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A protocol for the conceptualisation of an agro-ecosystem to guide data acquisition and analysis and expert knowledge integration

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ABSTRACT

Innovative agricultural systems need to combine the production of goods with the provision of environmental services. When agronomists analyse or design multifunctional agro-ecosystems, they thus need to include knowledge of an increasing range of scientific disciplines (plant biology, soil science, ecology, etc.) while continuing to use their systemic approach as a cornerstone. Increasing amounts of knowledge of different types (concepts and data) will thus have to be included in systemic approaches that are developed in the agronomic domain. Knowledge integration and sharing are frequently hampered by the lack of detail in the assumptions made in each discipline. We hypothesise that a standardised description of the conceptual model underlying data collection and the analysis of agro ecosystems would improve transparency and knowledge integration.

Here we propose a protocol to formalise the conceptual modelling of an agro-ecosystem (CMA) related to a specific agronomic issue. The CMA protocol is implemented in four iterative steps: (i) structural analysis, (ii) functional analysis, (iii) dynamic analysis, and (iv) consistency check. The final product is a conceptual model of an agro-ecosystem whose key elements are a structured knowledge base and associated graphical representations. The protocol was drawn up based on three case studies concerning three different biophysical objects (coffee agroforest, cotton, grapevine) with different problems to be addressed. They are given here as an illustration of how to apply the CMA protocol, and to show how it can be used as a tool to build a systemic representation of a complex agro-ecosystem, as a tool for agronomic diagnosis and yield gap analysis, or as a tool to elicit a range of expert knowledge to design new field experiments.

The CMA protocol proved to be efficient in guiding the process of conceptualisation up to the point at which the variables that need to be measured in the field are identified and interlinked. It enabled elicitation and integration of knowledge from different biophysical disciplines and different types of expertise during the conceptualisation process. It also enabled identification of knowledge gaps, and the design and analysis of experiments to tackle complex problems. The CMA yielded by the protocol could be used again, thanks to its transparency and modularity. Further work is underway to improve the CMA representation and its uses in numerical model specification and in participatory methods for the design of cropping systems.

1. Introduction

One major change in agronomy in the last 10 years has been the increasing complexity of the systems investigated using experiments, field surveys and models in order to design multifunctional cropping systems that combine productivity and ecosystems services (Wery and Langeveld, 2010, Brussaard et al., 2010). To address these multidimensional problems (Millenium Goal Assessment, 2005: http://www.maweb.org/en/Index.aspx) agronomists collaborate with experts from a range of biophysical disciplines (plant biology, soil science, ecology, etc.) using agro-ecological approaches (Dalgaard et al., 2003). Each discipline has its own terminology and concepts and focuses on a particular way into the

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agro-ecosystem (plant organ, soil layer, field, landscape, etc.). In agronomy, the concepts used rely mostly on the dynamic interactions between a crop, a soil, a climate in a given agro-ecosystem (Balls, 1953, Brisson et al., 2006) and a farmer who pilots the system (Le Gal et al., 2010). These concepts have been built using other sciences such as physics (e.g., light interception, Monteith, 1977), plant physiology (e.g., radiation use efficiency and its regulation by water stress and nitrogen stress, Sinclair, 1986) or ecology (e.g. competition, Tilman, 1980). With the ongoing development of agro-ecology (Dalgaard et al., 2003), the inclusion of concepts from other disciplines in systemic analysis of crops and farms is likely to increase. Agronomic research deals with increasingly large sets of qualitative and quantitative data that concern different processes (e.g. plant physiology, soil biology, plant protection, ecosystems services), at different scales (cell, tissue, organ, plant, plant community) and for different time horizons (day, season, year, decade). To design innovative cropping systems, researchers also have to integrate knowledge from crop experts who have practical knowledge of the management and performance of cropping systems (Lançon et al., 2007). Collaboration with other biophysical disciplines requires a common view of the agro-ecosystem and of the problem to be addressed among experts from different disciplines. For such collaboration to function efficiently, each expert needs to have confidence in the common view of the system, and to understand how his/her knowledge is used i.e., how the specific scale and process of the system's structure, dynamics and performance used in his/her discipline will be integrated in the common view.

Building a shared view of a system is a critical step in successful interaction between experts (Voinov and Bousquet, 2010). A problem can be approached in many different ways depending on the disciplinary background of the expert concerned, on the different temporal and spatial analytical scales (Voinov and Bousquet, 2010), and on the mental model of their discipline (Heemskerk et al., 2003). These mental models act as "information filters" which are built on personal experience and which determine the theories and assumptions we use (Johnson-Laird, 1983). Mental models are "so basic to our understanding that we are hardly conscious of them" (Johnson-Laird, 1983). This generates "unspoken language" (Jacobsen, 1994), which needs to be explained for in-depth sharing. Another information filter can be the structure of a database, as it can limit the representation of information which is not easy to convert into numbers (Russell et al., 1999).

In software science, conceptual modelling is a standard step in the development of software models and databases. Its aim is "representing the problem domain performed for the purpose of understanding and communicating between developers and users" (ISO, Organisation for Standardisation, conceptual modelling standard; Juristo and Moreno, 2000). Conceptual models are also used to obtain a software description that is independent of the programming language (Dieste et al., 2003) and automatic code generation in the model-driven engineering approach (Papajorgji and Pardalos, 2006). Protocols for the conceptualisation of systems to be simulated are used in ecology and agronomy (e.g. Leffelaar, 1999), and are organised around the formulation of state and rate equations (Forrester, 1961). Today, however, these representations are still strongly oriented towards the implementation of software models. Consequently, they do not allow details to be included about the assumptions made concerning the structure and the functioning of the system or the logic behind the selection or non-selection of biophysical processes in the description of the system. It is also difficult to use such representations to include information acquired from qualitative data, expert knowledge, or field observations on key aspects of the problem since such information is hard to translate into rate and state equations. However it should be noted that a modelling environment like Simile (Muetzelfeldt and Massheder, 2003) can be useful to extract domain knowledge even when it is not used to generate simulation software.

During the period when the use of multi-agent models was expanding, they faced the problem of being understood and used by others than those who developed them. Grimm et al. (2006) observed that "readers cannot understand why some aspects of reality are included in the models while others are ignored". This led these authors to propose a standard to describe multi-agent models (Overview Design Details) to help make the model description more complete and easier to understand. This analysis led us to hypothesise that a standardised description of the conceptual model underlying data collection and analysis on agro-ecosystems would improve their transparency and facilitate the elicitation and integration of expert knowledge in a systemic view of a problem in the agronomic domain.

The objective of this paper is to propose a protocol for the conceptualisation of an agro-ecosystem to guide data acquisition and analysis, and integration of expert knowledge. The protocol was designed based on three case studies with different objects (a single plant or a crop) and different objectives (data analysis, data acquisition, and integration of expert knowledge).

2. Methodology for the conceptual modelling of an agro-ecosystem and case studies

2.1. The CMA protocol

The protocol for the conceptual modelling of an agro-ecosystem (CMA) is based on the principles of system analysis developed in biology (Von Bertalanffy, 1968), in industry (Walliser, 1977), in ecology (Odum, 1983), and in agronomy (Rabbinge and De Wit, 1989). The aim of the standardised protocol is to guide the translation of a specific problem (i.e., the type of question to be addressed concerning a specific cropping system) into a conceptual representation of the system. The protocol is organised in four steps combined in an iterative process which starts with problem definition (Fig. 1).

The starting point of the CMA protocol is the problem definition step, i.e. a specific systemic representation of the question to be addressed concerning a tangible object, in our case an agro-ecosystem. Although this may not seem very important, it needs to be done to avoid possible ambiguity concerning the problem to be addressed, particularly when experts from other disciplines may perceive the problem differently. A system is defined and organised with reference to a specific goal (De Wit, 1968; Odum, 1983), and is consequently not a self-existing entity. Agro-ecosystems are considered here as biophysical systems influenced by human interventions aimed at achieving agricultural production and other ecosystems services (Le Gal et al., 2010). Depending on the problem to be solved, they can be defined at different spatial scales (e.g. a plant or a field) and temporal scales (e.g. a month or several decades). Defining the object means specifying the type of crop-soil-management objectives.

The first step of the CMA protocol is the structural analysis the aim of which is to identify the limits of the system, its components and its environment. Agro-ecosystems interact with a multidimensional environment (i.e. biophysical, social, economic, and institutional; Ewert et al., 2009). In order to keep the major interactions within the system, we suggest breaking down the environment into active and passive environments (Walliser, 1977). The *active environment* comprises the elements from other systems that act on the system related to the problem (e.g. the climate and the technical system used by the farmers; Le Gal et al., 2010). The *passive environment* comprises the outputs of the system, which can be used to indicate the impacts of the system on other related systems.

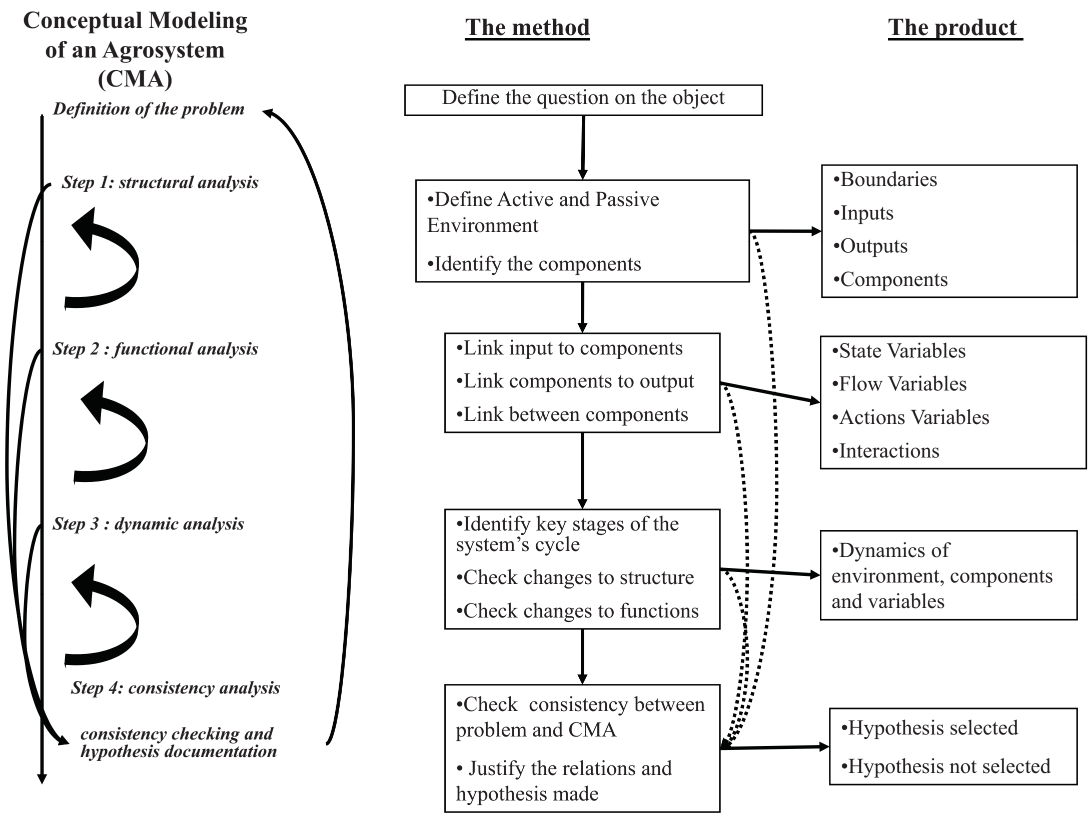

Fig. 1. The four steps of the protocol for the conceptual modelling of an agro-ecosystem (CMA) and the main components of its product.

The elements of the passive environment may be the performances of the system itself (e.g. yield, energy use efficiency) or the services it provides to other systems (e.g. clean water infiltrating into the groundwater, habitats for wildlife).

Most often, the *limits* of the agro-ecosystem are conceptualised as a volume defined by a soil area, a soil depth and a canopy height. The *components* of the system can be different biophysical entities (e.g. soil, plants, micro-organisms, animals), basic crop processes (e.g. photosynthesis, leaf growth; Wery, 2005, Adam et al., 2010a) or sub-systems (i.e. interacting components, Fig. 2). Like in dynamic modelling (Leffelaar, 1999), we characterise each component using one or several *attributes*, which are either state variables or parameters.

Step 1 yields a graphical representation (Fig. 2) which identifies the environment, the components and their justifications as an attached text giving the assumptions selected (or not) to define the structure of the CMA. The components of the system and the environment elements must be chosen with parsimony, keeping only those that have most influence on the system's behaviour with respect to the problem to be addressed. This avoids having an excessive number of relationships between components in the functional analysis (in Step 2).

The second step is the functional analysis, which corresponds to the identification of the main biophysical processes needed to solve the problem, while also taking knowledge and data availability into account. This implies identifying the major relationships which link: (i) each element of the active and passive environments to at least one component of the system, and (ii) each component to at least one other component. To facilitate quantitative analysis, we represent these relationships, as far as possible, as *flows* of matter (e.g. water or nitrogen), energy (e.g. light) or information (e.g. root to shoot signals). The other relationships are represented as *actions* by default (e.g. impact of a disease on biomass production) or actions by nature (e.g. leaf area reduction by an insect, removal of a bud during pruning by the farmer, etc.).

To avoid an increase in the number of variables to be measured or calculated, it is essential to rank these relationships in order of influence and to keep only those which are indispensable to solve the problem concerned. This implies that, instead of defining the variables of the model *a priori* with the components, they should be defined progressively and with parsimony during the course of functional analysis.

The third step is the dynamic analysis, i.e. studying how the CMA structure and functions are modified during the life span of the system (Fig. 1). One basic assumption of the protocol is that if Steps 2 and 3 have resulted in the correct representation of the structure-functions aspects of the agro-ecosystem, its dynamics will rely only on the evolution of the state variables of its components. The key temporal stages of the system dynamics (e.g. the phenological stages of a crop used to determine yield) are identified; then the structural and functional changes that occur between these stages are checked. Finally, this dynamic analysis could lead to modifying the preceding steps, i.e. adding or removing a component or a relationship which appeared to be essential (or not) at a particular stage of the system.

The fourth step is the consistency analysis. This is mainly achieved by iteration during the previous steps. In this step, the protocol needs to answer the following questions concerning both the knowledge used and the representation of this knowledge: Are the key assumptions concerning agro-ecosystem functioning correctly represented in the relationships among the components of the CMA? Do changes in the environment cause a change in the functioning of the system? Are the output variables of interest correctly represented and linked to the system?

It is also important to check that all the elements of the system (i.e. the system components or the elements of the environment)

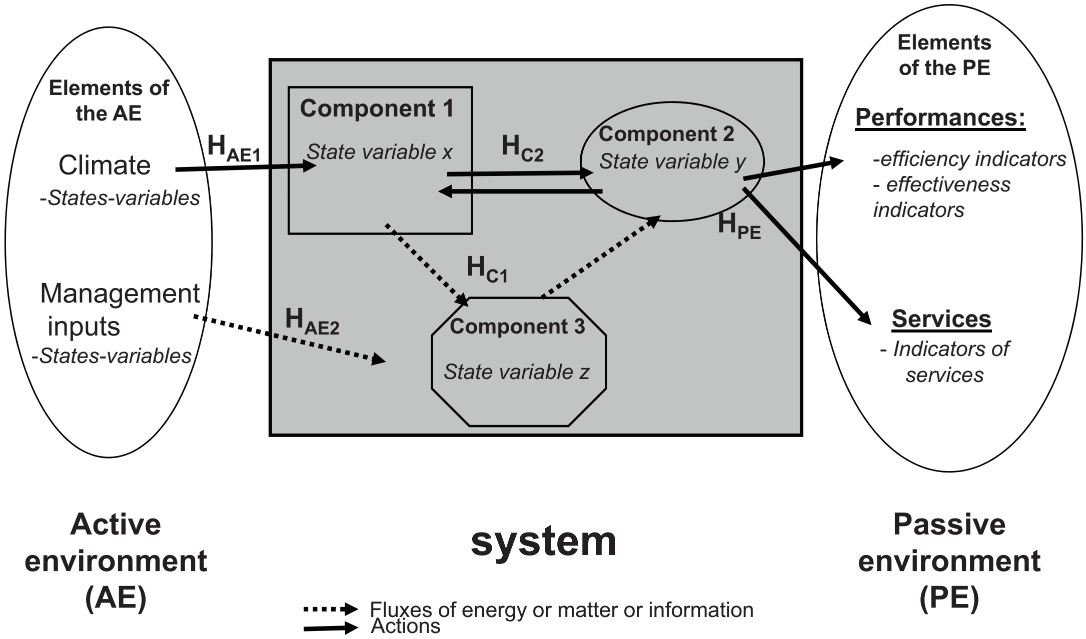

Fig. 2. An example of a conceptual model of an agro-ecosystem (CMA). The diagram should be read from left to right. The active environment (AE) groups the elements that influence the system (e.g. climate, management). They are characterized by state variables which define how they influence the system's components. The system is a combination of *n* components of different types (here $n = 3$) and its boundaries. Each component is characterized by state variables ($x;y;z$) that allow the relationship of each component with the active environment, with the other components, and with the passive environment (with flow or action variables) to be expressed. It shows the assumptions according to which the elements of the active environment are linked to the components of the system (H_{AE}), assumptions linking the components among themselves (H_C) and assumptions linking the components to elements of the passive environment (H_{PE}): e.g. H_{AE1}: the climate acts on component 1 through an action variable, modifying the state variable *x*; H_{AE2}: the management input state variable determines the flow of component 3 thus changing the state variable *z*. H_{C1}: component 1 acts on component 3, this action triggers an action by component 2 which influences component 3 (Indirect relation between components 1 and 2 through component 3). H_{C2}: component 1 acts directly on component 2 which in return acts on component 1 (feedback loop).

are linked to at least one other element. If an element remains isolated, it should be removed from the system or a relationship should be added. At this step, it is important to check that the assumptions concerning the structure, functioning, and dynamics of the system selected to produce the CMA are correctly documented (Fig. 1). This documentation should include the hypotheses concerning the structure and functioning of the model that have been retained and also those that support the exclusion of some candidate components/processes known to occur in the agro-ecosystem but considered to be minor with respect to the problem addressed. This documentation is essential for the transparency of the CMA, its update and for its re-use by others or to tackle other problems.

This protocol yields what we call a Conceptual Model of the Agro-ecosystem (CMA), which is a particular knowledge base dedicated to a specific question concerning a specific agro-ecosystem. The application of the protocol implies that the CMA has a number of different characteristics. The first characteristic is its hierarchical structure based on the definition of the systems, sub-systems and components connected by relations symbolizing either actions or flows. The second characteristic is the type of attributes of the CMA components and relations. Such attributes include the names of the related parameters or variables but also the key hypotheses concerning the system structure and processes that were identified during the different steps of the protocol. A convenient way to browse the CMA is to extract graphs from it, for instance the top level graph representing the system with the active and passive environments (see Fig. 2). Another typical graph that can be extracted is the graph of the components influenced by an element of the active environment (see Fig. 5).

2.2. Case studies

Our CMA protocol was drawn up progressively based on three case studies, each representing a specific combination of an object (a type of agro-ecosystem) and a question in the agricultural domain. Table 1 lists the range of agro-ecosystem and agricultural problems covered by the case studies together with the range of applications and bibliographical sources of the CMA (Table 1).

2.2.1. Case Study 1: Coffee agroforests in Guinea (West Africa)

In Guinea, agricultural development projects have failed to improve the livelihood of farmers through the introduction of improved coffee varieties and crop management because the farmers' practices were not taken into account in the design of the projects (Correia et al., 2010). Recent field surveys and interviews with farmers resulted in a sizeable pool of knowledge about their management of the agroforest and it performance, i.e. (i) the products provided by the coffee agroforest, their nature and uses (Diabaté et al., 2009); (ii) the effect of the diversity of the canopy over the coffee stands and their management by farmers on long term agro-forest dynamics (Lamanda and Wery, 2010a); (iii) the services provided by coffee agroforests in terms of coffee production (Lamanda et al., submitted for publication) and in the conservation of tree diversity (Correia et al., 2010; Lamanda et al., submitted for publication).

We used the CMA protocol to obtain a systemic representation of coffee agroforests in order to understand how the management of coffee agroforest fields could be further improved to increase farmers' incomes.

To be able to make proposals based on the links between farmers' practices, the structure of the canopy over the coffee trees, and the services provided by the coffee plants in the agroforest, the CMA needed to include the diversity of fields observed during field surveys. A researcher, who had taken part in the surveys as well as in data acquisition, used the protocol as a way to extract the knowledge acquired on the structure-function-performance relationships of a typical coffee agroforest plot in this region. It took

Table 1
The three case studies.

Case Study	Aim of using the CMA	Problem definition	Initial source of data and knowledge to build the CMA	Data and knowledge characteristics	References
Case study 1	*Ex post* formalisation of knowledge acquired during 2 years of field observations and interviews with farmers	What are the products and the level of tree biodiversity in coffee agroforest plots and their determining factors?	Farmers' surveys and field observations on canopy structure and composition, and coffee plants Personal experience of the author on agroforestry systems	Diverse by nature Wide range of situations	Diabaté et al., 2009 Correia et al., 2010 Lamanda and Wery, 2010a, 2010b Lamanda et al., submitted for publication
Case Study 2	Logical ordering of assumptions concerning the effects of the environment and of management on cotton yield in Mali, so that these assumptions could be tested individually with field data	Which biotic and abiotic factors explain the variability of yield between farmers' fields in the study area and to which farmers' practices are they related?	Expert knowledge and farm surveys	Wide range of situations Local and generic knowledge on cotton	Rapidel et al., 2006 Barrabé et al., 2007 Rapidel et al., 2009 Lançon et al., 2007
Case Study 3	Integration of expert knowledge of different types and at different scales	Which factors explain the decline of individual Syrah grapevines, taking into account the variability of the appearance of symptoms in space and over time?	Expert knowledge	Multidisciplinary knowledge	Delmotte et al., 2008 Claverie et al., 2011

about a week of work to implement the protocol, including further reading of field notes and survey results.

2.2.2. Case Study 2: Understanding the causes of cotton yield variability in Mali (West Africa)

The CMA protocol was used as a tool for diagnosis of crop performance (yield) in cotton fields managed by small scale farmers in Mali (Rapidel et al., 2006). Cotton acreage in Mali has increased steadily in the last 20 years. The new cotton production areas are located in agro-ecological areas where the soils are less favourable than in the agro-ecological areas where cotton has already been cultivated for decades. New farmers have entered the sector. The historic increase in yields ended in the 1990s, and, since then, yield variability has increased across fields and years. Understanding and ranking the factors responsible for yield variability was a precondition for designing innovative cropping systems in this region (Lançon et al., 2007).

The CMA protocol was applied by a team of cotton researchers working in collaboration with local farmers' advisors for *ex ante* formalisation of hypotheses concerning the effects of biotic and abiotic environmental factors and of farmers' practices on yield. Each hypothesis was expressed as a relationship between two variables of the CMA. This version of the CMA then guided (i) the selection of farmers' fields to be examined in detail, (ii) the measurements to be made, and (iii) the relationships between variables to be tested to check each hypothesis (data analysis). This case study showed that the CMA protocol could be used to guide the acquisition and analysis of data collected in field surveys and for the final integration of knowledge concerning a particular crop in a given region.

2.2.3. Case Study 3: Decline of the Syrah grapevine in southern France

Here the aim of the CMA protocol was to collect and combine dispersed disciplinary knowledge to produce a shared view of the plant syndrome (Syrah decline), in order to formulate new hypotheses on this complex system that would be tested in field experiments (Delmotte et al., 2008).

The decline of the Syrah grapevine was first observed in southern France in the 1990s. The first symptoms are cracks at the grafting point on some vines randomly distributed in the vineyard. A few years later (how much later varies with the field and the vines) leaves undergo early reddening in summer, sometimes resulting in the early death of the vine. Despite 15 years of observations and experiments (Spilmont et al., 2005), apart from a slight difference in sensitivity among clones (Spilmont et al., 2005), no single factor has been identified to explain the variability of the symptoms and of the final death, leaving wine growers with no means to overcome it (Chrétien et al., 2004). Several hypotheses linked to pathology, genetics, root physiology, etc., have been formulated but have never been tested or included in a systemic analysis of the syndrome.

The CMA protocol was used by two researchers in collaboration with 39 experts from different disciplines (agronomy, ecophysiology, genetics, molecular biology, pathology, and farmers' advisors) who work on vines or on other woody species. The first version of the CMA was developed in collaboration with five vine experts with knowledge of Syrah decline. It was then used as a systemic representation of plant dysfunction to elicit specific knowledge from the other 34 other experts. Each interview was conducted in four steps, with a maximum duration of 2 h, in order to: (a) explain the syndrome and review available knowledge with the expert, (b) ask for his/her opinions/assumptions about the dysfunction, (c) present the first version of the CMA and (d) ask him/her to reformulate his/her hypotheses in the framework of the CMA. If the factors or relations suggested by the experts could be consistently linked with components, states or flow variables and with the symptoms of the decline, they were included in the CMA. If not, the information was not included in the model but was kept along with the bibliographic references, in written form.

3. Applying the CMA protocol on cases studies

3.1. CMA as a tool to build a systemic representation of a complex agro-ecosystem from scattered data and field observations (illustrated with Case study 1)

In Case Study 1, the problem was reformulated as "What are the plant products and the level of tree biodiversity in coffee agroforest plots and their determining factors?" The limits of the system were defined as a 3-dimensional biophysical object. The system is a small area (from 0.5 to 2 ha) that corresponds to a portion of a farmer's land with a homogeneous canopy over the coffee stands (i.e., all the coffee trees were planted at the same date, the vertical profile had a similar number of strata, the same practices were applied, and the soil was assumed to be homogeneous). The other system dimensions were the maximum height of the trees in the tree strata and the deepest soil layer explored by the coffee tree roots in this type of soil.

Fig. 3 shows the CMA of the coffee agroforests resulting from the structural analysis (Step 1 in Fig. 1). The active environment was defined as a combination of three elements: (i) the technical system (Le Gal et al., 2010) which was defined by coffee tree pruning, hand weeding, selective cutting of timber trees); (ii) the climatic conditions, in this case limited to incoming light which partly determines coffee yield, and the tree diversity of the coffee agroforests; (iii) the immediate vicinity of the plot, whose nature and composition influence the recruitment of weeds and seed trees in the system as well as the functional biodiversity related to coffee pests and diseases. The system had five components: "Soil", "Weeds", "Coffee-tree stratum", "Pests and diseases", and "Tree strata". The "tree strata" was split into sub-components according to their height. The species composition and the species density of each sub-component were recorded. The passive environment was limited to indicators of the different products (e.g. coffee yield, quantity of oil palm) and of the resulting level of tree biodiversity (e.g. indexes of species richness; Correia et al., 2010).

During the functional step (Step 2 in Fig. 1), we formalised the hypotheses on the relationships between farmers' practices, canopy structure and services provided by the coffee agroforest plots. The main hypothesis was that the main process influencing the system's functioning was partitioning of light among the canopy strata (Fig. 4, hypothesis $H.AE_{1a}$). We assumed that incident solar radiation (one element of the active environment) enters the system through the tallest tree stratum and is shared among the substrata as a function of the height and percentage of canopy cover of each stratum. The amount of light received by the coffee tree stratum was also assumed to be the main variable influencing the activity of pests ($H.AE_{1b}$ in Fig. 4). This assumption was based on local observations that the severity of attacks by major pests differed according to the light conditions (Bah, personal. communication).

In accordance with the parsimony principle of the protocol, we did not retain the initial hypothesis on the effect of rainfall on the system as it appeared to be of secondary importance for production and biodiversity conservation in these humid tropics. Hypotheses were added concerning the impacts of farmers' practices on the "tree strata" ($H.AE_2$ in Fig. 4), on the "coffee tree stratum" ($H.AE_3$: in Fig. 4) and on the "weed stratum" ($H.AE_4$ in Fig. 4). A hypothesis related to the effect of the neighbouring vegetation was also added to account for the recruitment of trees from seeds originating from nearby vegetation. It was assumed that this factor affects tree biodiversity and in particular the presence of threatened wildlife species in the system ($H.AE_5$ in Fig. 4). The nature and composition of the neighbourhood were also assumed to influence attacks by coffee pests ($H.AE_6$ in Fig. 4).

The elements of the passive environment were easily linked with specific components of the system as they were derived from the attributes and state variables of these components. For example, the quantity of mature coffee berries (an indicator of the system's productivity) can be derived from coffee tree density, the number of stems per coffee tree, the number of berries per stem and average berry weight. The index of tree species richness was related to the composition of the "tree strata" component through the number of species and the number of trees per species in each substratum.

The dynamic analysis (Step 3 in Fig. 1) covered the life span of the coffee trees (more than 30 years) which was assumed to be the main factor that determines farming practices and services (production and tree diversity). This means that we considered the stages of the other components to be less important to address the problem. Using the key phenological stages of coffee trees, the coffee life span was divided into four stages (Table 3). We then checked if the proposed CMA needed to be modified to describe the different stages of the system's life span adequately. Table 2 shows that the structure of the CMA was able to describe changes in the coffee agroforest services (output of the CMA) across the different stages of the system only as the result of changes in farmer's practices (used as inputs into the CMA). The different types of plots identified in the region, as well as a generic plot, can be represented by adjusting inputs and the state variables of the components (e.g. variations in the number and composition of the tree strata above the coffee stands can be represented by varying the attribute of the "tree strata" component; Lamanda and Wery, 2010b)

The CMA in Case Study 1 and its corresponding hypotheses were easy to share with other agronomists working on similar cropping systems (Jagoret, personal communication). The CMA is now being extended to cocoa agroforests. It represents a dialogue tool in a collaborative process between agronomists working on agroforests based on perennial crops. Its hypotheses will be further tested in a network of farmers' fields to validate the CMA so it can be used as a basis for improving farmers' management of agroforests (as shown in Case Study 2).

An alternative (and more traditional) way to explore the pool of data acquired in field surveys and interviews with farmers would have been statistical analysis (e.g. PLS regression, CPA, Torabi and Soltani, 2010). But without starting hypotheses based on a functional analysis of the biophysical system, the results of such statistical methods are often difficult to analyse (Dagnelie, 1998), and do not really help derive a systemic view of the structure-function-performance of the agro-ecosystem (Loyce and Wery, 2006). The CMA protocol resulting in the formulation of hypotheses on system functioning is thus a tool for pre- and post-analyses in statistical factorial analysis, rather than an alternative approach

3.2. *The CMA protocol as a tool for agronomic diagnosis and yield gap analysis (illustrated with Case Study 2)*

The CMA protocol was used to rank the limiting factors of cotton yield in farmers' fields in Mali (Rapidel et al., 2006). The problem was formulated as "what are the biotic and abiotic factors that explain yield variability between farmers' fields, and to which farmers' practices are they related?"

The active environment was a combination of specific elements of the technical system and of the climate expressed as variables determining the water balance and plant phenology: sowing, thinning, weeding, organic and mineral fertilisation, insecticide application, and rainfall. Other environmental variables were also considered (solar radiation and temperature), but at the scale of our small study area, their spatial variability was too limited to be included in the CMA. This assumption related to elements that were not included in the CMA was added to the knowledge base. The passive environment was limited to seed cotton yield, separated into average boll weight and number of bolls per square meter. The components were chosen as being significant for the physiological functioning of the system with regards to the active and passive environment (i.e., stand density, LAI and above-ground biomass, soil mineral status and water status, and pest infestation).

The functional analysis linked seed cotton yield to the number of bolls per hectare, which in turn depends on boll set – itself related in a non-linear way to total biomass (Wery, 2005) – and to the boll retention rate. Next, each biotic factor (e.g. water stress) or the agricultural operation (e.g. weeding) was linked to the main

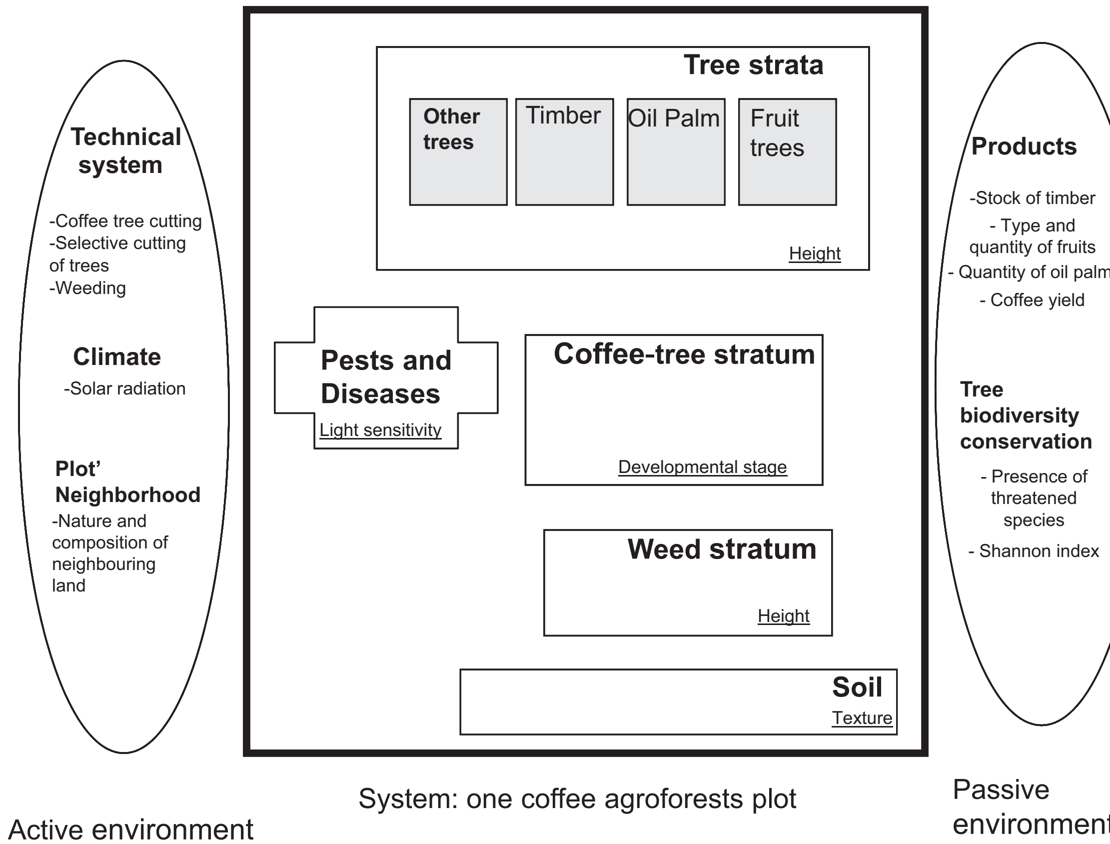

Fig. 3. An example of a structural representation of an agro-ecosystem produced by Step 1 of the CMA protocol in Case Study 1. The diagram represents the three-part structure of the CMA (Active Environment, System, and Passive Environment). From left to right it shows:

(i) The selection of the main elements of the active environment which influence the system in the case of the problem concerned (farmers' practices, climate and neighbouring land).
(ii) The selection of the set of system components identified as necessary and sufficient to describe the agro-ecosystem for the problem at stake. The different shapes of the boxes representing the components indicate the different natures of the biophysical entities chosen as components (weed, coffee trees and other tree strata, pests, soil). Like in numerical models, the attributes of these components (underlined) are either variables or parameters.
(iii) The selection of the elements of the passive environment and the variables that define it with respect to the problem at stake.

According to the parsimony principle, only the main elements are selected and represented. For example, rainfall is not included in the diagram because we assumed that the partitioning of solar radiation among the components is the main climatic factor explaining coffee agroforest services and performances in the conditions prevailing in Guinea.

variables or to the variables preceding them (e.g. LAI at flowering, related to subsequent biomass build-up) (Rapidel et al., 2006).

The CMA organised agronomic knowledge on cotton grown in Mali around the identification of five main hypotheses on the origins of yield variability. The hypotheses were inserted in the CMA in the form of relationships between the state variables of specific components. The hypotheses were then tested sequentially using the measurements made on state variables of the components in a network of 30 farmers' fields (Rapidel et al., 2006). The main hypothesis of the CMA was that in an indeterminate crop like cotton, the number of bolls depends on the balance between carbon sources (linked to light interception by mature leaves) and carbon sinks (linked to leaf growth and stem branching) (Wery, 2005). This hypothesis, which implies that the number of bolls can be linked to a particular type of curve representing shoot biomass dynamics during the crop cycle (Rapidel et al., 2006), was also tested. It was validated by field measurements which revealed a relationship between the type of biomass accumulation curve and the number of bolls per square meter across all the fields (Rapidel et al., 2006). Some initial CMA hypotheses were kept while others were discarded, as they did not explain the observed yield variability. For example, pest incidence was low, probably due to systematic spraying of insecticides, and was not correlated with yield variability. Other variables had to be added to the model, for example, soil water content was identified as being positively correlated with the vegetative development of the stand, despite the fact rainfall was relatively homogeneous in the small study area. Thus, water infiltration was assumed to be a major factor explaining the variability of water status. In this way, the initial CMA was calibrated became the final CMA which provided a systemic representation of yield determination in the study area (Rapidel et al., 2006). The final CMA was used to identify possible pathways for the improvement of the cotton cropping systems, and these were then tested in farmers' fields (Barrabé et al., 2007) or at experimental stations (Rapidel et al., 2009).

What other methods could have been used to achieve the same objective? On-station experiments assessed using variance analysis (Lançon et al., 2007) do not satisfactorily cover the variability of field conditions and are thus not a valid option. A regional agronomic diagnosis (Doré et al., 1997, 2008) could have produced the same results, but given the lack of an initial conceptualisation of the system, it would have probably meant measuring more state variables in each field. By imposing the formalisation of a limited number of hypotheses linked to state variables of specific components, the CMA reduces the set of measurements required. Another alternative method would be yield gap analysis by removing the limiting factors in small experimental plots, and comparing the results with those achieved with farmers' practices (e.g. Cretenet

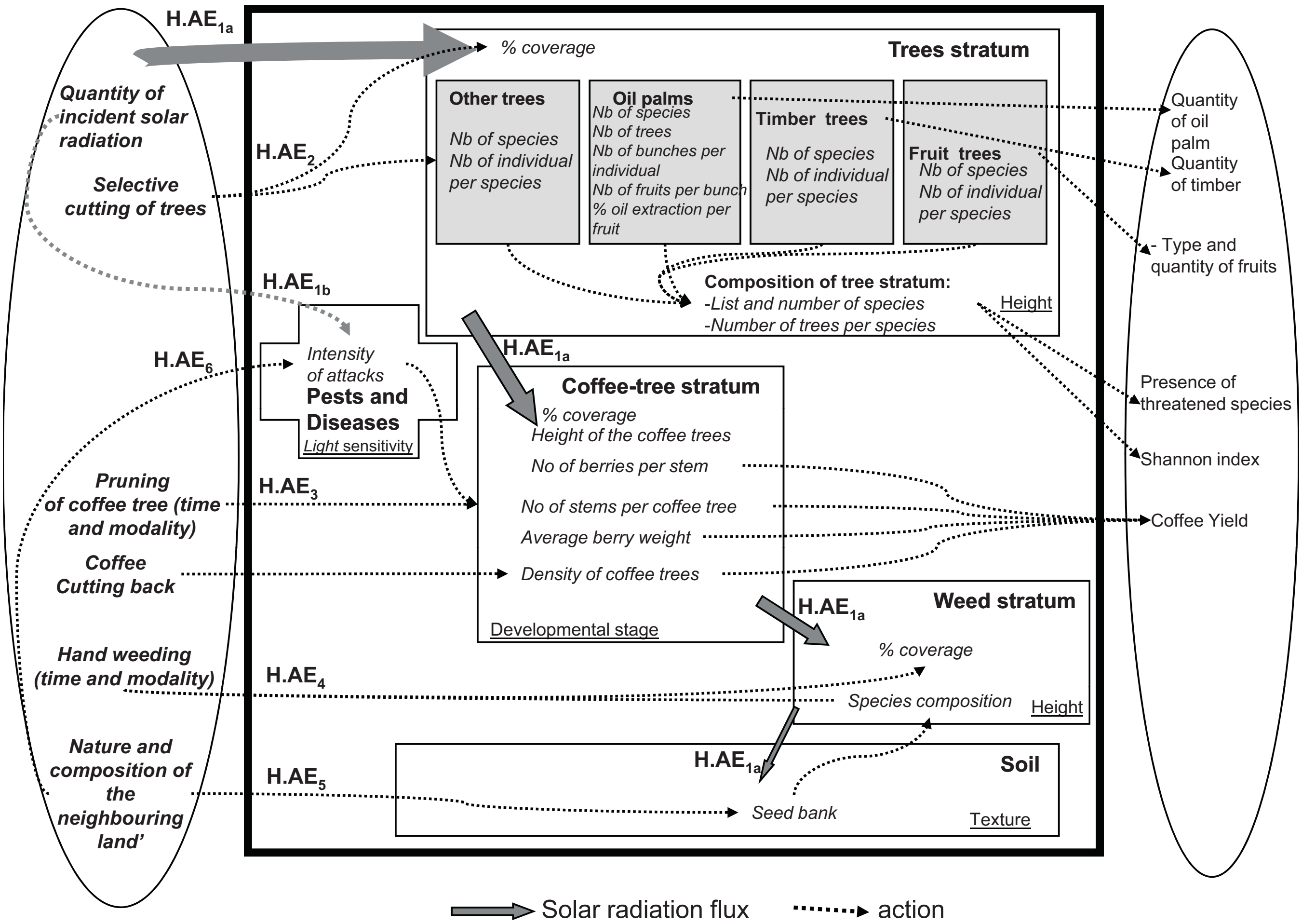

Fig. 4. Functional analysis of plant production and tree biodiversity conservation in farmers' fields in coffee agroforests in Guinea. The diagram shows the main hypotheses and the state variables (in *italics*) linking the structural elements of the system:

- $H.AE_{1a}$: A given quantity of light is shared among the strata according to their percentage of coverage and determines production (coffee yield, quantity of palm oil, number of oil palm trees, quantity of timber, type and quantity of fruits) and tree biodiversity (presence of threatened species, Shannon index).
- $H.AE_{1b}$: The amount of light affects the intensity of attacks by pests and diseases which may reduce the coffee yield.
- $H.AE_2$: The selective cutting of trees controls the species composition of the tree strata (on which the conservation of tree biodiversity is evaluated) and the nature and quantity of the products harvested.
- $H.EA_3$: The time and modality of coffee tree pruning affects the number of stems per coffee tree, and the number of berries per stem, which are used in determining coffee yield.
- $H.EA_4$: The time and modality of hand weeding controls species composition and the percentage coverage of the weed stratum.
- $H.EA_5$: The nature and composition of the vegetation in the vicinity of the plot influences the seed bank, and thus affects the level of tree biodiversity and the presence of threatened species.
- $H.EA_6$: The nature and composition of the neighbouring land affects the occurrence and the intensity of attacks by pest and diseases in the coffee agroforest plot.

and Tittonell, 2010). This method has already been applied in Mali (Barrabé et al., 2007), but the number of factors to be tested is limited and with this approach there is a risk of focusing on factors that are easily managed in small plots (i.e. growth regulators, fertilisers and pesticides). CMA is a complementary protocol to these two methods. It has to be implemented before field work in order to conceptualise the selection of the hypotheses to be tested and the variables to be measured, rather than as an alternative method to factorial experiments and in-field yield gap analysis.

3.3. The CMA as a tool to integrate broad interdisciplinary expert knowledge (illustrated with Case Study 3)

In Case Study 3, the aim of the CMA was to integrate broad interdisciplinary expert knowledge to answer the following question: "Which factors explain the decline of individual Syrah grapevines, taking into account the spatial and temporal variability of the appearance of the symptoms?" Before this study, the main hypothesis was that reddening and death were linked to (i) the presence of cracks at the grafting point (due to genetic incompatibility between the shoot and the rootstock genotypes, possibly combined with the presence of a pathogen), (ii) modulated in some way by several biophysical factors (plant, soil and climate) after planting (Spilmont et al., 2005). However, none of the experiments conducted identified a clear relationship between any particular biophysical factor and the syndrome. In the CMA, the 2-dimensional boundaries of the system were defined by the shoot and root extension of a mature grapevine. The active environment was reduced to the main climatic factors which influence soil water status (rainfall, reference evapotranspiration). The passive environment was defined by indicators of the system's dysfunctioning: the probability of a vineyard expressing the symptoms and the number of vines that die as a

Table 2
Dynamic analysis in Case Study 1 (tree biodiversity conservation and production of farmers' coffee agroforest plots).

Element of the CMA	Stage of coffee production			
	Unproductive (0–5 years)	Beginning of productive stage (6–15 years)	Productive stage (16–30 years)	Decline in yield (>30 years
Active environment	- Farmer's practice specific to this stage: "planting of coffee trees"	- Two new practices: pruning of "coffee trees" and "selective cutting" in the component "tree strata" - Continued "hand weeding"	- No change in farmers' practices	- A new practice "selective regeneration of coffee trees by cutting back"
Passive environment	- No element linked to the component "coffee trees"	- Appearance of a new output: "coffee yield" - Change in the output "Shannon index and presence of threatened species" - Change in products (in nature or quantity)	- Increase in the output "coffee yield" - Change in the output "Shannon index and presence of threatened species" - Change in products (in nature or quantity)	- Output "quantity of coffee" decreases - Change in the output "Shannon index and presence of threatened species" - Change in products (in nature or quantity)
Structure of the system	Appearance of the component "coffee tree stratum", below the component "weed stratum"	- Changes in the order of the components ("coffee tree stratum" moves above "weed stratum") - Changes in the component "tree strata" with a decrease in the number of some subcomponents due to cutting of trees by farmers	- Change in the component "tree strata" with a decrease in the number of subcomponents	- Splitting of the component "coffee tree stratum" with a new component "regenerated coffee trees"
Functioning of the system	- Flow of solar radiation is split among the plants according to their height	- The component "coffee tree stratum" increases its percentage coverage and its interception of solar radiation - The component "tree strata" decreases its interception of solar radiation with its percentage cover	- The component "coffee tree stratum" is at its maximum solar radiation interception - The component "tree strata" decreases its interception of solar radiation	- The component "coffee tree stratum" decreases its interception of solar radiation

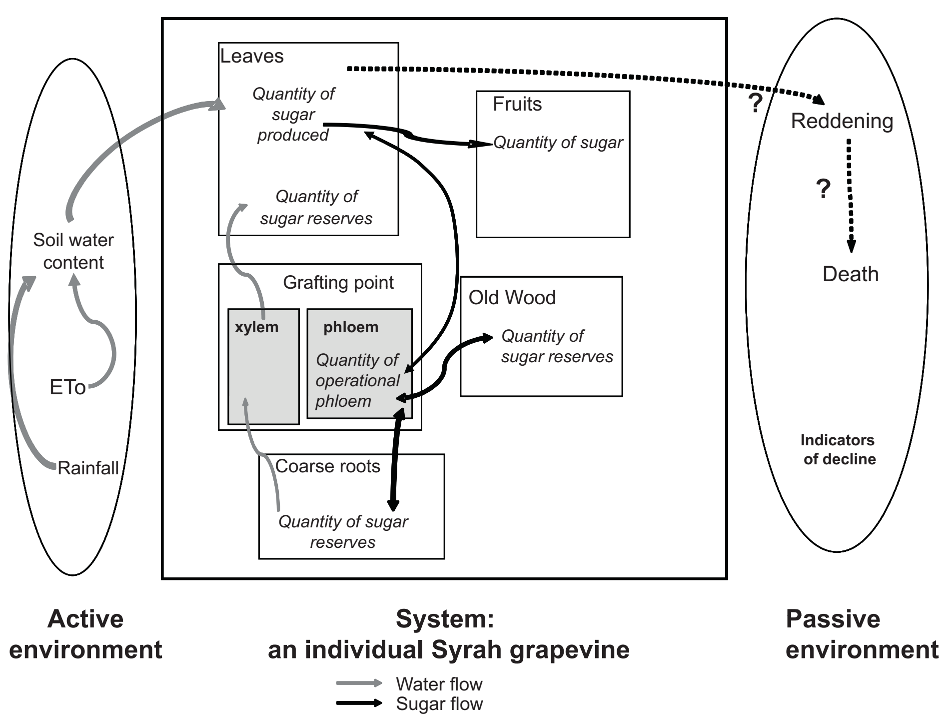

Fig. 5. Example of a representation of the functional analysis of Syrah decline in Case Study 2. The CMA represents an individual Syrah grapevine. The system has four components: coarse roots, grafting point, old wood, mature leaves and fruits. The state variables that characterise each component are in *italics*. The elements of the active environment are biophysical factors only (reference evapotranspiration, (ETo), rainfall and its effect on soil water content) and we define the passive environment using indicators of deterioration (reddening of the leaves, death of the plant). The grey arrows show the major water flows in quantitative terms. The black arrows show flows of carbohydrate.

result of the syndrome. Fig. 5 shows the structural analysis of the system, which was initially built in collaboration with five experts of Syrah decline (the first version of the CMA). At this point, there was no hypothesis indicating which type of flow to focus on (water, carbon, nitrogen, hormones) to explain the decline. The functional analysis was built progressively in collaboration with each plant physiology expert. Each interview led to the modification of flows and, by iteration, to modifications in the structure of the model.

For example, during feedback between the functional and structural steps, the component "coarse roots" was added because these roots are involved in the storage of soluble carbon and nitrogen and its use for the development of the bud and primary stems the following year.

The dynamic analysis (Step 3 of the CMA) covered a time span of one year i.e. an entire crop cycle, including dormancy and growth. Key stages were identified on the basis of source-sink relationships during the plant cycle (Table 3). This analysis of changes in water and soluble carbohydrate flows within the plant was used to check that the knowledge from different disciplines yielded a coherent system. It allowed the succession of the symptoms of decline to be explained by source-sinks relationships across the key stages of the annual plant cycle and in two or three successive years (Claverie et al., 2011). The starting hypothesis (which formed the basis of the CMA) was formulated by several experts i.e. (i) the cracks at the grafting site reduce the diameter of phloem tissues and as a consequence, reduce the transport of carbohydrates. Complementary hypotheses were formulated based on the analysis of flow dynamics: (ii) reddening could be due to an accumulation of carbohydrates in the mature leaves, leading to the synthesis and accumulation of anthocyanins (Solfanelli et al., 2006). This accumulation of carbohydrates could be the result of a reduction in the down flow of carbohydrates whereas a certain level of photosynthesis is maintained; (iii) in the following spring, the lack of carbohydrates stored in the roots could explain the death of the plant due to the absence of root growth (Bates et al., 2002) or of water pressure in the xylem (Ameglio et al., 2001); (iv) the irregular appearance (or not) of the reddening and plant death across years could be explained by the cumulative effect of the phloem deficiency on root reserves combined with the occurrence of late water stress in a particular year leading to a cessation of photosynthesis (Roitsch, 1999). In the case of late water stress, no reddening would appear but sudden death of the grapevine could occur. This is consistent with the sequence of events observed in the field (Claverie et al., 2011).

An alternative method to integrate expert knowledge to create a common view of a complex syndrome such as Syrah decline would be mind mapping (Lloyd et al., 2010; Magcale-Macandog and Ocampo, 2005). This approach would probably have made interactions with experts easier and quicker and facilitated the formalisation of the system's structure. But as mind mapping methods are based on the absence of initial structuration of the plant system, it would have complicated the identification of the functional and dynamic aspects of the system. In addition, the CMA protocol forces experts to identify a limited set of key assumptions that are translated into relationships between specific state and flow variables. The final version of the CMA, which was shared and validated in a group meeting (attended by experts who had not been previously interviewed), enabled the definition of the experimental design (growing conditions and the variables to be measured) to test the CMA hypothesis under field conditions (Claverie et al., 2011). These experiments are still underway but preliminary results already enabled rejection of one hypothesis (bud deficiency at the beginning of the cycle due to a reduction in the flow of carbohydrates in the previous autumn) and suggest that phloem reduction is the main determining factor. These results could form the basis of improved crop management to avoid Syrah decline (Spilmont and Claverie, 2009).

4. General discussion about the CMA protocol

In the three case studies, the CMA protocol proved to be an efficient tool to guide the process of conceptualisation of an agro-ecosystem up to the point at which the variables to be measured in the field are identified and interlinked. Thanks to its transparency and modularity, the CMA protocol helps capture and integrate knowledge from different disciplines and of different natures in the conceptualisation process. It is therefore complementary to existing methods used to collect data on agro-ecosystems (experiments, field surveys) and to analyse them (statistical analysis, dynamic modelling). However, its use in the three case studies drew our attention to three aspects which need improving (i) the normative nature of the protocol, (ii) the representation of the CMA for transparency and re-usability and (iii) the need to link it with numerical simulations.

4.1. The normative aspect of the CMA protocol

The CMA protocol may appear constraining because of its systematic and normative approach (Fig. 1). For example, Case Study 2 showed that the progressive building of the CMA in four steps was too long for the experts concerned, most of whom were also crop modellers. They were tempted to define the main relationships without taking the necessary time to define the problem and the structural elements. We also observed that the parsimony principle, which is a key aspect of the CMA protocol to reduce the number of variables to be measured, is not easy to apply when selecting components, relationships or assumptions. For example, in Case Study 1, in the first version of the CMA, we kept a large number of components (Fig. 4) because we were unable to rank them with respect to the problem to be addressed.

The successive steps of the CMA protocol (structural, functional, dynamics) and the iterative consistency check is a way of ensuring the transparency of the CMA. The documentation of the hypotheses and knowledge used at each step is essential for future updates or for re-use of the CMA: addition of new knowledge, its application to other problems or objects, and even its re-use by users other than its developers.

The application of the overall CMA protocol with its successive steps can be time consuming. While it only took a week to implement it in Case Study 1, four months were needed to collaborate with the 39 experts in Case Study 3. Although this amount of time need could be considered as an limiting factor, it was still acceptable compared to the cost of carrying out unsuitable experiments e.g., 15 years of inconclusive experiments as was the case in Case Study 3. It appears to be difficult to reduce the time and effort needed to document the CMA of a complex system, to ensure it is independent of the mental models of its developers and therefore more transparent for others and easier to use for the collection and interpretation of field data.

4.2. The representation of the CMA

The representation issue has two aspects: the knowledge base associated with the CMA and its link to a set of graphical representations that can be shared with other users than its developers.

In Section 2.2, we described a formalism based on graphs for the graphical representation of the CMA (i.e. a structured representation made up of the components, their relationships and their underlying assumptions). To better manage the complexity of the system, this formalism needs a dedicated software tool. In particular, at the end of the functional step, the large number of components and relationships makes the diagrams and their documentation difficult to draw and hence difficult to read by others. A dedicated CMA representation tool would help build this representation at different scales and for different processes, while keeping the full set of information that defines the CMA in a single knowledge base. One important feature of such a tool would be its ability to represent different spatial scales (e.g. organ, plant, canopy) of the system and to move backwards and forwards between scales while adjusting the complexity of the description to

Table 3
Dynamic analysis of the CMA in the analysis of the causes of Syrah decline.

Element of CMA	Stage of annual plant cycle					
	Before bud break	At bud break	Between bud-break and fruit setting	Between fruit setting and ripening	Between ripening and sugar maturity (harvest)	After harvest
Active environment	Soil temperature	Soil and air temperature	ETo, rainfall	ETo, rainfall	ETo, rainfall	ETo, rainfall
Passive environment	Plant death?	Plant death	–	–	Leaf reddening	Leaf reddening
Structure of the system	Old wood and roots, buds	Old wood and roots, buds	Old wood and roots, leaves	Old wood and roots, leaves	Old wood and roots, leaves, fruits	Old wood and roots, leaves, buds
Functioning of the system	Water enters the roots, passes through the old wood via the xylem to hydrate the buds	The buds consume their stock of sugar, roots send some sugar and finally young leaves produce sugars (photosynthesis)	Leaves produce sugar using the water that is absorbed by the roots, sugar used for leaf growth and root reserves	The production of sugar by leaves may be reduced by water stress. The amount of sugar decreases, but still goes to roots, wood and leaves. A small amount goes to flowers	Some of the sugar produced starts to be sent to fruits and the remainder to roots. If water stress is strong and photosynthesis low, no sugars may go to roots	Once the grapes have been harvested, the sugars produced are used by the roots and the old wood to renew their reserves. If the flow of sugar to roots is limited by a reduction in phloem at the grafting point, sugar remains in the leaves causing leaf reddening

the type of expert involved. For example, focusing on specific relationships linking components (e.g. carbohydrate flow in Case Study 3) requires discussion with a plant physiologist, whereas focusing on the input/outputs (e.g. in Case Study 1) requires interacting with farmers and advisers. In some cases, the representation of the diversity and spatial heterogeneity of the system (soil type, canopy structure, etc.) which may be inherent to a particular field (e.g. in Case Study 1) or to a network of fields (e.g. in Case Study 2), may also be difficult to manage. As pointed out by Ratzé et al. (2007), hierarchical organisation of the system is essential to address the problem of the graphical representation of complex systems. It means complexity can be broken down into scales, component diversity and heterogeneity, and the system's structure can be linked to biophysical processes.

A CMA representation tool would also need to be able to link graphical representations to a hierarchical organisation of the knowledge base. This means that the available expert knowledge and the assumptions need to be linked to the structural or functional elements of the graphical representations. To our knowledge, existing representation tools (either graphical or knowledge-based) only partially fulfil these requirements. For example, the UML language (http://www.uml.org/) could be used to improve the graphical representation. This language could provide compact standard notations that are useful for the representation of the structure of the system (e.g. generalisation or aggregation relationships could help cope with spatial heterogeneity). But the whole CMA could not be written in UML, which is not suited for the hierarchical documentation of the knowledge base associated with the graphical representation. In contrast, software tools like AKT (Agroecological Tool Kit) would make it possible to merge the perceptions of different actors related to a system (Dixon et al., 2001; Rebolledo et al., 2009). AKT has been used to store and organise data based on local and expert knowledge on crop-environment interactions in coffee agroforestry systems (Rebolledo et al., 2009). However the graphical representation it creates did not satisfactorily represent the many relationships among the elements of the system contained in the database (Rebolledo et al., 2009), mainly because the associated knowledge was not organised hierarchically. Further investigations are underway to solve the problem of the CMA representation and we are moving from a combination of individual diagrams and documentation (used in the case studies reported here) to a specific software tool combining a knowledge base and a graphic user interface able to generate specific diagrams.

4.3. Linking CMA with numerical simulations?

The primary aim of the CMA protocol is not the specification of numerical simulation software as is the case with other methods coming from the field of systems analysis (Leffelaar, 1999). But since the CMA protocol results in the formalisation by experts of the knowledge base corresponding to a specific question concerning an agro-ecosystem, it has certain properties that could help perform this task. Embedding domain knowledge representation in a visual modelling environment (e.g. Muetzelfeldt and Massheder, 2003) or in a simulation platform is proposed for example in Müller (2007) and Beck et al. (2010). In Roux et al. (2010), the CMA was explicitly used as the representation of a crop model in the agronomic domain, interacting with representations in mathematical and software domains.

The CMA can be used as accompanying documentation for numerical software: it provides details on the agronomic hypotheses and their validity domain and could thus help prevent misuse of the associated simulation tool (Roux et al., 2010). But the CMA protocol could also be useful for building models, because it generates some characteristics of a dynamic simulation model: components, input and output variables, state variables, and parameters. More generally, the CMA can be considered as a level of representation designed for knowledge sharing between model developers and scientists who are not experts in numerical modelling. For instance, using the CMA can help select an existing model on the basis of a shared conceptualisation of crop functioning, variables and parameters (Adam et al., 2010b). To be efficient for agronomic research, we believe that the description of this conceptualisation should remain in the agronomic domain. This implies that it remains clearly separated from simulation environments in order to be fully understandable by experts in basic crop processes who are not experts in numerical modelling (Wery, 2005; Adam et al., 2010a).

5. Conclusion

To our knowledge, this paper is the first attempt to formalise a systematic protocol for the conceptual modelling of an agro-ecosystem. The method was tested on three case studies and was shown to be efficient in guiding knowledge formalisation (Case Studies 1 and 3) and data acquisition and interpretation (Case Study 2) on a range of biophysical objects (from an individual plant to a complex cropping system). While guiding the building of a common view of a problem into a description of the system, the Conceptual Model of an Agro-ecosystem (CMA) protocol enabled the collection, discussion and sharing of concepts and assumptions that are often concealed within scientists' mental models or difficult to read at this level of detail in computer model documentation (Roux et al., 2010). The final version of the CMA can be seen as a shared synthesis of knowledge which can also be used to organise data acquisition, analysis and synthesis in networks of farmers' fields (Case Study 2), to design field experiments for complex systems (Case Study 3), or to identity knowledge gaps (Case study 1). Further development of the CMA protocol is currently underway using farming systems (scaling down and scaling up between field and farm levels), which will enable more tests of the method and the scope of application to be extended to the design of cropping systems at farm scale (Merot et al., 2009). The protocol is also currently being used to teach agronomy at MSc level as a tool to formalise and discuss knowledge extracted by students from lectures and papers. Further improvements in the representation of the CMA, using specific software tools, are also underway, with the aim of enabling the re-use of CMA by agronomists and the sharing of these conceptual models with other disciplines (mathematics and software engineering) for the development of crop models (Roux et al., 2010).

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