is introduced as a possible improvement. An example from the Brazilian Amazon shows that by including an integrated set of factors and feedbacks, Fuzzy Cognitive Maps can capture (future) dynamics of deforestation. The example substantiates the tool's capacity to improve the consistency of narrative storylines and the diversity of quantitative models. The tool is designed, however, to be simple and therefore has important drawbacks. Future improvements should be made in the light of applications within a larger toolbox of scenario methods.

1. Introduction

The world is undergoing rapid changes while globalising constantly, which gives the consideration of the future new urgency and importance. Scenario development has emerged as a key method when taking a long-term view, especially when attempting to harmonise socioeconomic and environmental goals (Raskin et al., 1998; Kok et al., 2007). Scenarios are developed specifically to consider a variety of possible futures, rather than to focus on acquiring an accurate, single-outcome prediction. Scenarios are intended to be used predominantly in situations where factors shaping the future are highly uncertain and largely uncontrollable (Peterson et al., 2003).

1.1. Story-and-Simulation

Scenario development is a relatively new tool in the field of environmental sciences, and consequently there is no agreement on what the tool exactly entails. We define a scenario as a story about the future that can be told in both words and numbers, offering an internally consistent and plausible explanation of how events unfold over time (Gallopín et al., 1997; Raskin et al., 2002). The key element in the context of this paper is that scenarios can be either qualitative (told in words) or quantitative (told in numbers). In that spirit, many of the recent (global) scenario exercises have been structured as what has become known as a Story-and-Simulation (Fig. 1) approach (Alcamo, 2001).

Alcamo (2001) describes a 10-step approach where narrative storylines are developed and linked to dynamic models in an iterative procedure. Stories are developed by a stakeholder panel consisting of the relevant actors in the region under study, while models are developed and applied by experts. Examples of global exercises that have used an approach similar to Story-and-Simulation include the Millennium Ecosystem Assessment (Carpenter et al., 2005); the Global Environment Outlook (UNEP, 2007); European studies such as PRELUDE (EEA, 2007); and a growing number of regional and local studies (e.g. Kok et al., 2006; Kok and Van Delden, 2009). Alcamo lists a number of strong and weak points of the methodology that all still stand today. The approach is costly – both in terms of money and time – but direct stakeholder participation ensures that scenarios are relevant for and credible to end-users, while models provide state-of-the-art scientific input.

Although it has only been hinted towards published literature (see Kok and Van Delden, 2009), the experiences with linking qualitative and quantitative scenarios have uncovered an additional weak link in the Story-and-Simulation method. To understand the nature of the problem, it is important to grasp the fundamentals of constructing narrative storylines and dynamic models. Table 1 lists some of the (archetypical) characteristics of dynamic models and narrative stories. There is a high degree of potential complementarity between stories that involved stakeholders and stimulated creative thinking, and models that are

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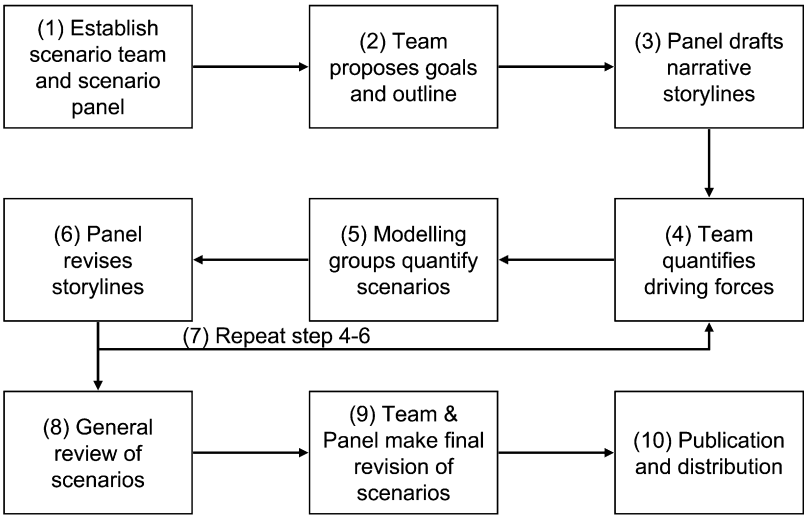

Fig. 1. The Story-and-Simulation approach to scenario development (based on Alcamo, 2001).

quantitative and rigorous. In fact, this is the very reason that the Story-and-Simulation approach has been suggested and successfully adopted. However, the large degree of complementarity might also be the largest drawback of the method. Consider for example the *Sustainability First* scenario as developed as part of the Global Environment Outlook (UNEP, 2007). The backbone of this scenario is best described as a "new sustainability paradigm". The scenario projects a strong and total change in human behaviour cutting across all sectors and all scales. To typify the new situation, the story uses phrases such as "new environment and development paradigm"; "simplicity and community replace consumerism and competition"; and "a more ethical way of living". In short, *Sustainability First* depicts a future world in which our entire system of values and beliefs has radically changed. In turn, this is assumed to have far-reaching consequences for economic, political, and institutional systems. The models that were used to quantify the storylines, however, were constructed based on more conventional assumptions of future system changes. Like most mathematical models, they rely on availability of (spatially explicit) data and many complex relationships that were calibrated and validated on the current system, which necessarily limits their flexibility. Thus on the one hand, not all assumptions of the narratives could be incorporated in the models, while on the other hand, models require quantitative information on a wealth of parameters that is often difficult to extract from storylines. In other words, there is a mismatch between storylines and model parameters (Steps 3–4 in Fig. 1), as well as between model output and revised stories (Steps 5–6). In practice, particularly the translation of stories into quantified model input is often *ad hoc* and does not do justice to either the richness of the stories or the quantitative complexity of the models. The weak link between the qualitative and quantitative scenarios might well be the most problematic aspect of the Story-and-Simulation methodology.

The main objective of this paper is to introduce, explain, and illustrate the potential of a possible improvement to the Story-and-Simulation methodology, Fuzzy Cognitive Mapping. Note that this tool cannot serve to completely bridge the fundamental differences between qualitative and quantitative scenarios, and that its addition is not intended to do so. Because of the relative novel character of the application in the field of environmental sciences, this paper will give a detailed explanation and two illustrative (hypothetical) examples rather than an actual application. The examples serve to identify the weak and strong points of the method. Further research on the possible applications of Fuzzy Cognitive Maps is ongoing, and subsequent papers will provide a more in-depth analysis of the applicability.

The specific aims of this paper are as follows:

- to introduce and illustrate Fuzzy Cognitive Mapping as an addition to the current scenario development methodology;
- to link Fuzzy Cognitive Maps to the concept of resilience, thus substantiating a major potential strength;
- to critically evaluate the strengths and weaknesses of Fuzzy Cognitive Maps in the context of developing scenarios.

Table 1
Key characteristics of qualitative (storylines) and quantitative (mathematical models) scenarios.

Narrative storyline	Mathematical model
Credible	Internally consistent
Not implausible	Plausible
Creative, out-of-the-box thinking	Depending on model architecture
Developed by stakeholders during workshops	Developed by scientists
Qualitative	Quantitative
Based on perception of stakeholders	Based on scientific state-of-the-art thinking
Not limited by data availability	Data-driven
Focus on social changes	Focus on biophysical data

2. Fuzzy Cognitive Mapping

2.1. System dynamics

System dynamics is an umbrella term for all approaches aiming to understand the behaviour of complex systems over time. Generally, approaches deal with internal feedback loops and time delays that affect the behaviour of the entire system. What makes system dynamics different from other approaches studying complex systems is the use of feedback loops and stocks and flows. These elements help describing how even seemingly simple systems can display strong nonlinear behaviour. Fuzzy Cognitive Mapping can be regarded as a system dynamics method, particularly because of its focus on feedbacks. Conclusions drawn for Fuzzy Cognitive Maps apply to some degree to other conceptual modelling tools that have been developed to capture system dynamics, such as Causal Loop Diagrams (Sterman, 2000); the Syndromes approach (Eisenack et al., 2007); and Bayesian networks (Pearl, 2000).

2.2. Definition and background

A Fuzzy Cognitive Map is a representation of a belief system in a given domain. It comprises of concepts (C) representing key drivers of the system, joined by directional edges or connections (*e*) representing causal relationships between concepts. Each connection is assigned a weight e_{ij} which quanties the strength of the causal relationship between concepts C_i and C_j (Kosko, 1986). A positive weight indicates an excitatory relationship, i.e., as C_i increases C_j increases, while a negative weight indicates an inhibitory relationship, i.e., as C_i increases C_j decreases (see also Giles et al., 2007). In its graphical form, a Fuzzy Cognitive Map provides domain knowledge as a collection of 'boxes' and 'arrows' that is relatively easy to visualise and manipulate. Key to the tool is its potential to allow feedback among its nodes, enabling its application in domains that evolve over time. It is particularly suited for use in soft-knowledge domains with a qualitative, rather than quantitative, emphasis. The tool is said to be semi-quantitative, because the quantification of drivers and links can be interpreted in relative terms only. Axelrod (1976) introduced cognitive maps in the 1970s to represent social scientific knowledge. These were later extended by Kosko (1986), whose work on Fuzzy Cognitive Maps is groundbreaking.

Fuzzy Cognitive Mapping is flexible tool that has been successfully applied in a large number of disciplines (Stach et al., 2005). Applications can be found in fields ranging from electrical engineering to medicine, and from political science to using performance indicators. In the field of environmental sciences the number of applications is much smaller but equally diverse. Worth mentioning are group decision support (Khan and Quaddus, 2004); lake ecosystems (Özesmi and Özesmi, 2003, 2004); forest fire propagation (Carvalho and Tome, 2004); and education (Cole and Perichitte, 2000). A few key research themes are emerging, namely combining multiple Fuzzy Cognitive Maps (e.g. Koulouriotis et al., 2003); developing indices for analysing and comparing Fuzzy Cognitive Maps (Çoban and Seçme, 2005); and analysing the dynamic output of a Fuzzy Cognitive Map (Stach et al., 2005). Despite the diversity of applications, the aspect of analysing the dynamic behaviour the Fuzzy Cognitive Map is surprisingly underexposed. Because of its importance in the context of scenario development, it will be one of the main aspects of this paper.

2.3. Properties

The elements of a Fuzzy Cognitive Map are as follows:

- *Concepts*: $C_1, C_2, \ldots, C_n$. These represent the drivers and constraints that are considered of importance to the issue under consideration.
- *State vector*: $A = (a_1, a_2, \ldots, a_n)$, where a_i denotes the state of the node C_i. The state vector represents the value of the concepts, usually between 0 and 1. The dynamics of the state vector is the principal output of applying a Fuzzy Cognitive Map.
- *Directed edges*: C_1C_2, etc. These represent the relationships between concepts, visualised as arrows in the directed graph.
- *Adjacency matrix*: $E = (e_{ij})$, where e_{ij} is the weight of the directed edge C_iC_j. The matrix contains the values of all relationships between concepts, usually between -1 and +1. Note that contrary to most applications, non-zero values on the diagonal are considered here.

The next state of the concepts (the state vector) can be calculated by a matrix calculation $A \times E = B$. This multiplication can be repeated as often as desired.

2.4. Hypothetical example

A hypothetical example can illustrate the procedure of a dynamic Fuzzy Cognitive Map. Consider three concepts C_1, C_2, and C_3 with:

state vector $A = (1, 0, 1)$

$$\text{adjacency matrix } E = \begin{pmatrix} 1 & 1 & 0 \\ -0.1 & 0 & 0 \\ 0 & 0.5 & 1 \end{pmatrix}$$

$$\begin{aligned} \text{new state vector } B = A \times E &= (1, 0, 1) \times \begin{pmatrix} 1 & 1 & 0 \\ -0.1 & 0 & 0 \\ 0 & 0.5 & 1 \end{pmatrix} \\ &= 1 \times (1, 1, 0) + 0 \times (-0.1, 0, 0) + 1 \times (0, 0, 5, 1) \\ &= (1, 1, 0) + (0, 0, 0) + (0, 0, 5, 1) = (1, 1.5, 1) \end{aligned}$$

The calculation of a new state vector can be repeated infinitely, during which four possible patterns can emerge: (1) the concepts can "implode"—all concepts converge to zero; (2) the concepts can "explode"—all factors increase/decrease continuously; (3) there is a cyclic stabilisation; (4) all concepts can stabilise at a constant value. In theory, the procedure should be repeated at least $2 \times n$ (total number of concepts) times to allow for all indirect effects to play out. In practice, the pattern can usually be determined after 20–30 iterations, although total stabilisation can take more than 100 iterations. Fig. 2 shows two directed graphs of the Fuzzy Cognitive Map and the development of the values of state vector *A* for the first 30 iterations. The right-hand side graph has one additional relationship $e_{23} = -0.5$.

2.5. Interpretation of Fuzzy Cognitive Maps

All input and output of a Fuzzy Cognitive Map is semi-quantitative in nature. Information is provided as numbers but can only be interpreted relative to other numbers. As shown in Fig. 2, after 30 iterations the value of C_2 is lower than the value of C_3 but higher than the value of C_1. Similarly, the value of C_2 first increases strongly, and then decreases gradually back to its starting value of 0. The most straightforward interpretation of a Fuzzy Cognitive Map – provided it reaches equilibrium – is by considering the final stable values of the concepts relative to stable states that are based on a different set of relationships. In this example, the final value of C_3 is 1.5 without feedback from C_2, while it is -1.1 with feedback. Note that although the value of C_2 stabilises at 0 in both cases, the final value of C_1 differs between -0.5 ($e_{23} = 0$) and +0.6 ($e_{23} = -0.5$). Because the value of C_2 decreases more rapidly in the second case, the negative impact on C_1 is less, as a result of which C_1 stabilises at a higher value. This example thus also shows how even in very simple systems relationships can have strong indirect effects. Additionally, it 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 precisely where the strength of Fuzzy Cognitive Maps lies.

2.6. Calibration and evaluation of Fuzzy Cognitive Maps

Calibration is a crucial step in the development procedure of any model. The semi-quantitative nature of the values, however,

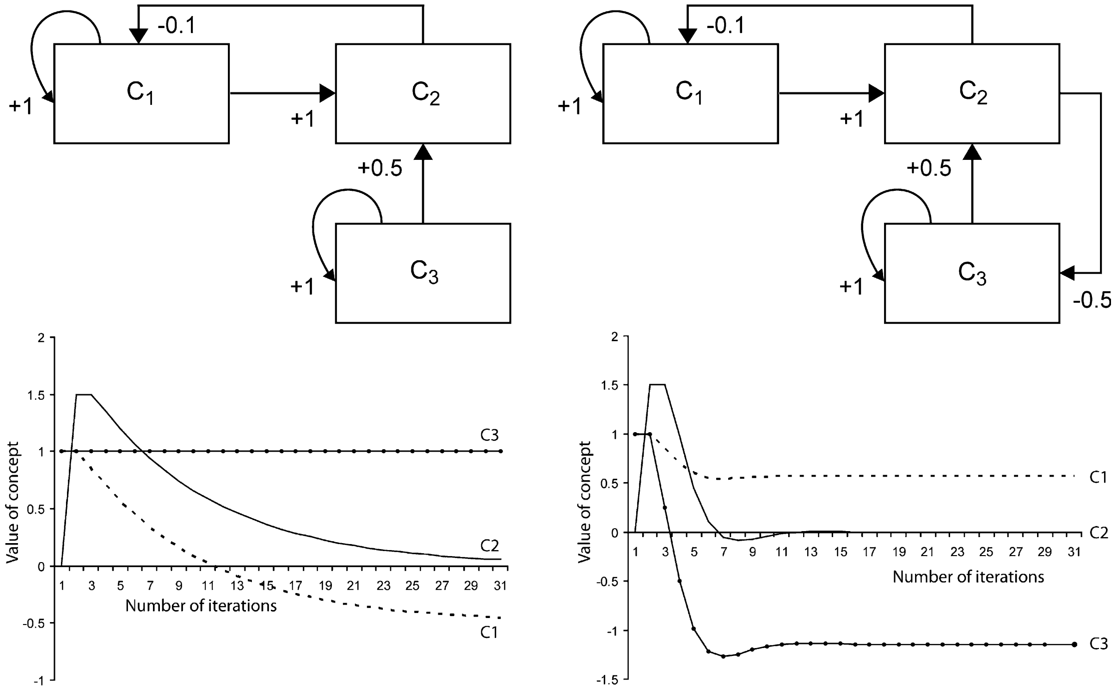

Fig. 2. Directed graphs (upper part) and values of concepts (lower part) for the first 30 iterations of two adjacency matrices.

limits the applicability of standard calibration methods used for quantitative models. Nevertheless, there are a number of steps that can be taken. Firstly, the underlying assumption will normally be that the system is in or near equilibrium. Therefore, stabilising the values of the state vector can be used as a method to calibrate. Secondly, existing information on changes of the value of specific drivers can be used to calibrate the state vector. Thirdly, because Fuzzy Cognitive Mapping is a matrix-vector calculation, standard matrix calculations can be used to analyse the adjacency matrix. Particularly promising is the use of *eigenvalues* and *eigenvectors*, which are standard properties of any square matrix. These can also be used to stabilise the state vector. Finally, when values of concepts are based on statistical information, Akaike's Information Criterion can be used to select the best model. This method has successfully been applied to another type of qualitative model (see Lundquist, 2007). Additionally, a standard sensitivity analysis can be performed to determine which weighting factors are important and for which the system is insensitive. In this simple example, the calibration consisted of stabilising the state vector by varying the strength of the additional feedback.

3. Fuzzy Cognitive Maps to understand complex systems—the Brazilian Amazon example

To further illustrate the potential of Fuzzy Cognitive Maps, an example of the application to the issue of deforestation in the Brazilian Amazon is given. This example is illustrative because of its multi-scale character; its multitude of factors that are influential; the uncertainty on the relative importance of the factors; and the polemic that has unfolded in scientific literature. It is beyond the scope of this paper to provide an in-depth literature review or synopsis of the wealth of publications on the issue of deforestation in the Brazilian Amazon. Good starting points for further reading are Câmara et al. (2005); Fearnside (2001, 2003); Laurance et al. (2001); and Pacheco (2005).

3.1. Constructing the Fuzzy Cognitive Map

3.1.1. Identifying concepts

Following the definition of a Fuzzy Cognitive Map, only those factors were included that are "easy to manipulate", i.e. which operate on a relatively short and similar temporal scale and on which indications on the relative importance could be found in literature. Slow factors such as soil degradation and vague or complex concepts such as consumer behaviour were therefore excluded. Furthermore, the analysis was limited to factors related to agricultural expansion, excluding e.g. logging and mining. Thus, all *concepts* represent a direct or indirect driver/constraint of agriculturally induced deforestation, while all *relationships* are the processes by which the drivers influence each other. The twelve most important drivers as mentioned in literature and included in the Fuzzy Cognitive Map were as follows:

C_1: *Squatters and speculation*. This group of drivers encompasses the four most important processes by which land titling can change, namely land expropriation, land grabbing, land squatting and, as a result, land speculation. The role of these processes is heavily debated, but it is generally accepted that changes in land titling are an important trigger of deforestation.

C_2: *Infrastructure expansion*. This group of drivers includes mainly the large-scale infrastructural improvement plans from the national government (Avança Brasil). It is generally accepted that roads are an essential prerequisite for deforestation, and that paving major roads will lead to deforestation.

C_3: *Conservation units*. A large percentage of the Amazon (close to 33%) is classified as some kind of protected area. This includes indigenous reserves, federal parks and national parks. Only about 5% is strictly protected, although it is argued that 'paper parks' can also be effective.

C_4: *Forest accessibility*. The amount of forest that is accessible, interpreted as the potential for deforestation. This concept is a necessary addition to capture the effect of the spatial drivers.

C_5: *Rainfall*. The hypothesis is that decreasing rainfall and increasing drought and fire occurrence can result in a positive feedback and strongly increase forest accessibility.
C_6: *Agricultural expansion*. A measure for deforestation caused by agricultural expansion.
C_7: *Land use intensification*. This group encompasses both the introduction of new high-intensity crops (soya, biofuel) and the intensification of current crops (pasture). Agricultural intensification is often mentioned as one of the key solutions to decrease the pressure on forest.
C_8: *Profitability*. This issue includes profitability of all agricultural crops. Key to the role of this factor is its potential to reduce the demand for agricultural land, while stimulating land prices and thus land speculation.
C_9: *Demand*. Demand of production of all main agricultural land uses.
C_{10}: *Export*. This group includes the international demand for agricultural products (soya, biofuel).
C_{11}: *Population growth*. This group includes both national and international growth and the influence on demand for agricultural products.
C_{12}: "*Policies*". This group includes all kinds of policies, both actual and hypothetical.

It is important to emphasise that the core of the discussion on the main drivers of deforestation in the Amazon splits between those that point at spatial drivers (infrastructure, rainfall, conservation units, land prices) and those that 'blame' non-spatial drivers (export, demand, population growth). The top half of Fig. 3 represents the spatial factors, the bottom half the non-spatial ones. In this graph spatial factors should be understood as the 'sum of all localities'. Note that the number of relationships between spatial and non-spatial factors is relatively low, which might also be due to the polarised discussions and analysis in literature.

3.1.2. Semi-quantifying relationships

Selecting the weighting factors for the semi-quantification of relationships is arguably one of the weakest points in the approach. The most common approach found in literature is either to combine multiple Fuzzy Cognitive Maps from individual stakeholders, or to develop one version in a participatory workshop setting. In both cases, the product is a consensus of various opinions. A number of methodologies are available to structure the weighting procedure. First and foremost, a paired comparison analysis can help to provide a framework for comparing each course of action against all others, and to show the difference in importance between paired factors. Although this does not directly provide weighting factors, the analysis is specifically designed to compare apples and oranges. Additionally, a number of raking methods can help. By regarding the arrows as interval variables, scoring the data points will provide the order of data as well as the precise numeric distance between data points (see Runyon, 1991), which is what is needed here.

The procedure followed here drew heavily from the exhaustive study of Kaimowitz and Angelsen (1998) and especially from the more recent analysis of Scouvart et al. (2007). The latter study focused on the Brazilian Amazon using a Qualitative Comparative Analysis based on a Boolean minimisation procedure. Assigning the values of the relationships was based on information from these and other studies, using a mix between classifying and ranking. Relationships were classified in ranked groups, within which relationships were ranked again. This ranking was further refined by a paired comparison analysis. Scouvart's study was particularly helpful to exclude a large number of possible combinations. A final step was the incorporation of knowledge on indirect effects.

Defining the order does not define the absolute value of the variables, for which these general rules were followed:

1. The maximum value was set at 0.9 ($C_{10} \rightarrow C_9$). A complete link between two issues was assumed not to exist in this example where most issues are a complex of multiple sub-issues.
2. The minimum was set at 0.2, indicating that all relationships <0.2 were assumed to be 0.
3. Relationships were divided into three main groups (strong, medium, and weak), which were subdivided into three groups again.
4. The strongest and weakest relationships were determined first, the remaining edges were positioned relative to those.
5. Calibration to stabilise the state vector. It was assumed that the system is near equilibrium.

The groups, ranking, and final values for all processes are given in Table 2. The resulting directed graph is presented in Fig. 3.

Crucial in determining the value of a relationship is the balancing act between its position relative to others, and its absolute position as indicated in literature. A few examples illustrate this process:

Strongest relationships: The link between export and demand is set at 0.9, given that growth in export markets will translate almost completely in a demand for agricultural products. It is assumed that 10% will not be fulfilled because of ignorance of markets. The influence of profitability on demand is set at 0.8. The link is crop specific and is especially strong for cash crops such as soya, sugar cane, and coffee. There is some controversy about the profitability of cattle, but recent publications assume a strong link. The link between infrastructure and forest accessibility is set to 0.8, given that 20% of the area alongside the roads in the Amazon consists of steep slopes, wetlands, or is otherwise inaccessible.

Direct effects: Three processes directly influence the demand for agricultural products. The change in export is assumed to be one of strongest drivers of demand increase based on Kaimowitz et al. (2004). Relative to this, changes in profitability are slightly lower ($C_8 \rightarrow C_9$ (+0.8)), although this process is one of the key drivers of the system as well. Population

Table 2
Summary of values of all relationships in the Fuzzy Cognitive Map for the Brazilian Amazon.

First-order class	Second-order class	Relationship	Value
Strong	Strong	$C_{10} \rightarrow C_9$	0.9
	Medium	$C_2 \rightarrow C_4$	0.8
		$C_4 \rightarrow C_6$	
		$C_8 \rightarrow C_9$	
	Weak	$C_2 \rightarrow C_1$	0.7
Medium	Strong	–	0.6
	Medium	$C_3 \rightarrow C_4$	0.5
		$C_4 \rightarrow C_7$	
		$C_{11} \rightarrow C_9$	
		$C_7 \rightarrow C_8$	
		$C_8 \rightarrow C_1$	
		$C_1 \rightarrow C_6$	
		$C_9 \rightarrow C_2$	
		$C_9 \rightarrow C_6$	
Weak	Strong	$C_7 \rightarrow C_1$	0.4
		$C_9 \rightarrow C_7$	
	Medium	$C_4 \rightarrow C_2$	0.3
		$C_6 \rightarrow C_1$	
		$C_6 \rightarrow C_7$	
	Weak	$C_5 \rightarrow C_4$	0.2
		$C_7 \rightarrow C_6$	

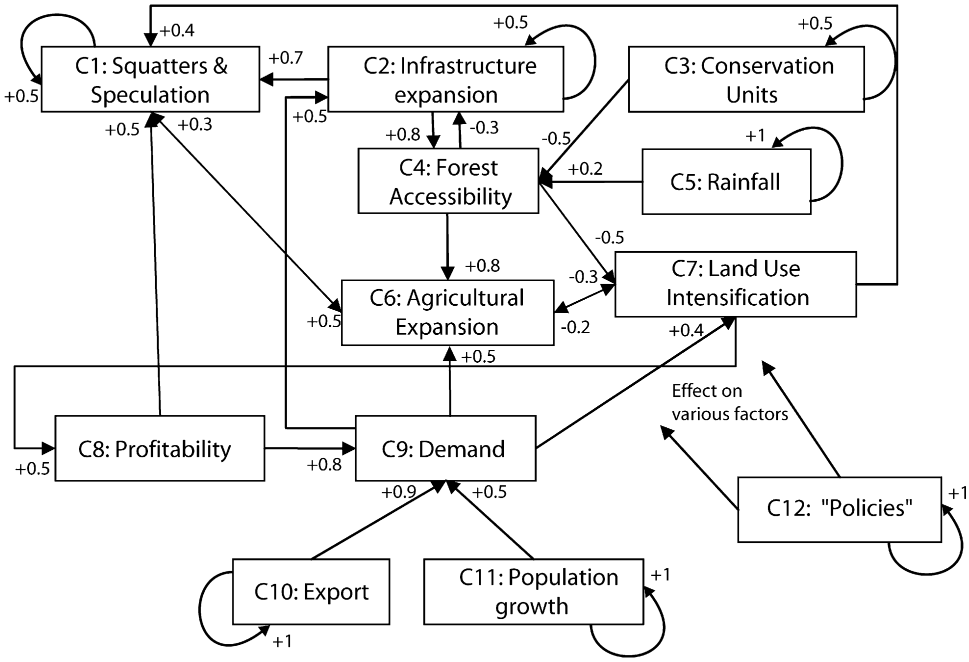

Fig. 3. Directed graph of deforestation in the Brazilian Amazon.

growth is a less important factor, but relative to other processes is it still a medium important driver. The relationship between demand and agricultural expansion is set at +0.5, given that part of the demand is fulfilled by imports, part is not fulfilled, and part is fulfilled by increasing productivity ($C_9 \rightarrow C_7$ (+0.4)).

Indirect effects: There is an ongoing discussion how land use intensification will influence deforestation. On the one hand, intensification leads to more production on the same area, and therefore less pressure on forest ($C_7 \rightarrow C_6$ (+0.2)). However, high producing land triggers land speculation, which in turn leads to higher land prices, which will attract land squatters and lead to more deforestation ($C_7 \rightarrow C_1 \rightarrow C_6$ ($0.4 \times 0.5 = 0.2$)). Based on the meta-analysis by Kaimowitz and Angelsen (1998), I concluded that evidence of the effect of agricultural intensification on deforestation is ambiguous. I therefore equalled the indirect and direct effects of land use intensification.

Calibration: As a last step, the Fuzzy Cognitive Map was calibrated to stabilise the state vector. Values of relationships were modified in a few cases, but always with the first order group to which they belonged. For example, the influence of rainfall on forest accessibility was lowered from 0.4 to 0.2. This system proved to be especially sensitive to changes in self-reinforcing relationships (e.g. $C_1 \rightarrow C_1$). This holds for most Fuzzy Cognitive Maps.

3.1.3. Exploring dynamic changes

To illustrate the potential of the dynamic aspect of Fuzzy Cognitive Maps we present several outputs of the changes in state vectors. Fig. 4 and Table 3 show the results of the basic situation as presented in Fig. 3 and a number of alternative developments:

- *Export restrictions*: assumed is a policy that restricts export. As a result, demand for a number of agricultural products, most importantly soya and beef, is reduced. Added to the FCM was $C_{12} \rightarrow C_{10}$ with a strength of −0.5.
- *Infrastructural restrictions*: assumed is a partial termination of the Avança Brazil programme, strongly reducing the expansion of paved and unpaved roads. Added to the FCM was $C_{12} \rightarrow C_2$ (−0.8).
- *Multiple "policies"*: in addition to export and infrastructural restrictions, measurements are assumed that slow the pressure of land squatters and that reduce land speculation, and the

Table 3
State vector after >100 iterations of different Fuzzy Cognitive Maps.

Factor	Current situation	Infrastructural restrictions	Set of spatial policies	Export restrictions	Multiple "policies" (C_{12} = 1)	Multiple "policies" (C_{12} = 0.8)
C_1: squatters and land speculation	0.8	0.4	0.0	0.2	$-\infty$	−0.7
C_2: infrastructure	0.3	−0.1	0.0	0.1	$-\infty$	−0.3
C_3: conservation units	0.0	0.0	0.5	0.0	$+\infty$	0.0
C_4: forest accessibility	0.4	0.0	−0.1	0.2	$-\infty$	−0.2
C_5: rainfall	0.5	0.5	0.5	0.5	$+\infty$	0.5
C_6: agricultural expansion	1.4	0.6	0.2	0.5	$-\infty$	−0.9
C_7: land use intensification	−0.4	0.1	0.3	−0.1	$+\infty$	0.2
C_8: profitability	−0.2	0.0	0.2	−0.1	$+\infty$	0.1
C_9: demand (in Amazon)	0.6	0.7	0.7	0.2	$-\infty$	−0.4
C_{10}: export	0.5	0.5	0.5	0.0	$-\infty$	−0.7
C_{11}: population growth	0.5	0.5	0.5	0.5	$+\infty$	0.5
C_{12}: policies	0.0	0.5	0.5	0.0	$+\infty$	0.0

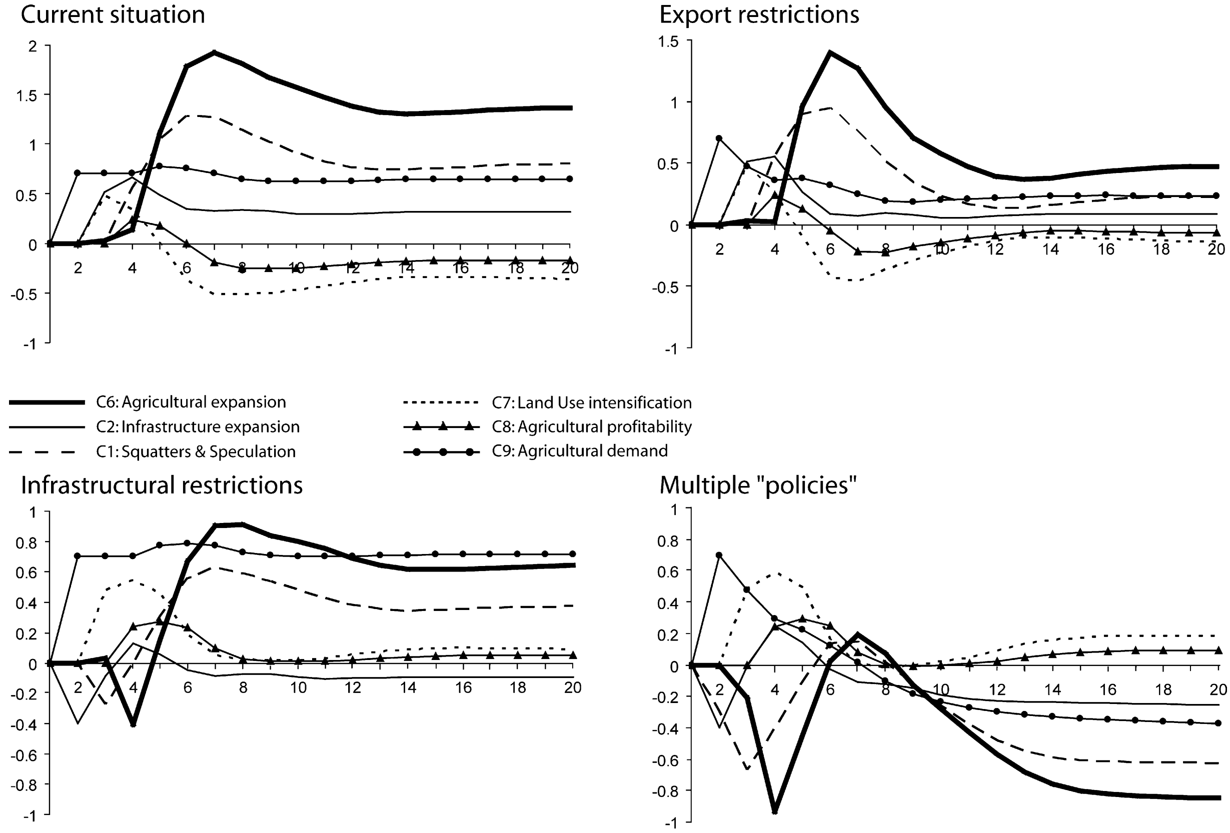

Fig. 4. Output of various Fuzzy Cognitive Maps. *X*-axis: number of iteration steps; *Y*-axis: value of selected concepts.

institutionalisation and protection of more conservation units. Added to the FCM were $C_{12} \rightarrow C_1$ (-0.5) and $C_{12} \rightarrow C_2$ (+0.5). Assumed was furthermore that these measures would act over a short time period only. To simulate this, $C_{12} \rightarrow C_{12}$ was set at 0.8, which resulted in a decreasing influence of all "policies" to less than 0.20 after 5 iterations and less than 0.05 after 10 iterations.

3.2. *Interpreting the dynamic output*

3.2.1. *The current situation*

After about 20 iterations, the value of all concepts has stabilised in the graph that represents the current situation (top left of Fig. 4). The new equilibrium reflects the current situation of deforestation in the Amazon, with a high value for agricultural expansion ($C_6 = 1.4$). Land titling issues ($C_1 = 0.8$); infrastructure expansion ($C_2 = 0.3$); and demand for agricultural products ($C_9 = 0.6$) all drive deforestation. Despite the importance of high-intensive crops such as soya, the increased forest accessibility ($C_4 = 0.4$) results in a system where overall yields ($C_7 = -0.4$) and profitability ($C_8 = -0.2$) are low.

3.2.2. *Export restriction*

Restricting export (top right of Fig. 4) substantially reduces deforestation ($C_6 = 0.5$), but the system in equilibrium is very similar to the current situation. Demand, land speculation, and infrastructure development are all still positive; land use intensity and profitability remain negative. Note that demand remains positive, which can mainly be attributed to the assumed population growth and urbanisation rates ($C_{11} = 0.5$). In other words, limiting the export of soya and/or beef can slow but not stop deforestation, because of an internal demand that is sufficiently high to keep a very similar system in place.

3.2.3. *Limit infrastructure expansion*

Despite the fact that the limitation of road expansion was set relatively high (-0.8), deforestation continues unabated ($C_6 = 0.6$) in the new equilibrium (Fig. 4, bottom left). Note that infrastructure drives itself ($C_2 \rightarrow C_2$ (+0.5)), under the assumption that road expansion will also take place without any outside influence. This partly counters the imposed "policy" restrictions resulting in a value that is only slightly negative ($C_2 = -0.1$). Yet, the new system continues to be similar. Although profitability and land use intensity are now slightly positive, demand and land speculation are strongly positive. The system described here is a future where the soya boom continues with an expansion along the edges of the Amazon, strongly driving other land uses (mainly pasture) and accompanying processes such as land speculation. However, in the first five iteration steps agricultural expansion is negative, following an increase in land use intensification and a decrease in land speculation/land prices. It shows the potential positive influence of limiting road expansion.

3.2.4. *Multiple "policies"*

The combination of limiting road expansion, export, and land speculation/land squatting, while stimulating park protection has very strong effects. In the new equilibrium, agricultural expansion is strongly negative ($C_6 = -0.9$), within a system that is fundamentally different from the current situation. Demand will decrease ($C_9 = -0.4$); the pressure of land squatters will decrease ($C_1 = -0.7$); and infrastructure will not be improved further ($C_2 = -0.3$). At the same time, land use intensification and profitability will increase. This system is close to a situation described as desirable in literature, where agricultural demand can be satisfied by using less land more intensively. It is not surprising that such a system can potentially be in equilibrium. It is more significant that it can be maintained without any policy incentive ($C_{12} < 0.05$ after 20 iterations). In terms of the Fuzzy Cognitive Map, using the end vector without policies as a starting vector would immediately stabilise. This alternative thus indicates that short-term powerful incentives to abate deforestation can lead to a long-term sustainable situation with a substantially lower deforestation.

4. Scenarios, resilience, and Fuzzy Cognitive Maps

The radically different equilibriums between the current situation and the multiple "policies" alternative can be linked to the theories of resilience and adaptive capacity as coined by Holling in the 1970s (Holling, 1973), and further elaborated by a rapidly growing number of research groups, notably those involved in the Resilience Alliance (e.g. Gunderson and Holling, 2002; Folke, 2006). Walker et al. (2004) used three properties of a stability landscape to characterise the resilience of a system. Fig. 5 is a two-dimensional representation of the Brazilian example in which two of those properties are visualised, namely the depth of the cup and the distance to the edge of the cup. The *current situation* is a system that is very resilient. Strong disturbances to the system are absorbed and when the disturbance stops the system returns to its previous equilibrium. The *economic restrictions* alternative is a good example of such a disturbance. The external demand for agricultural products is lowered, but the system of ongoing deforestation remains in place. However, the system has been brought closer to the edge of the cup. The *infrastructural restrictions* bring a more fundamental change. By paving less roads, the internal structure of the system starts to change as the agricultural sector start to intensify. In the stability landscape, this is represented by a lower depth of the cup. Similar to the previous situation, the system is closer to the edge, but it would return to the current situation if road expansion would be resumed. Only when multiple "policies" are applied simultaneously, the system is pushed out of its current state to end up in another domain of attraction. It will now require active counter measurements to return the system to its previous state.

Modelling ecosystem resilience has a longer history and a number of successful quantitative methods have been put forward as possible tools to model resilience. However, research on so-called social–ecological resilience is still in its exploratory phase (Folke, 2006). A suggested approach of using systems models (Bennett et al., 2005) is in fact a type of system dynamics model and thus similar to Fuzzy Cognitive Maps. Bennett et al. also emphasise simplicity, transparency, and ease to replicate as key virtues. Fuzzy Cognitive Mapping thus offers possibilities to model social–ecological resilience.

There is a strong link between thinking in terms of resilience and multiple domains of attraction, and thinking in terms of scenarios. This link has been made very explicit in various sets of global scenarios. In one of the earlier global assessments by the Global Scenario Group, scenarios were differentiated by different "sideswipes" or major surprises (Gallopín et al., 1997; Raskin et al., 2002). The Global Environment Outlook scenarios (UNEP, 2007) are strongly connected to the work of the Global Scenario Group. Perhaps more significantly, the Millennium Ecosystem Assessment set out to develop scenarios that were built on multiple ecosystem theories (see Cumming and Peterson, 2005). Carpenter et al. (2006) conclude that the Millennium Ecosystem Assessment considered the risks and consequences of regime shifts, and that resilience played a major role in the scenarios. In many ways, the creative aspects of qualitative scenarios as mentioned in Table 1 are more often than not related to fundamental changes in the system, which could be translated in terms of a transition to another domain of attraction in a stability landscape. This indicates that tools such as Fuzzy Cognitive Maps that can model social–ecological resilience are especially suitable to be linked to scenarios that are often based on similar system changes.

5. Strong and weak points of Fuzzy Cognitive Maps

5.1. Fuzzy Cognitive Mapping as addition to the Story-and-Simulation approach

Fig. 6 illustrates how the Story-and-Simulation approach could be expanded to incorporate Fuzzy Cognitive Maps. As before, a scenario team and a scenario panel will be established and narratives will be developed (Steps 1, 2, and 3a; see also Fig. 1). Based on the storylines, the most important concepts can be identified and a first (semi-quantitative) estimation of the values of the relationships can be made (Step 4a). Ideally, those that draft the storylines should also be those that define concepts and edges. In most cases this will be a group of stakeholders in a workshop setting. The dynamic output of the Fuzzy Cognitive Maps (Step 5a) can be generated and evaluated during the same meeting. In a subsequent meeting, narrative storylines can then be updated (Step 6a) based on the results of the Fuzzy Cognitive Maps in an

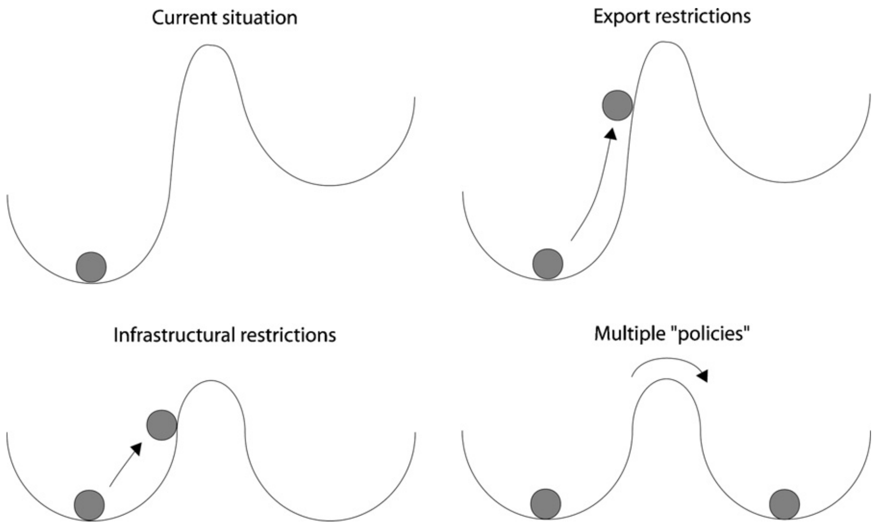

Fig. 5. Two-dimensional stability landscapes, represented as balls and cups, for various Fuzzy Cognitive Maps.

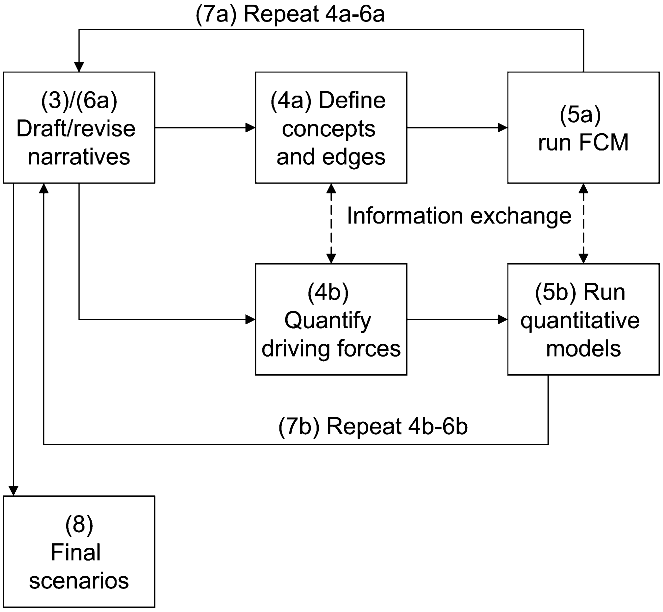

Fig. 6. Suggested additions to the Storyline-and-Simulation approach by incorporating Fuzzy Cognitive Maps. Numbers equal to those in Fig. 1.

iterative procedure (Step 7a). Because of the low development time of narratives and Fuzzy Cognitive Maps, the number of iterations can potentially be high (>2). The immediate input of a semi-quantitative model developed by the stakeholders is anticipated to improve the internal consistency and clarity on the role of key feedbacks in the narratives. This, in turn, will improve the possibilities to link the (revised) qualitative scenarios to a quantitative model (Steps 4b and 5b). The potential of incorporating Fuzzy Cognitive Maps in the Story-and-Simulation approach further increases when strengthening the link between the Fuzzy Cognitive Map and the mathematical models.

The weakness of this link, and therefore the necessity to improve the Story-and-Simulation approach, was also noted by those contributing to the Millennium Ecosystem Assessment: when reviewing a number of global scenarios, Cumming et al. (2005) conclude that there are "many uncertainties and potential inconsistencies in existing scenarios and in our understanding of the relationships between different drivers in ecological, social and economic systems". Similarly, mathematical models using in scenario development often remain a stand-alone product, and are not a tool specifically designed to be combined with storylines. Although I have not seen it committed to paper, it is my personal opinion that the products of global models often depict scenarios as variations on a Business-As-Usual scenario, rather than a number of radically different futures as sketched in the narratives.

The successful incorporation of Fuzzy Cognitive Maps in the Story-and-Simulation approach depends on the link with narrative storylines as well as on the link with quantitative models. Table 4 provides an overview of the strong and weak points of Fuzzy Cognitive Mapping, subdivided into general points and points related to these two essential links. Below some of these points are discussed in more detail.

5.2. *Fuzzy Cognitive Maps—general strong and weak points*

The general strengths and weaknesses, i.e. when used as a stand-alone application, as in this paper, have been pointed out in Sections 3 and 4. The strongest point of the methodology is the insight it can provide on the role of key feedbacks in the system. As shown in Section 3.2, these feedbacks can remain hidden and can be uncovered by applying a tool such as Fuzzy Cognitive Mapping. The tool can provide a lucid representation that, especially when used in combination with the theory of resilience, can help understanding short-term and long-term dynamics. One of the key general weaknesses is the poorly developed method to derive to the semi-quantification of relationships. This weakness becomes less consequential when multiple persons are involved in the construction of the Fuzzy Cognitive Map and the emphasis is on representing a belief system.

5.3. *Linking Fuzzy Cognitive Maps and narrative storylines*

The strongest added value of Fuzzy Cognitive Maps is the potential to integrate them in the process of developing storylines.

Table 4
Strong and weak points of Fuzzy Cognitive Mapping.

Strong points	Comments	Weak points	Comments
General			
Focus on feedbacks	Possibility to uncover previously hidden system properties	Methods for semi-quantification are not very structured	
Provide a lucid representation of complex systems			
Linking with stories			
Approach can quickly be explained to stakeholders	Can be developed in a workshop setting	Too much focus on numbers	Discussion might hamper the creative process
High level of integration	Does not limit creativity	Being concrete requires experts	Not all stakeholders can be included
Forces users to be explicit on strength of relationships	Facilitates concrete discussion and reduces opaqueness of storylines	Addition will increase time pressure	Stakeholders usually note a lack of time during workshop
Direct insight on effect of impacts	Broadens information base of stakeholders		
Linking with models			
Underlying assumptions of models are made explicit	Comparison with assumptions of models is possible	Relationships are only semi-quantified	Results are difficult to interpret in absolute terms
Semi-quantitative output can inform models	Relative changes can be used to estimate normalised quantities	Incomparable factors are compared	Not all factors can be included
		Quantification partly arbitrary	The role of weighting factors is essential but methods can be *ad hoc*
		Time is ill-defined	The output is semi-dynamic

Narratives often tell a story of a regime shift, moving from one basin of attraction to another. As argued in Section 4, Fuzzy Cognitive Maps can provide a similar but semi-quantitative insight in the resilience of the system. As such, the potential added value of linking the two methods is high. Much more than with a quantitative model, there can be a quick iteration between a Fuzzy Cognitive Map and a storyline. An additional advantage is that Fuzzy Cognitive Maps can be developed by the same group of people that developed the story, although this is not a prerequisite. Stories could thus be compared with Fuzzy Cognitive Maps that exactly match the perception of the stakeholders. Because the approach can be explained to stakeholders quickly, Fuzzy Cognitive Maps are particularly useful in a participatory setting, where time and money are limited. Furthermore, the high level of integration does not limit creativity when working with stakeholders, while the semi-quantitative character forces the users to be concrete.

There are, however, three weak points when linking Fuzzy Cognitive Maps and narratives. First and foremost, having stakeholders construct a Fuzzy Cognitive Map requires some level of understanding of system dynamics. Similarly, stakeholders will need to be sufficiently informed to estimate strength of relationships. Thus, the participation of stakeholders is somewhat limited and excludes for example laymen and freethinkers—groups that can be of great value when drafting storylines. Secondly, focusing the discussion on numbers might distract stakeholders and hamper the creative process. A final drawback is that introducing an additional method will yet draw out a process that is already very time-consuming. This might undermine the feasibility of including Fuzzy Cognitive Maps in a standard scenario exercise. A perhaps more feasible option when time is limited, is to completely substitute full quantitative models with Fuzzy Cognitive Maps. Although it will strongly depend on the importance of quantitative models, this could be a feasible option where those models are primarily used to visualise storylines (see Kok and Van Delden, 2009).

Given that all drawbacks are relatively small and further modifications to the Story-and-Simulation can help to overcome them, the potential value of using Fuzzy Cognitive Mapping as additional tool in the participatory process of constructing storylines is high.

5.4. Linking Fuzzy Cognitive Maps and quantitative models

There are a number of possible ways in which semi-quantitative information from Fuzzy Cognitive Maps can be translated to models. Firstly, Fuzzy Cognitive Maps provide an estimate of the relative change of key concepts such as deforestation or land prices. These can be compared with or translated to normalised changes of the same variables in a model. In theory, values for a large number of variables could be estimated by the dynamic state vector of a Fuzzy Cognitive Map. A similar procedure could be used to calibrate a quantitative model: the relative settings of key relationships can be compared to normalised weights in a quantitative model. However, potentially the largest added value of Fuzzy Cognitive Mapping is in the possibility to compare the system definition made by the stakeholders, and on which the logic of the storylines is based, with the system definition of the model, possibly rewritten as a Fuzzy Cognitive Map. As mentioned before, the possibilities to compare and combine Fuzzy Cognitive Maps through matrix algebra are large. This does not provide a direct link, but it can enhance the understanding of modellers for narrative storylines and vice versa.

Yet, there are two weaknesses of Fuzzy Cognitive Maps – both inherent to the methodology – that limit the linking possibilities. Firstly, relationships are only semi-quantified, which obstructs any interpretation in absolute terms, even though normalisation of input and output of models can facilitate a (partial) link. The weakest point of the methodology is probably in the semi-quantitative character of the temporal dynamics. The output of a Fuzzy Cognitive Map shows the value of key factors after a number of iterations, which cannot directly be translated into time. The problem can partly be overcome by only including processes that act at approximately the same time scale. When this can be assumed, one iteration step equals one unit of time. In the Brazilian example, changes in deforestation, policies, land use intensification, and land speculation are assumed to operate at the same time scale. Changes in rainfall, however, are expected to be slower. As long as these factors are included as external drivers – as is the case here – lowering the starting value of the concept can serve as a similar solution.

5.5. Comparison with existing Brazilian scenarios

A comparison of the method and results presented here with other scenario studies in Brazil serves to highlight where Fuzzy Cognitive Maps might be helpful in practice, both qualitatively and quantitatively. Despite the wealth of information and detailed studies on the functioning of the Brazilian land use system, very few papers include an integrated long-term future outlook on deforestation in the Amazon. In this comparison I included two well-known spatial modelling approaches (Laurance et al., 2001; Soares-Filho et al., 2006) and a non-spatial general equilibrium model (Cattaneo, 2002).

5.5.1. Qualitative comparison

Laurance et al. (2001) and Soares-Filho et al. (2006) have proposed a number of qualitative scenarios for the Amazon forest. Two comparable scenarios are termed ‘Business as Usual’/‘non-optimistic’ and ‘Governance’/‘optimistic’. The governance scenario contains terms like “multiplication of current experiments in frontier governance” and “law enforcement” (see Soares-Filho et al., 2006). Although not particularly elaborate, the storylines contain a rich background on fundamental changes that need to take place. However, the model output by and large shows the impact of only one factor, road expansion. The subsequent scientific debate has focused on these model outputs, largely ignoring the underlying assumptions in the narratives. As a result, various groups have accused others of being ‘simplistic’ (see Câmara et al., 2005) or worse. Introducing Fuzzy Cognitive Mapping can help broadening the discussion, or refocusing it on drivers other than road improvement. Moreover, the Fuzzy Cognitive Map as constructed in this paper might also help to suggest qualitative scenarios other than the two that are most heavily discussed at present.

5.5.2. Quantitative comparison

As mentioned in Section 5.4, normalised changes in any model variable can be compared with the relative values of key concepts in a Fuzzy Cognitive Map. Table 5 compares the normalised changes in deforestation of the aforementioned studies with Fuzzy Cognitive Map model runs.

Soares-Filho et al. (2006) developed a number of scenarios that are very comparable to the Fuzzy Cognitive Maps as described in this paper. The resulting differences in deforestation rates are nevertheless less pronounced. Even a complete set of policies similar to the measures assumed in the multiple “policies” Fuzzy Cognitive Map run, results in a much lower but ongoing deforestation. This is primarily due to assumed indirect effects of policies in the Fuzzy Cognitive Map on factors such as land speculation and particularly land use intensification. Laurance et al. (2001) describes two scenarios, both of which include the execution of the Avança Brasil programme. In their model, park protection is introduces as a measure to (slightly)

Table 5
Comparison of relative deforestation rates.

Future outlooks for Brazilian Amazon	Relative deforestation rate	Fuzzy Cognitive Maps	Relative deforestation rate
Soares-Filho et al. (2006) year: 2050		This paper stabilised	
Historical (no further road paving)	0.95	Infrastructural restrictions	0.6
Business-as-usual	1	Current situation	1.4
Government without further road paving	0.2	Multiple "policies"	−0.9
Laurance et al. (2001) year: 2020			
Non-optimistic (+road improvement)	1.2	Current situation	1.4
Optimistic (road + park protection)	1.1	Park protection	1.6
IFPRI (Cattaneo, 2002) long-run equilibrium			
Combination "current"	1.4	Current situation	1.4
Combination "export" (devaluation of the real)	0.9	Export restrictions	0.5
Combination "multiple policies"	−1.1	Multiple "policies"	−0.9

The settings for the Fuzzy Cognitive Maps can be found in Table 3, except for the park protection run. Simulated in that run was the effect of changing $C_3 \rightarrow C_3$ to +1.

slow deforestation. An additional Fuzzy Cognitive Map run that was executed to simulate a similar effect shows an *increase* of deforestation. This opposite effect is due to feedbacks in the Fuzzy Cognitive Map: more protection leads to less available land, which in turn will increase land use intensification, and therefore increase land prices, which stimulates land speculation. This in turn will lead to an increase of deforestation. Noteworthy of both spatial approaches is the lack of scenarios that project deforestation to stop or become negative. This is partly due to the fact that both models are *deforestation* models, i.e. primarily designed to answer the question where deforestation will take place. Both studies serve to illustrate how relatively straightforward land use change models in Brazil are at present, and how including indirect effects and feedbacks as shown in this paper can results in scenarios with a different rate of deforestation, the direction of change, or both.

IFPRIs study (Cattaneo, 2002) analysed the effects of a multitude of separate factors such as devaluation of the Brazilian currency, technological changes, and road improvement, without developing integrated scenarios. The values listed in Table 5 are a combination of several separate effects mentioned in this study. Of all studies included here, the projections of the IFPRI model are closest to the Fuzzy Cognitive Map output. For example, this study explicitly includes strong negative effects on deforestation, particularly when removing land speculation or introducing a deforestation tax. Interestingly, IFPRI attributes the strongest potential impact to land use intensification including both positive and negative effects. Similar to the spatial studies, no indication of interactions between sectors and/or feedbacks is given.

Concluding, current spatial models develop scenarios that are relatively straightforward focusing on the effects of road improvement on deforestation. This lack of diversity, indirect effects and feedbacks could be resolved by a link with Fuzzy Cognitive Maps. IFPRIs quantitative model does not include feedbacks or indirect effects either. However, it does serve to indicate that changes in deforestation rates as strong as computed by the Fuzzy Cognitive Maps are plausible.

6. Future challenges

This paper intended to introduce Fuzzy Cognitive Maps and critically evaluate the added value in the context of scenario development. Below I revisit the expanded Story-and-Simulation approach, focusing on those strengths that can and should be tested and those weaknesses that need to be improved. Only when answering these questions, the added value of Fuzzy Cognitive Maps can truly be assessed. Most of the proposed improvements are currently underway in a variety of projects.

1. *Can Fuzzy Cognitive Maps be developed during a participatory stakeholder workshop*? It is crucial for the Story-and-Simulation approach to test if Fuzzy Cognitive Maps are sufficiently flexible, transparent, and understandable to enable development as additional part of a 2–3 days scenario development workshop.
2. *Will Fuzzy Cognitive Maps enhance the value of narrative storylines*? The effects of developing Fuzzy Cognitive Maps together with narrative storylines should be analysed.
3. *Will adding Fuzzy Cognitive Maps limit stakeholder participation*? It needs to be closely examined whether stakeholders successfully use Fuzzy Cognitive Maps and learn from the results, or whether they show signs of refusal to accept the method.

   Activities are ongoing to develop Fuzzy Cognitive Maps in 10 cases studies during participatory stakeholder workshops in a European project called SCENES (Kämäri et al., 2008). First results indicate that Fuzzy Cognitive Maps can be developed without hampering other activities and without limiting stakeholder participation, while stakeholders indicate an improved understanding of the system.
4. *Can semi-quantitative information be used to inform quantitative models*? This will entail either semi-quantifying mathematical models (e.g. through normalisation), or quantifying Fuzzy Cognitive Maps. The latter could entail using the shape of the functions as present in the output of Fuzzy Cognitive Maps and using those to define differential equations.
5. *How can "time" (and "space") be better represented in Fuzzy Cognitive Maps*? Particularly the semi-dynamic character of Fuzzy Cognitive Maps should be improved. The use of delay factors and/or dummy variables to manage speed of processes is currently being investigated.
6. *Is Fuzzy Cognitive Map a good tool to model resilience*? Any further development of Fuzzy Cognitive Maps should account for the possibility to specifically model social–ecological resilience.

Within a project that aims at modelling the resilience of the Dutch Agro-Green sector (see Veldkamp et al., in press) these three aspects are being studied.

7. Conclusions

In conclusion, there are a number of arguments in favour of adding Fuzzy Cognitive Maps to the Story-and-Simulation approach. Fuzzy Cognitive Maps can particularly play a role as an aid to develop more structured narrative storylines that are better informed on key feedbacks. A second added value is the possibility to make more explicit what is the system understanding of those that develop narratives. Given that the added time constraints are small and the tool is very flexible, it can potentially be included in many scenario development exercises. Similarly, the added value of using the output of Fuzzy Cognitive Maps instead of stories facilitates the translation into model parameters. Additionally, Fuzzy Cognitive Maps could contribute towards the understanding of resilience in social–ecological systems. However, the semi-quantitative character of the information may limit its usability, depending also on the type of model that is being used. In other words, semi-quantification can be a blessing and a burden. In the worst case, Fuzzy Cognitive Maps may be less flexible than narrative scenarios and not sufficiently quantitative to facilitate the link with mathematical models. A number of possible improvements linked to these strengths and weaknesses should be tested and implemented to prevent the worst case from becoming a real threat. However, the tool is designed to be simple and transparent, and therefore it has – almost by definition – a number of important drawbacks. Rather than attempting to perfect Fuzzy Cognitive Maps, it is should be regarded as a tool that can become part of a larger toolbox, such as the Story-and-Simulation approach, and improvements should be made in the light thereof.

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