CAPSIS : Computer-Aided Projection for Strategies In Silviculture : Open architecture for a shared forest-modelling platform

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ABSTRACT

Forest scientists build models to study, understand and represent stand growth and dynamics. They are particularly interested in the evolution of ecosystems, at the tree and compartment levels and in the consequences of forest management on volume, shape, wood quality, structural evolution of the stand or sensitivity to meteorological and sanitary problems. Specific computer tools are often developed to implement these models, to test and to explore the consequences of the underlying hypotheses on real or virtual stands. Sometimes, a team may invest in the development of a more integrated tool, based on a parameterisable growth model.
The Capsis project aims at integrating several types of forest growth and dynamics models - stand models, distance independent or spatially explicit tree models,... - and providing forest management tools to establish and compare different silvicultural scenarios. The objective is to build a perennial, open and dynamic software platform (1) to contribute to the development of models and test their sensitivity to some parameters by simulating the manager's actions, (2) to share tools and methods, (3) to compare results of different models, (4) to transfer models to the managers and (5) to serve as teaching material. Most models implemented in Capsis are described in a web database hosted by the European Institute for Cultivated Forest (www.iefc.net).
Capsis is a portable software, designed around a kernel which provides an organizational data structure - session, project, scenario step. The kernel also proposes generic data descriptions - stand, compartment, tree,... These descriptions can be completed in modules - one for each model - which implement a proper data structure and a specific evolution function (growth, mortality, regeneration, dissemination,...) with a chosen simulation step. A plug-in architecture provides the possibility to build tools for management, construction of graphics, data exportation, tree group construction, stand representation or connections with other software. At the present time, Capsis hosts six modules, several other integration projects are planned and model integration training sessions are periodically proposed.

INTRODUCTION

In order to manage forest stands, foresters need specific tools to predict the growth of the stand, as well as wood quality. Many growth models have been developed that simulate the dynamics of a forest stand at various scales (Houllier *et al.*, 1991). These models report the species-related dynamics but also the environmental effects (site, climate, competition,...) and the influence of forest management. These increasingly complex models are often incorporated in computer programs to ease their calibration, their evaluation on concrete cases and their dissemination.
In this paper, we introduce a generic computer platform aimed at hosting a wide variety of forest growth or dynamics models and stand intervention mechanisms to study the evolution of forest ecosystems. The *Capsis* platform helps

the modellers to elaborate, calibrate and share their models, it can be a decision making tool for forest managers and a practical support for education.

After a brief review of the different types of software implementing forest growth models, we detail the modular architecture of Capsis and the models already implemented in this platform. We then discuss the limits of the software and its possible evolutions.

STATE OF THE ART

To calibrate their models and help for their validation, modellers often build computer programs. These custom software present a number of advantages : their authors have complete control over them and can choose freely their data structures, their algorithms and the user interface that suit them best : *Cep* (Houllier *et al.*, 1995), *Fagacées* (Dhôte, 1995 ; Nepveu and Dhôte, 1998), *Formind* (Köhler, 2000), *Selva* (Gourlet-Fleury, 1999), *Sexi* (Vincent and De Foresta, 1998), *Simcop* (Ottorini, 1991 and 1995).

However, these isolated developments produce specific programs which are sometimes uneasy to use by others. It is also often difficult to make such programs communicate with each other because their architectures and technical solutions are too different.

To benefit from reusable tools in various situations, some teams have chosen to build simulators around a parameterisable model. Generally, a common data structure and a set of functionalities are proposed (growth, competition, environment, management, analysis,...). The program can then be calibrated for several species or forest types : *BWin* (Nagel, 1999), *CO2fix* (Mohren and Klein, 1990), *FVS* (Van Dyck, 2000), *Jabowa* (Botkin, 1993), *MOSES* (Hasenauer *et al.*, 1995), *Prognaus* (Monserud and Sterba, 1996), *Silva* (Kahn and Pretzsch, 1997), *SORTIE* (Pacala *et al.*, 1993), *TASS* (Mitchell, 1986).

More generic approaches can give software based on exchangeable growth models or on composite models for which components can be chosen : *LMS* (McCarter *et al.*, 1998), *MUSE* (Gignoux *et al.*, 1996), *Symfor* (McLeish, 1999).

It is also possible to use general usage simulators and apply them to forestry. Models can be expressed in descriptive formalisms offering a great number of possibilities : *ModelMaker* (Cherwell Scientific, 1999), *Simile* (Muetzelfeldt and Taylor, 1998), *Stella* (High Performance Systems, 1987). On the counterpart, it is sometimes difficult to build under these platforms the domain-specific control and analysis tools that are needed by the forest modellers.

For all these tools, forest management, when considered, is generally expressed by a management plan which is run simultaneously with the growth process.

The Capsis platform is used as a simulator for a number of French forest models (Dreyfus and Bonnet, 1997). It is strongly dedicated to forest models and generic enough to integrate very different kinds of models. Thus, the current *Capsis4* release (Coligny *et al.*, 2003) integrates spatially explicit models, which was not the case with the former *Capsis2* version.

ARCHITECTURE

Capsis was built around a *kernel*, offering common services and generic data structures. Growth models - in a broad sense - are integrated into Capsis as *modules*.

These modules contain their own data structures, extending some templates chosen from the kernel. They also contain the algorithms to be applied on these structures to model evolution along time. Management can be automated in the modules or processed externally, in platform extensions (plug-ins).

Capsis extensions include not only management tools, but also especially viewers and data extractors to check the state of the stand and data import/export facilities (Fig. 1).

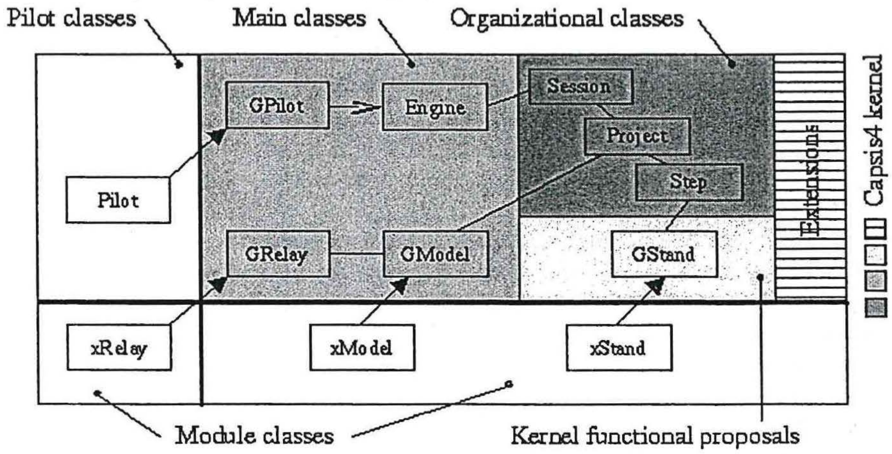

Figure 1 : Capsis Architecture (Unified Modeling Language class diagram). Kernel superclasses can be extended differently in the various modules.

Simulations are driven through a *pilot* corresponding to an usage context. The interactive pilot proposes a graphical user interface with menus and dialogs. The script pilot can be used to run long or repetitive simulations with no user actions required.
Capsis also provides libraries of data structures and processes which can be used by every modeller.
This architecture was strongly influenced by the Object Oriented Programming concepts, especially the class (description) inheritance. Thus, the generic patterns are described by kernel superclasses with subclasses representing the derived descriptions in the modules. The latter inherit the properties - variables and functions - of the former and can modify them or add new ones.

The kernel

Capsis kernel contains fundamental classes for the application to function, an organizational data structure description, and proposals for generic domain-related data structures to be extended in the modules (Fig. 1). This possibility for the modules to inherit from kernel-proposed descriptions is one of the main principles of Capsis.
The Engine is the main class in Capsis. It contains some essential functions to detect and load the modules, and also to manage the calculated data which are grouped in projects (new, save, close,...).
Each project is linked to a parameterised model object at the beginning of the simulation and owns a root step which is associated to an initial stand. A simulation consists in computing successive states of this stand, by delegating evolution phases to the module, and by processing interventions with extensions. Calculated stands are linked to new steps coming after the root step. A set of successive steps represents a silvicultural scenario. Several projects can coexist, they then constitute a session.
The kernel describes a generic stand (GStand) which must be used as a basis for the stand description of each module and to which must be added the module-specific properties. This abstract template is the only obligation for describing the module data structure. It is purposely not too demanding to be usable in every module, whatever their architecture may be. Other domain related generic descriptions are proposed in the kernel (stand with tree list, individual tree with spatial coordinates,...), but only the generic stand usage is mandatory.
It can be noted that some generic tools can process actions on kernel generic descriptions. The modules that rely on these descriptions can directly benefit from these compatible tools.
The kernel also describes a generic model class (GModel) which contains only technical properties, particularly to manage its association to a project. This generic model class is extended in each module to describe the algorithms of the matching model.

The modules

A Capsis module is a set of data structure descriptions and of related processes, partly relying on kernel descriptions (Fig. 2). The two main elements in a module are the stand class and the model class. The latter particularly contains the function to simulate evolution with a loop, calculating the successive states of the stand, and adding them in the project under new steps.

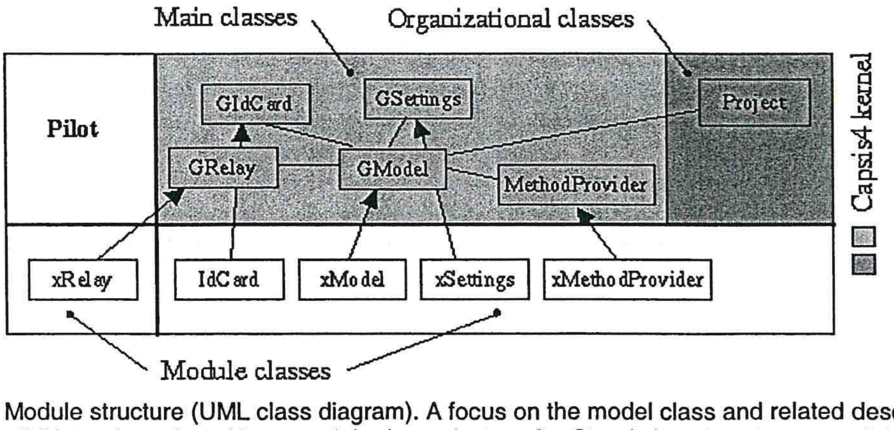

Figure 2 : Module structure (UML class diagram). A focus on the model class and related descriptions. The "x" letter is replaced by a module-dependent prefix. Stand class is not represented.

At the time of project creation, a module can be automatically detected thanks to naming conventions to find a module information class. Module loading - consisting in the model class instantiation - is then done by the engine class.
Project creation goes on by setting the module parameters (grouped in a parameter class) and by loading the simulation initial stand. This load process is delegated to the model class (inventory file or virtual generation). Finally, the engine creates a root step for the project and links this initial stand to it.
A project associated with a parameterised model class and containing a root step with an initial stand is the minimal guaranteed configuration for a project until its closing. As a matter of fact, it is then impossible to delete the root step

or to modify the module parameters once the project is created. They constitute the context for all the simulations to be run from the root step.
During the loading of the module, the engine looks for a pilot relay for the module matching the current usage mode (interactive or script) and builds it. Through this relay, Capsis can trigger actions in the module. Thus, for example, to be usable in interactive mode, a module must provide an interactive relay, which generally appears with descriptions of dialog boxes for parameter input and real stand (inventory file) or virtual stand (generation parameters) loading.
Conventionally, Capsis modules finally contain a method provider which proposes calculation methods for some variables, chosen by the modeller (basal area, dominant height,...). These functions can be detected and used by some tools, generally extensions, to create graphics and reports.

The extensions

The kernel was designed to give stability to Capsis. It evolves slowly to allow the development of perennial modules. New tools which are needed to exploit the modules are generally built in the form of platform extensions. The extension classification contains tool families, grouped by kind of usage. These tools can be developed by everyone.
Intervention mechanisms can simulate any action which is not part of a module and which modifies the state of a stand (thinning, pruning, fertilization, fire,...). Their use generates a new stand resulting from the intervention, associated to a new step in the project.
Stand viewers and *data extractors* provide representations of the stand at a certain time or along time (maps, curves, histograms, tables,...). They make it possible to observe the simulation results. However, they are not supposed to replace the modellers' usual data analysis tools which are still usable by exporting the calculated data.
Import/export extensions can be used to load inventory files and export data on request in some previously prepared formats. Exportation is particularly used for file exchange with other software.
Model tools can trigger any process on a particular scenario step which does not result in a new step (3D viewer, network connection with another software,...).
Filters can be applied on stands to create groups which are usable with other extensions (ex : trees more than 10 cm diameter,...).
Finally, *generic tools* offer general services (file browsing, checking the execution log,...).
All the extensions share a set of common functions to get practical information concerning their name, type, description,... A particular function can be used to check the extension *compatibility* with a given object. It processes a number of tests on the object type or on its properties values to determine if the extension can be applied on it or not.
This compatibility can be evaluated by requesting the kernel *extension manager*. Thus, for example, it is possible to request the list of the extensions of a given type which are compatible with a given module. This central interlocutor knows all the available extensions and can load them on request.

The pilots

Capsis architecture was designed to enable simulations to be run in either interactive or automatic mode. In interactive mode, scenarios can be built step by step, by specifying each new step according to the result of the previous one and possibly by comparing with other scenarios, thanks to the various outputs showing past simulated evolution. In automatic mode, the simulation is run according to a previously prepared plan which either describes a list of scenarios to be compared, or several replications of one single scenario. The latter can be used to evaluate the influence of various input parameters or the effects of stochastic issues and to help calibrate the modules.
To either usage mode corresponds a pilot through which the user can trigger some actions in the Capsis engine or in a given module. The two pilots share the same basic functionalities : module loading and parameterising, project creation, associated with a root step carrying an initial stand, triggering the module evolution process and calling the extensions which can be used with the pilot.

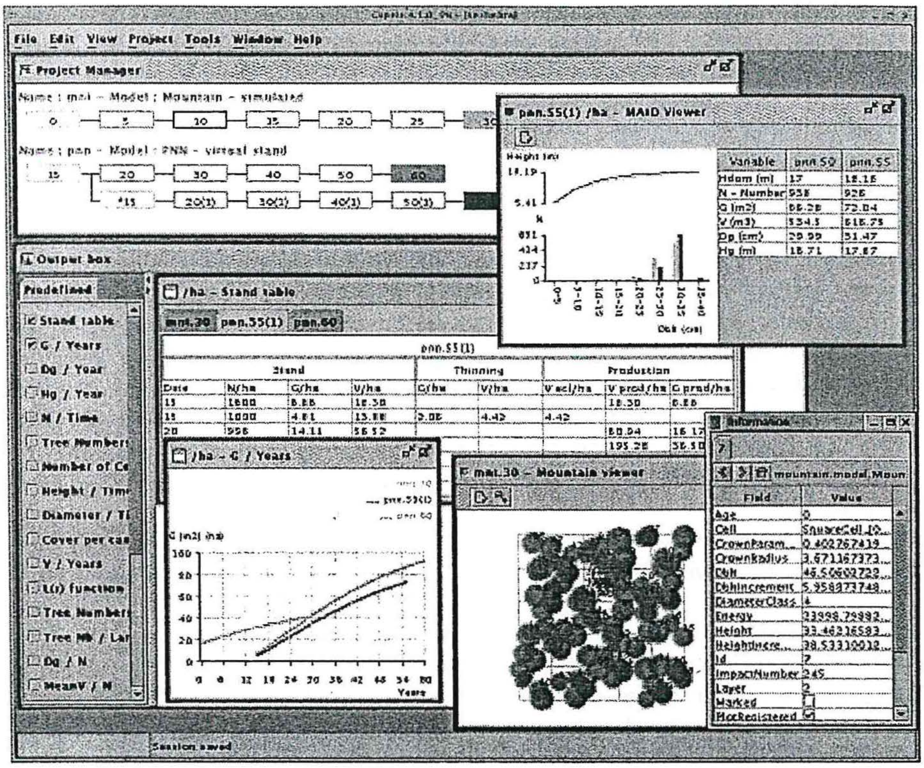

Figure 3 : A glance at Capsis4 interactive pilot under Linux (same look & feel under Windows). Project manager, stand viewers with tree inspector, data extractors.

The pilot communicates with the module through its piloting relay which transmits its requests and the answers of the module. Therefore, a module owns a relay for each pilot the modeller is interested in. A relay contains descriptions for the parameters of its module concerning initialisation and evolution. Interactive relays also describe dialog boxes to input these parameters interactively.

The interactive pilot is bilingual (French, English) and can be easily adapted to other languages. It drives the simulations through a project manager (Fig. 3), showing the calculated steps. It is then possible to trigger an evolution phase or an intervention on one given step by using the mouse and a contextual menu. Graphical viewers and data extractors can be synchronized with the project steps to observe the effects of the simulation.

The script pilot can be used to plan long or repetitive simulations in a command file. This script can then be run without user action. The results of each scenario can be evaluated within the script to choose the next actions or can be saved in files for future analysis.

The libraries

Besides housing forest growth and dynamics models, Capsis hosts various tools and models which can be used in several modules. These resources are grouped in transversal applied libraries. Modellers can also use technical libraries resources to build their modules.

APPLICATIONS

Most forest growth and dynamics models implemented in Capsis are described in a web database hosted by the European Institute for Cultivated Forest (www.iefc.net). This database allows all modellers to add their own models into an international list thanks to an online form. It combines keywords to select the models according to the kind of model (Growth, Dynamics, Wood quality,…), the species, the inputs, the outputs, the country, the institutions… and open fields for website references, bibliography and contacts.

The architecture of the Capsis modules was designed to ensure the integration of very different kinds of models. The modeller can freely choose the data structures, the processes - empirical equations or functional processes -, the simulation steps, the level of detail of the descriptions and the chosen scale (hectare, landscape,...). The modeller can thus integrate models that either calculate global variables for the stand, or describe each tree, possibly looking at its environment to consider local competition. The following short descriptions of the modules currently under development in Capsis illustrate these possibilities.

Mountain is a module devoted to the simulation of uneven-aged monospecific conifer forest dynamics. This distance-dependent model considers the spatial coordinates, height, diameter, crown base height and extension of each tree on rectangular plots of a size ranging between a quarter to one hectare. A detailed light interception model calculates the energy intercepted by each tree and a map of light reaching the ground, considering canopy geometry, plot slope and aspect. Tree growth and probability of death are calculated for each tree higher than 1.3 m Regeneration is calculated at the scale of 1 m wide ground cells. *Mountain* has been used until now to simulate long term dynamic patterns in monospecific forests, to compare silvicultural strategies (Courbaud *et al.*, 2001) and to train students and forest managers to tree marking.

Selva is a distance-dependent tree model, designed for the natural tropical rainforests of French Guiana (Gourlet-Fleury, 1999), running on plots of several hectares. The three fundamental processes of forest dynamics are described : growth (Gourlet-Fleury and Houllier, 2000), mortality (split into standing dead and two types of windthrow) and recruitment. For particular species, the whole regeneration cycle from seed dispersal to ingrowth is modelled. Silvicultural operations can be realized automatically (diameter cutting limit) or interactively.

The *PNN* module is a distance-independent tree growth model for pure even-aged stands of Black pine (*Pinus nigra nigricans*) in France and Hungary (Dreyfus, 1993). Thinning design considers target stocking (N, G, V, relative spacing, CCF after thinning) and ratio of tree average diameter (quadratic mean) after to before thinning. The growth model and thinning design have migrated from the former version Capsis2 (the branching model and stem profile relationship should migrate soon).

PP3 is a distance-independent tree growth model with a whole-stand growth regulation for pure even-aged stands of Maritime pine (*Pinus pinaster*) in Landes of Gascogne (southwest of France ; Lemoine, 1991). The growth model and thinning design have migrated from Capsis2. The branching model and stem profile relationship are to be implemented directly in Capsis4.

Eucalypt is a distance-independent tree model (dendrometric approach) developed for the 43,000 ha of Eucalyptus clonal plantations in Congo (Saint-André *et al.*, 2002 ; Cornillon *et al.*, 2002). The objectives are (i) to assess stand production under different silvicultural options (thinning/fertilization) and under different perturbations (insect damage, fire), (ii) to evaluate the risk of nutrient deficiencies and non sustainable production, and (iii) to estimate the economic return of different harvesting strategies. The work is in progress. Three specific features are developed in this module : (i) the management of coppice (several stems per stump), (ii) the integration of a great number of models (in the worst case, there is one model per clone), (iii) the link between Capsis and a Geographic Information System (arcInfo/arcView).

Ventoux is a semi-spatialized model (resembling a gap model) dealing with the evolution of aged artificial Pine stands towards mixed stands in the French Mediterranean hinterland mountains. Seedling occurrence of invasive native species is driven by the distance to potential seed sources (Beech and Silver fir stands). For a multi-level spatialization, the forest is divided into homogeneous units (site, overstorey species, age), then in grids of small cells (10 x 10 m) containing non-spatialized trees and seedlings. Management can be automated (given a management strategy, each stand in the forest is thinned or regenerated according to age, cutting cycle, species, stocking, time or height growth since the previous intervention) and - when simulation deals with one (or few) stand(s) - interactive (using several thinning methods).

The *Spatial* library contains specific tools concerning the spatial structure of forest stands. On the one hand, the *Ripley* data extractor describes the spatial pattern of a stand, using the L-function derived from Ripley's K-function (Ripley, 1977 ; Besag, 1977). On the other hand, we implemented specific classes to simulate virtual stands of various structures, using Poisson, Gibbs or Neyman-Scott processes (Cressie, 1993). These tools are available for all individual tree models (distance dependent or independent tree models) and have already been used with the *Mountain* module.

The *Biomechanics* library proposes classes to describe the internal structure of trunks (stem profile, succession of growth units) and simulate their biomechanical behaviour under external stress (Ancelin, 2001). Associated to the *WindStorm* extension, which is compatible with both distance-dependent and independent tree models, it simulates the effect of wind in forest stands. The first simulations were made with the *Mountain* module. They showed a relation between tree damage and the total height / diameter at breast height ratio. *WindStorm* should soon become an *intervention mechanism* to study the impact of silviculture on damage caused by wind as well as their consequences on the stand dynamics.

DISCUSSION

The Capsis project builds partnerships between various actors who contribute to its specifications. Thus, the partners decided together to write the platform in *Java*, a modern, portable (Linux, Windows,...), powerful and robust language which is accessible to beginners for shared development.

A *charter* defines the roles of the various actors. It must be accepted by all the project members. Developers deal with the Capsis kernel, pilots, common technical aspects, the whole project coordination, training and assistance. Modellers are in charge of the integration of their model. This is why Capsis is a shared development project. To facilitate the collaboration, the Capsis kernel, pilots, libraries and extensions are distributed as free software (General

Public Licence). Modellers can choose a particular licence for their module once its distribution has been decided. Developers and modellers are part of the *Capsis Community* within which all the source codes are shared.
Some modellers may also provide their modules to forest managers as decision making tools or to use simulation to rouse their awareness on some issues concerning long term management. Capsis can also be used to train students in forestry schools (forestry engineers,...).
Maintaining the development of modules in the hands of the modellers has many advantages. Modellers can therefore control completely their simulator and choose their planning freely. On the other hand, if Java may seem easy to learn for people who already know another programming language, it can be more difficult for beginners. To compensate this drawback, training sessions are proposed to the candidate modellers, covering the Java language as well as the complete building of a Capsis module. Custom assistance is also rendered at the beginning and whenever needed to help the modeller design his (her) module.
Capsis community members have frequent scientific debates and meet annually to discuss the progress of the project and future orientations. They decided in common to incorporate first the spatially explicit models and then the distance-independent models from the former Capsis2 version, and recently to design and develop the script mode.
The current Capsis4 release at present hosts six models, either finalized or still under development, and new integration work is under progress or planned : *Sexi* (Vincent and De Foresta, 1998) is a spatially explicit individual tree model for tropical agroforests (Indonesia), *PNL* is a tree distance-independent growth model for pure even-aged stands of Corsican pine (*Pinus nigra ssp. laricio*) in the Centre of France (Meredieu, 1998), which is being migrated Capsis2 (Meredieu *et al.*, 2001), and *Fagacées* (Dhôte, 1995) is a model for Beech and Oak in France. The *Ventoux* project introduces in Capsis the notion of seed dispersion. This project will continue with the coupling of demographic and genetic models.
The script mode can now help evaluate and calibrate the models by repeating many times previously prepared simulations. It can also be used for optimization processes.
Finally, some modellers want their module to be connected with other simulation or analysis software. Several concrete cases are already under consideration : evaluation of the quality of stands with *WinEpifn* (Houllier *et al.*, 1995 ; Leban *et al.*, 1996) for *PNL* and *Eucalypt*, construction of 3D scenes with *AMAPsim* (Barczi *et al.*, 1997), connection of the *PP3* module with *ForestGales* (Gardiner *et al.*, 2000) to study sensitivity of stands to wind.

CONCLUSION

In this paper, we have presented the Capsis software, a generic platform designed to integrate models and tools to simulate the dynamics of forest stands. We have shown how its modular architecture deals with various issues at various scales : wood production and quality in managed forests, biodiversity conservation in tropical forests, etc. The integrated models can be of very different kinds : from « mean tree » or « tree, without spatialization » models to more or less finely spatialized models, from the landscape to the tree scale, including branching and internal trunk structure (rings, growth units,...). Very diverse forest ecosystems are concerned : temperate, mountain or tropical, pure or mixed forests.
The architecture of Capsis and its capability of reusing components ensure easy evolution of the platform to deal quickly with new models and tools of different kinds.

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