RECORD: an open platform to build, evaluate and simulate integrated models of farming and agro-ecosystems

Jacques-Eric Bergez[1,2], Hélène Raynal[3], Frédérick Garcia[3]
1: INRA, UMR 1248 AGIR, BP 52627 F31326 Castanet Tolosan France – jbergez@toulouse.inra.fr
2: INP-T, UMR 1248 AGIR, BP 52627 F31326 Castanet Tolosan France
3: INRA, UR0875 UBIA, BP 52627 F31326 Castanet Tolosan France

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Abstract
The rapid change in the agricultural industry requires the development of new methods of production to guarantee sustainable agriculture. In silico approaches offer the possibility to identify more quickly new systems to tackle current social, political and environmental concerns. Numerous agro-ecosystem functioning models already exist. Nowadays the main issue is more to couple and use them at different spatial and temporal scales rather than developing new ones.
INRA set up an integrated modelling framework to gather, link and provide models and companion tools to answer new society questions regarding agriculture. Functional specifications were drawn during a two-day meeting in January 2007. Requirements are: to develop new models as modular components, to re-use and combine them to represent cropping and farming systems at different time and spatial integration steps; to allow the modelling and simulation of farmer's decision making process; to link with statistical packages to perform model calibration or in silico experiment analyses; with economics and optimization software and risk analysis; with databases and GIS; to include random weather generators to work on climate change and uncertainty.
After different tests, the RECORD platform was built under VLE, a generic modeling and simulation environment based on the discrete event formalism DEVS It allows the design of atomic and coupled models. It proposes standard mathematical formalisms (e.g. difference equations, differential equations, state charts) and decision formalism to model agro-ecosystems. It makes possible the use of different time steps and spatial scales within a model. A graphical user-interface was designed to simplify coding tasks and a dynamic link to the R software has also been realized in order to enable statistical work.
A variety of research projects already use RECORD. Examples are given showing the ability to recode simple models, encapsulate more complex ones, link with GIS and databases, and use the R statistical package to run models and analyse simulation outputs.

1. Introduction

Changing context requires the development of new methods of production in order to guarantee sustainable agriculture. Field-based approaches have been tested and used successfully. These approaches are too slow however to provide timely responses to rapid contextual changes and are unable to explore a large number of systems (Rossing et al., 1997). In-silico approaches could more quickly identify systems that respond to current social, economic, political and environmental concerns (Loyce and Wery, 2006; Bergez et al., 2010). However, building, testing, evaluating and using models is far from being a straightforward task. Numerous models that can address questions about agro-ecosystem functioning already exist. The major issue now is how to combine or couple these models and use them at different spatial and temporal scales rather than develop new models (Rotmans, 2009).

To help the French researcher community working on agro-ecosystems, the French National Institute for Agricultural Research (INRA) set up a 4-year project to develop an integrated modelling framework to gather, link and provide models and companion tools to answer new society questions regarding agriculture. This paper describes how the RECORD platform (“REnovation and COORDination of agro-ecosystems modelling”) was developed and demonstrates some uses in scientific projects. The first section describes RECORD’s functional requirements. The second section shows the technical choices. The next section presents some examples of models developed using RECORD, illustrating its usefulness in a wide variety of situations. The last section gives some elements for future developments.

2. Functional requirements of the platform

The functional requirements were defined thanks to a survey and a 2-day seminar. Approximately 50 French researchers, from different disciplines, who use models to understand, analyse and develop cropping systems took part in this meeting. The main requirements raised during the workshop were:

1. Scope. The platform must be able to simulate agro-ecosystems and interactions with the surrounding territory.

2. Users. Four types of users were identified: i) researchers working on and designing agro-ecosystems and crop-management models, ii) researchers using agro-ecosystem models to simulate some outputs iii) extension service personnel who wants to test new system proposals and iv) graduate students being trained in modelling.

3. Accepting various formalisms. Most current models are dynamic with discrete time steps. However, the platform also should be able to incorporate static and stochastic models and different formalisms.

4. Focusing on management. Management is fundamental when dealing with agro-ecosystems. Modelling technical operation sequences, competition among agricultural tasks, spatial distribution of agricultural practices and choice of crop rotations in a field must be possible.

5. Using existing models. Existing crop models cover a wide variety of crops, crop-management options and spatial and temporal scales. The architecture of the platform should enable integration of these different types of models, either by recoding (i.e. completely rewriting new code) or by encapsulating existing code (i.e. dealing only with interface code).

6. Accepting various time steps within a model. Different time steps must be permitted: from hourly simulation up to several decades for sustainability studies.

7. Accepting various spatial aggregations. Spatial aggregations include a plot or a set of plots representing one or more farms, including, if necessary, interstitial areas and larger areas such as a territory when dealing with natural resources.

8. Functioning and outputs. The platform should facilitate i) implementation and use of optimisation methods by simulation, ii) use of statistical methods for uncertainty, sensitivity analysis of models, parameter estimation and evaluating models, iii) implementation and use of methods of multicriteria choice, iv) comparison of cropping-systems models and v) use of data-mining techniques to exploit simulation results. For all these kinds of work, the links with the R-statistical software appeared to be a key point issue for the platform.

2. Designing RECORD

After a large survey of the different existing platforms (from ModelMaker® (2004) to Ptolemy II (Goderis et al., 2007)) we chose VLE (Virtual Laboratory Environment) (Quesnel et al., 2009) that appeared to be the most relevant. The choice was based on i) a modular approach which facilitates the reuse of modules to compose new models; ii) structural decomposition of the modelled system into sub-systems which makes management of system complexity and hierarchy easier iii) commonly-required services such as a simulation engine, numerical integration and management of inputs and outputs, iv) integration and coupling of models which are based on different formalisms, v) representation and simulation of complex systems and vi) ability to cover the entire modelling and simulation process.

VLE is a free and open-source software developed in C++ which provides a simulation engine, modelling tools, software libraries and an Integrated Development Environment. It is a generic modelling, simulation and analysis environment based on the DEVS (Discrete Event System Specification) formalism (Zeigler et al., 2000). There are two types of elementary objects in DEVS, an "atomic model" and a "coupled model", which exchange information in the form of "events". An atomic model is defined as a set of input and output ports and a set of functions: i) the internal-state transition, ii) the external-state transition, iii) a function that can generate events addressed to other models and iv) a function that manages the duration of the different states. A Graphical User Interface allows users to create and configure atomic models in the most appropriate formalism, import modules and couple models ("box and arrow") (Figure 1).

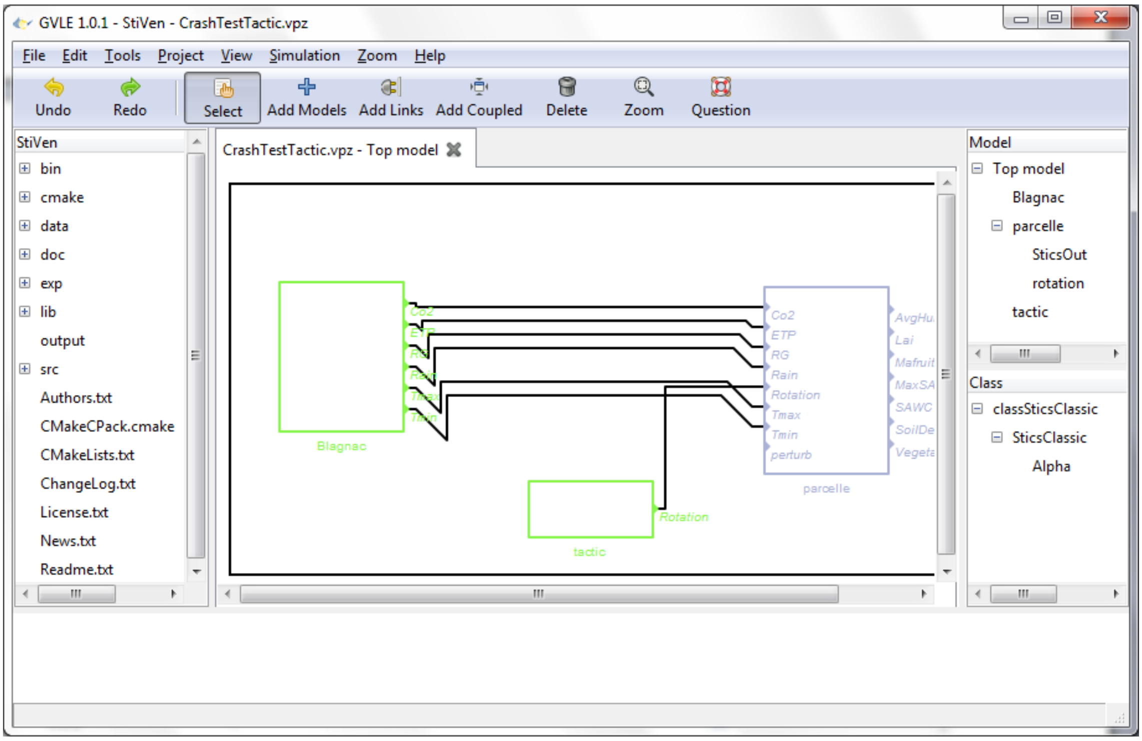

Figure 1: Overview of the VLE Graphic User Interface which is divided in four parts; The right hand part shows the hierarchical structure of the model, the center part shows the box-and-arrow representation of the model, the left hand part shows the different directories to describe the model (source, documentation, input data, configuration…) and the lower area is used for messages (errors, warnings …) when processing the model

Ordinary differential equations, difference equations, execution of activity plans based on decision rules and scheduling constraints are available. The dynamics are coded in C++, but this task is reduced thanks to code-generating plug-ins associated with the extensions. It is then quite easy to model dynamic processes such as crop, soil, animal functioning. A specific attention has been paid also to enable modeling management processes and planning activities (crop management strategy such as sowing, irrigation, fertilizing or animal and flock management).

Depending on their structure and programming languages existing models must either be rewritten under RECORD or may be directly encapsulated. This encapsulation method allowed for example to integrate the generic crop model STICS (Brisson et al., 1998). Various tools required to carry out the modeling and simulating work were missing from the kernel VLE. Thus, we developed a package which enables dynamic links between RECORD and the R statistical software and the work of calibration and evaluation of the models is done by using functions provided by the R libraries. A repository where models can be stored and accessed is also part of the RECORD project.

3. Two examples

Several projects have been developed using RECORD for the last five years. We will illustrate the functioning with two examples: one at the farm level dealing with crop allocation and one at the catchment level, dealing with nitrate leaching problem.

3.1 CRASH

To adapt to fluctuating contexts farmers have to modify their crop-allocation strategy. At the farm level, management of irrigation water is traditionally based on the selection of a dynamic suitable cropping plan. The CRASH model (Crop Rotation and Allocation Simulator using Heuristics) was developed to test dynamic-decision modelling at farm level.

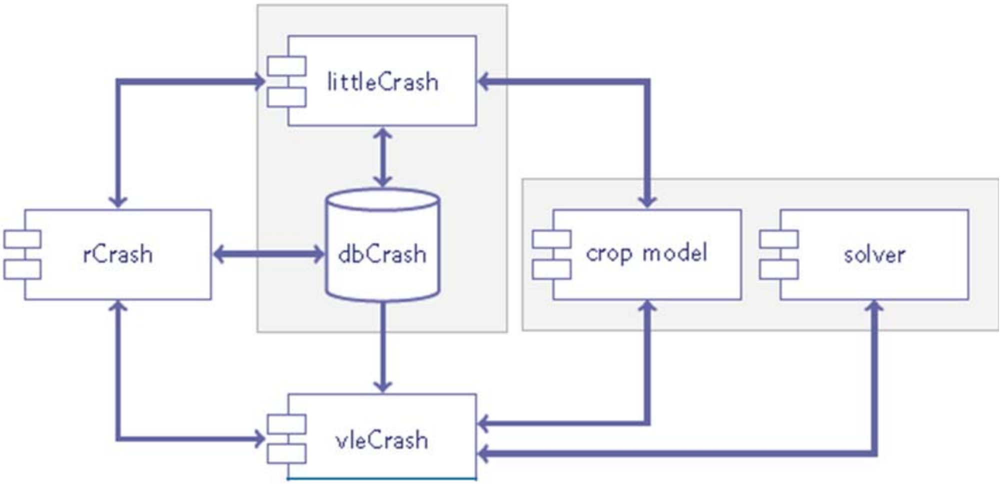

Figure 2: The main software components of the CRASH system-based modelling framework: (1) vleCrash the main agent-based simulator that is an agent-based simulator that integrates the STICS crop model. It also includes a rules-based interpreter to manage daily activities and constraint-reasoning algorithms for crop allocation and crop-preference management. (2) Input-management systems: dbCrash, a database used to store simulator inputs, which represent a farmer's expert knowledge, decision profile, and farm structure; littleCrash, a STICS-based simulator which generates input data on the farmer's expert knowledge about crop productivity. (3) rCrash, a set of R functions compiled as an R package which runs simulations and performs input/output analysis and graphing

CRASH takes advantage of the RECORD platform by integrating a set of interacting software components (Figure 2). It provides an extension dedicated to the design of activity plans. Following recent advances in modelling agricultural systems (Martin-Clouaire and Rellier, 2009; Le Gal et al., 2010), CRASH is structured as three interacting systems, namely the Agent, Operating and Biophysical systems which are three separate DEVS atomic models:

(i) The Agent system is structured as a Belief-Desire-Intention agent (Bratman, 1987) which updates the beliefs of the agent when new information arrives from the Operating or Biophysical systems.

(ii) The Operating System translates decisions made within the Agent system into actions that act on the Biophysical system by modifying particular states or fluxes. The Operating system is represented by a discrete and finite-state automaton.

(iii) The Biophysical system is a spatially explicit farm model. The farm model is a set of atomic models on which the crop model runs. The plant-soil simulation is performed by the STICS model (Brisson et al., 1998). Spatial units are defined by the biophysical heterogeneity of the farm (e.g. soil characteristics) and its organisation into management units (e.g. plots, management and irrigation blocks). The spatial characteristics of the farm are inputs for vleCrash and are included using the wkb format (Herring, 2006) provided by PostGIS.

A set of R functions compiled as an R package (rCrash) uses the link between the R-statistical package and RECORD to manage the simulations and to create graphical outputs.

3.2 CASIMOD’N (Catchment and Agricultural System Integrated MODel for Nitrogen)

Increases in fluxes of nutrients towards environment due to intensive agriculture have been largely reported. CASIMOD’N is a new integrated model considering livestock at the farm level, farmer strategy and nitrogen transfer and transformation at the catchment level. The aim of this model is to assess the effect of prospective scenarios that integrate the strategy and constraints of livestock farming and the physical environment, on the water quality at the catchment scale (Moreau et al., 2010). It differs from existing models at a catchment level, by integrating the farmers' strategies and constraints in order to assess as accurately as possible the impact of agricultural practices.

CASIMOD'N has been designed as an integration of different models (Figure 3) and RECORD has been used to couple them:

1) TNT2 (Beaujouan et al., 2002) simulates hydrological and nitrogen fluxes in catchments using a daily time step. It is process-based, uses difference equations, and is spatially distributed in order to account for spatial interactions such as bottom land denitrification related to nitrate leached upslope. The crop growth and nitrogen transformation modules are based on the generic plant-soil model STICS, which simulates at the plot scale (Brisson et al., 1998);

2) the farm model (TF) is based on the TOURNESOL (Garcia et al., 2005) and the FUMIGENE models (Chardon et al., 2008); it has a year time step. TOURNESOL simulates pluriannual crop allocation and FUMIGENE simulates animal waste allocation using optimization procedures. A procedure of optimization is included to select the best crop and waste plans. A module (ITKScheduler) uses TOURNESOL –FUMIGENE outputs and sends agro-technical events to TNT2 every day for each plot.

These models, whose native code source was written in C or C++ language, have been first encapsulated in the RECORD platform with little modifications, then they have been coupled and combined in order to produce the CASIMOD'N model. Key points concerning the implementation and the hierarchical organization of the model at the farm and catchment levels were facilitated by the native property of the platform concerning “hierarchical modularity”. The present integrated model can easily evolve thanks to its atomic structure in which each sub-model can be modified without changing the coupling architecture.

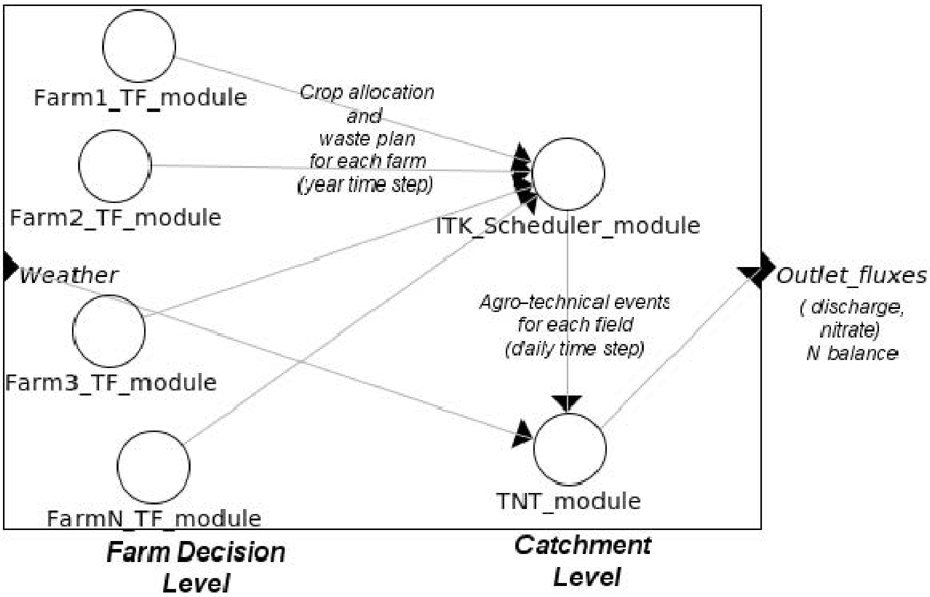

Figure 3: a simplified view of the CASINMOD'N model. Each farm model calculates the annual-crop and animal-waste allocation. A global scheduler daily sends to the TNT module the agro-technical events that occur on each field of the catchment. T stands for the TOURNESOL model, F for the FUMIGENE model and TNT for the TNT model (adapted from Moreau et al., 2010).

4. Discussion and conclusions

The RECORD platform was setup two years ago (http://www.inra.fr/record). Currently, a dozen of national or international research projects, with a wide variety of topics, are using its capability to reuse and develop models. More researchers will use it, more models will be made available for the community. In order to increase its applicability, we also developed an e-learning program and a user forum (http://record-elearning.inra.fr/record/). As shown by the previous examples, RECORD can be used to address a wide range of questions. Regarding the link with the R statistical package, choosing the most pertinent methods and appropriately applying them are not straightforward in the context of agro-ecosystems, so we are currently working with researchers (reseau-mexico.fr) to provide an R library specifically adapted for RECORD.

The models in RECORD could be of real interest as educational tools to improve understanding of agro-ecosystems or as tools for decision makers to integrate agronomic, social, economic and environmental issues. However, direct use of these models by non-scientific would be problematic because i) they require significant parameterisation to adapt them to individual contexts, ii) model validity is context-dependent and iii) working directly on the platform requires a minimal level of training. Therefore, we created integrated ergonomic applications around the simulation models in RECORD. To ease application maintenance, development and user- and rights management, we proposed a web-oriented tool, designing a specific infrastructure to develop web applications.

Future work will now focus to combine RECORD models with models developed in other frameworks and ways to link the RECORD platform with scientific-software environments such as Matlab or GAMS to foster collaboration with other disciplines such as economists.

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