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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.