PuMe — INTERACTIVE LEARNING ENVIRONMENT EMPLOYING THE PIPEQUAL MODEL FOR FOREST GROWTH AND WOOD QUALITY*

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ABSTRACT

Process-based models have advanced to a level which enables their utilisation for evaluating forest management options, as well as their use in environmental education. To date, such applications are relatively rare, but they could be promoted by means of appropriate interactive and user-oriented interfaces for model simulation.

The PuMe-software has been constructed as an interactive tool for forestry studies at secondary and university levels. The objective was to build an interactive and user-oriented interface for running a forest growth model with either user-designed or pre-determined inputs of forest management options such as stocking densities, thinning practices, site fertilities, and fertiliser application. The PipeQual model was chosen as the growth simulator because of its versatility in predicting traditional forestry characteristics, stem structure (stem shape, knot zones, heartwood, and sapwood), biomass, and carbon balance.

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The first version of PuMe is now in test-use in forestry education by universities and secondary schools, and by individual forest owners. However, it is applicable only to *Pinus sylvestris* L. (Scots pine) under a limited set of conditions. In an ongoing project, PuMe II, the software will be developed further by adding various new features: simulation of spruce growth, forest damage, fertiliser application, pruning, and more flexible thinning methods. Especially, a new module will be incorporated to allow for a more detailed visualisation of stem properties (growth rings, wood density, fibre properties).

Keywords: PuMe; learning environment; forest growth; timber quality; biomass; carbon balance; simulator.

INTRODUCTION

Process-based system models have become increasingly popular in forest sciences during the last few decades. They have proved to be powerful scientific tools in formalising hypotheses (Landsberg 1986), focusing the needs for further research, and providing a framework which combines disparate pieces of knowledge (Mäkelä *et al*. 2000). Recently, process-based models have also been applied to practical problems, such as decision-making in forestry (Hyytiäinen *et al*. 2005), and forest policies in a changing environment (Pussinen *et al*. 1997; Lasch *et al*. 2002).

In order to make full use of process-based models in practical applications, including decision making, education, and popularising scientific knowledge, it is not sufficient for the models to be available in the scientific literature, or on the scientist's computer in code intelligible only to the person who wrote it. The models need to be embedded in user-friendly, targeted software environments. The construction of such quality environments presumes multi-disciplinary work: assessing the needs of the target group, defining the related learning processes, and understanding the field of the process-based models utilised, as well as the process-based models themselves.

Forest growth is a complex phenomenon that is not easy for students to understand. From the educational point of view, it is not possible to study forest growth in an authentic setting, e.g., because of the long time-frame of forest development, and difficulties in controlling the driving variables. Simulation software, as well as any tools that allow the students to build hypotheses, test them, and explore alternative scenarios, can provide a "semi-authentic" setting for studying such complex issues.

This paper describes the development process of a software environment targeted at students of forestry at the secondary and university levels. The software is known as PuMe, an abbreviation of the Finnish term "Puusta Metsäksi" meaning "from tree to forest". The main difference between this software and existing forest growth simulators such as "FPS" (Arney & Milner 2000), "Tass" (Mitchell 1975), "FORSKA" (Prentice & Leemans 1990), "MOTTI" (Hynynen *et al.* 2005) is that it is aimed at a learning environment and consequently special attention is paid to the linked study material. The core of the software is a process-based model, PipeQual*, describing forest growth and the development of the tree structure in different environments and under different forest management options (Mäkelä 1997; Mäkelä *et al*. 1997; Mäkelä & Mäkinen 2003). Around the core model, a learning environment has been constructed to support the individual learning process. Technically, this involves text, pictures, video clips, etc. Pedagogically, these must be put together in a way that helps the students to understand information and learn. With this example, we aim to demonstrate more generally the types of questions encountered when a process-based model is embedded in a targeted software environment to be applied by a specific user group.

METHODS

Requirements Set for a Forestry Learning Environment

Learning theory suggests that perceiving and understanding a complex phenomenon challenges the students to control the complexity. This can be implemented in different ways. In order to support the development of understanding, information has to be presented in different modes, such as text, pictures, and video clips. The authentic situation often forms a starting point for the experimenting and learning process, helping in bringing about understanding. The PuMe environment systematically aims to structure the phenomena to be studied. This serves to develop a sound mental model about the target object which in itself is important for constructing relevant knowledge about forest growth (Enkenberg 1995; Enkenberg *et al*. 1995). Authenticity has been implemented by video clips and narratives in the PuMe system.

Programming the growth simulator

The first step in building the PuMe simulator was making the growth model function in the Windows environment (the original Fortran program operated in

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* A tree growth model is formulated based on structural relationships in a carbon balance framework. Three relations are applied: (1) an allometric relationship between crown surface area and foliage area, (2) the principle of functional balance, and (3) the pipe-model theory. These assumptions lead to a model where sizes of the functional parts of the tree are derivable from foliage weight, except for the pruning height of the crown. This is determined by defining “self-pruning coefficient” which controls the allocation of growth between height growth and foliage growth. The tree model is applied to an average-tree based stand growth model where both the self-pruning coefficient and tree mortality are made functions of crown coverage. The model is quantified for Scots pine growing in southern Fenno-Scandia. The overall behaviour of the model is realistic. The predicted development of the biomass compartments in individual trees agrees well with data on dominant Scots pine trees in Finland (Mäkelä 1997).

MS-DOS environment). We decided to keep the bulk of the growth model in Fortran and store it to a *dll* file which enables communication between programs written in different programming languages. For user interface development we chose the Delphi programming environment, with which it is easy to program modern user interfaces with Object Pascal.

We started constructing the new simulator by shortening the original main program of the growth model and dividing it to smaller sub-programs. After that all the sub-programs were put together in a *dll* file. The remaining part of the main program was translated from Fortran to Object Pascal. The shortened main program reads the input parameters required for the simulation, calculates growth by calling the growth model in *dll* file, and draws the figures of annual development of different characteristics in the result windows of the software.

Storing most parts of the growth model in *dll* file saved a lot of time; we did not have to translate the whole growth model to Object Pascal and the updating became much easier because it was possible to develop the growth model and user interface separately, as long as the call parameters remained the same. A schematic structure of the environment is presented in Fig. 1.

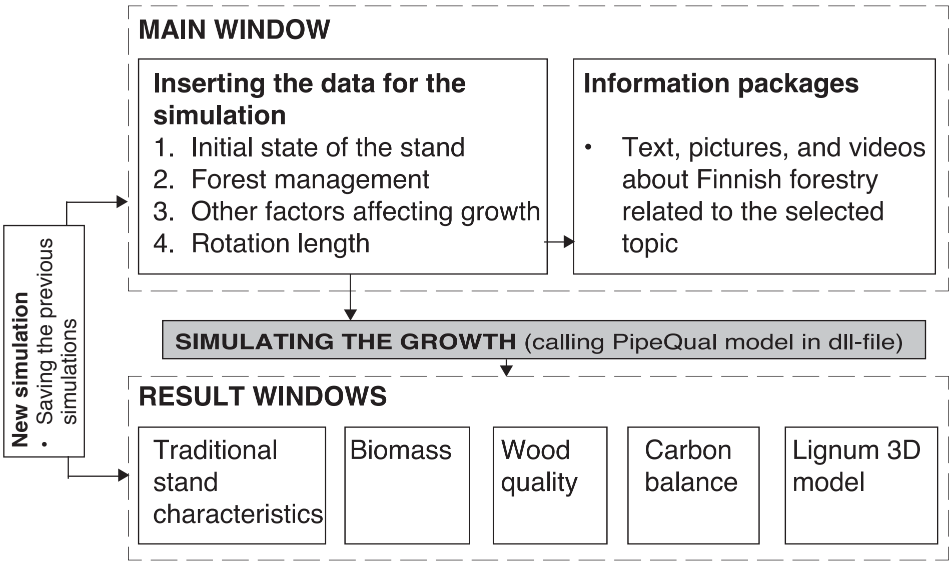

FIG. 1–A schematic structure of the PuMe environment.

Adding the study material to the software

After linking the growth model to the user interface, we started producing the study material to be added to the software. The study material contains different kinds of information (text, pictures, and video clips) about Finnish forests and their typical treatments. The text parts were written on the basis of information collected from forestry experts and literature, the pictures and the videos were taken from the forests of Eastern Finland. The study material was stored in html format, so the same sites can also be utilised in the web version of PuMe which will be developed during the ongoing PuMe II project.

Adding LIGNUM to the software

In order to visualise the structural differentiation of standing trees, a visual 3D model, LIGNUM (Perttunen *et al*. 1996; Sievänen *et al*. 1977) was added to the software in the PuMe II project (http://www.metla.fi/metinfo/kasvu/lignum/index-en.htm). PuMe stores the relevant data about the simulated trees (stem shape, location of branches, etc.) in a text file, which is used as input to LIGNUM. As LIGNUM describes crown structure in much more detail than PipeQual, disaggregation models were needed for transferring the PipeQual crowns to the detailed LIGNUM crowns. These were available from ongoing projects on the linkage between LIGNUM and PipeQual. Using this transformation, LIGNUM draws the 3D model of the simulated trees according to the stored data. The 3D trees can be zoomed or rotated by the user.

Adding permanent sample plot data

The software also provides an option for including data measured in permanent sample plots in Varpala (Savonlinna vocational school/Forestry). Using this option students can compare the simulated growth with their real measurements and examine the future growth of the sample plots. Also, video clips from these sample plots were added to the software. Further, there are four permanent plots in the LUSTO Forest Museum (Punkaharju, Finland), which have been measured so that PuMe can illustrate forest growth for visitors to the museum.

Developing the simulation system

Throughout its development, the PuMe system has been exposed to test use and assessment by students and experts in forestry and teaching, as well as by different forest owner groups and the general public. The feedback from these test users has been very helpful for developing the user interface and identifying needs for further options in the simulations. Some of these have involved alternative analyses of the results available from the models, e.g., adding more flexibility to the available thinning methods, or including options for tree pruning or energy wood removals. Others have required development of the simulation model itself. The highest priority was given by the users to including *Picea abies* (L.) H.Karst. (Norway spruce) stands in addition to Scots pine; this is now possible as the PipeQual model has been parameterised for spruce (Kantola & Mäkelä 2005). Also because of comments from users, we have developed simple models based on expert opinion for fertiliser application and needle damage to be added to the system. A further improvement will be provided by adding models of wood properties that are becoming available from other research projects (Mäkinen *et al.* 2005). Currently the wood properties are described according to Lindström (1997.

RESULTS

PuMe Environment

PuMe differs from most simulation software in that in addition to the simulation model, it also contains study material and video clips. When inserting the information the user can also read information packages (text, pictures, and videos) about the selected topic on the right-hand side of the screen. PuMe software (in Finnish and English) excluding multimedia can be downloaded at http://www.joensuu.fi/ktl/saima/pume_downloads1.htm. Using PuMe is easy: the user just follows the instructions on the screen and inserts the information required for the simulation. At the same time she/he can read information packages (text, pictures, and videos) about the selected topic on the right-hand side of the screen (Fig. 2).

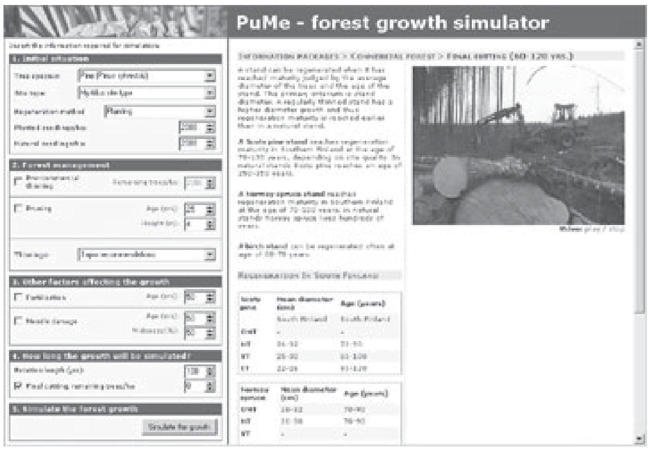

FIG. 2–Main window of PuMe.

With the latest version of PuMe it is possible to simulate both pine and spruce forests. Forest site type can be selected from the most fertile to the most dry site type according to the classification by Cajander (1949): *Oxalis-Myrtillus* (OMT), *Myrtillus* (MT), *Vaccinium* (VT), and *Calluna* (CT) type. The regeneration method can be either by planting or by natural regeneration with an initial stocking density of 100–15 000 stems/ha. The user can also select pre-commercial thinning, and simulate effects of pruning, fertiliser application, or possible needle damage.

Consequently, the simulator provides a tool for studying the effects of single and combined interactions of the independent variables (Table 1) on the behaviour of forest growth.

TABLE 1–Independent variables for the simulation.

Parameter	Range
Tree species	Pine/spruce
Forest site type	OMT/MT/VT/CT
Regeneration method	Natural/planting
Initial stocking density	100–15 000 trees/ha
Pre-commercial thinning	Yes/no
Number of remaining trees	1800–3000 trees/ha
Pruning	Yes/no
Age of pruning	
Height of pruning	
Thinning method	No thinnings / Thinnings with Tapio recommendations (latest Finnish recommendations for forest management) / Thinnings with sample plot data / Thinnings with user's own schedule
Fertiliser application	Yes/no
Age at application	
Needle damage	Yes/no
Age	
Density	
Final cutting	Yes/no
Age	Max 150 years
Remaining stems/ha in final cutting	

Simulation results (dependent variables) are presented in four categories:

(1) conventional stand characteristics

(2) biomass

(3) wood quality

(4) carbon balance and water use.

In the result windows there are mainly two figures presenting the development of characteristics: the upper figure shows the development during the rotation period and the lower figure shows the annual increment of the selected characteristic

(Fig. 3). The development of different tree size classes (dominant trees, intermediate trees, suppressed trees) can also be examined. Details of characteristics available in the result windows are presented in Table 2.

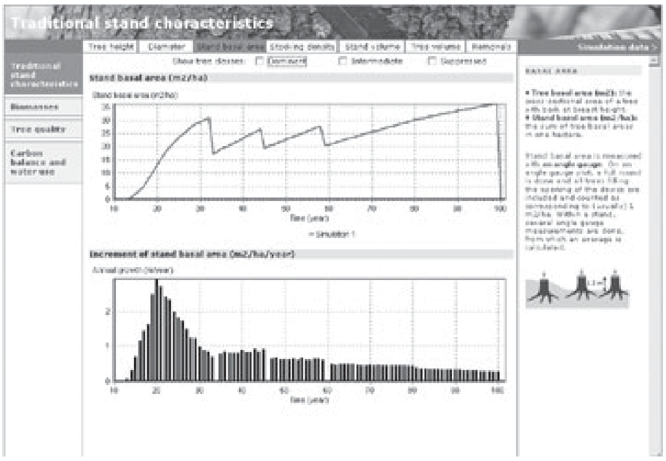

FIG. 3–Example of result window of PuMe.

TABLE 2–Contents of result windows in PuMe

Conventional stand characteristics	Biomass at forest/tree level
• Mean tree height and height of crown base (m) • Mean diameter (cm) • Stand basal area (m^2/ha) • Stocking density (trees/ha) • Stand volume (m^3/ha) • Tree volume (m^3) • Removals (saw timber/pulp wood/waste wood) in cubic metres and euros per hectare (with user-defined prices)	• Total tree biomass (kg/ha) • Stem biomass (kg/ha) • Branch biomass (kg/ha) • Needle biomass (kg/ha) • Coarse root biomass (kg/ha) • Fine root biomass (kg/ha)
Quality	**Carbon balance and water use**
• Branch zones • Heartwood and sapwood proportions • Tree rings • Latewood proportion (%) • Wood density (kg/m^3) • Fibre length (mm) • Fibre thickness (mm)	• Total carbon production (kg C/ha/year) • Carbon used for growth (total growth, net growth, litterfall) (kg C/ha/year) • Carbon used for respiration (total, growth, and maintenance) (kg C/ha/year) • Water use (litres/ha/year)

Conventional stand characteristics. This window contains the following characteristics: tree height, height of crown base, diameter, number of stems, stand basal area, volume, and removals. In the removals window the user can examine the possible revenue from sawn timber, pulp wood, and energy wood with different prices and interest rates. This information can also be exported to Excel for further use.

The *Biomass* window gives figures about the development of total tree biomass per hectare and biomass of different parts of trees (stem, branches, needles, fine roots, and coarse roots) on both the tree and the stand level.

Properties of tree structure can be examined in the *Quality* window which contains pictures of stem shapes including branch zones (Mäkinen 1999) and sapwood/heartwood proportions at the age of thinning. In the newest version of PuMe there are also more detailed figures about tree structure: tree rings, latewood proportion, wood density, fibre length, and fibre thickness.

In the *Carbon balance* window there are figures about the total carbon balance of forest trees per hectare. The annual amount of carbon stored in growth (divided into net growth and litterfall) and carbon in annual respiration (total, growth, and maintenance respiration) can be examined. There are also figures about annual water use on the forest and the tree level (Nikinmaa *et al.* 1996).

It is possible to save the figures of recent simulations and compare the results of different simulations (maximum three). In addition, the user can start the LIGNUM model and examine the 3D structure of the simulated trees.

PuMe is available in both Finnish and English. It requires Windows 98 or later as the operating system, 500 MHz processor or faster, and Flash Player for watching the videos.

Evaluation of the PuMe Environment

There are many different kinds of advanced tools available for simulating forest growth — for example, FOREST-BGC (Running & Gower 1991), SILVA (Pretzsch *et al.* 2002), and a shared modelling platform CAPSIS (de Coligny *et al.* 2002). PuMe differs from most of the existing simulators in that it is developed for forestry education, while the others are targeted mainly for research purposes or for decision-making tools for foresters. PuMe, in addition to the growth model, contains learning material related to Finnish forestry (text, pictures, videos, term explanations). The process-based PipeQual model included in PuMe also allows students to examine more versatile forest management scenarios than the traditional simulators using statistical growth models/yield tables.

PuMe has been used in forestry studies at various levels. At Savonlinna vocational school it has been utilised in different kinds of courses. At the University of Joensuu

PuMe has been used in exercises which have included simulating different management chains, with PuMe examining the effects of different treatments on forest growth and analysing the simulation results in a report. At the University of Helsinki, PuMe has been used by first-year undergraduates mainly utilising the video and photo material, and in graduate courses to analyse the development of tree structure and the impacts of thinning on wood quality. Learning with PuMe has been examined during these exercises, and PuMe has been developed according to the feedback received.An example exercise can be downloaded from http://www.joensuu.fi/ktl/saima/pume_exercise.htm.

The PuMe environment has generally been found interesting by teachers and students. However, it has been noticed that certain user groups are more interested in certain parts of PuMe than the others. For example, forest owners were mostly interested in the economic outcomes of their forests rather than the biological processes behind these outcomes, while the multimedia parts were found the most interesting by groups of foreign students. Preliminary results from tests done with different student groups also indicate that the students' learning with PuMe differs a lot depending on the students' level of studies, their knowledge about boreal forests, and the teaching culture they are used to, and of course their motivation.

CONCLUSIONS

The construction of the first learning environment took about 3 years by two persons. In addition, much effort went into supervising the functioning of the process-based model and testing the environment in forest education (Varpala, Vocational school of Savonlinna, Universities of Helsinki and Joensuu, Mikkeli polytechnic school, Forest museum LUSTO). The systematic testing of the environment as a teaching tool was not reported here but has been started by the University of Joensuu, Department of Teacher Education and Faculty of Forestry.

During the project it became clear that utilising a particular process-based model requires profound understanding of its functioning; therefore an "open code" of the process-based model is no guarantee that it will be applicable in a software environment. A minimum requirement for the code to be "stand alone" is that it be very clearly documented. A model archive documenting growth models according to a common standard could be helpful for making more process-based models applicable and attractive to users.

The production and appropriate usage of multimedia properties turned out to be a challenge. At the moment a pedagogical evaluation has been started on the significance of the multimedia used in PuMe in relation to the targeted information.

The distribution of the PuMe software was intended to be carried out by the administrative partner of the ongoing PuMe II project. In order to cover the distribution costs, a price of 50–240 Euros was set depending on the version (CD/ DVD/ Finnish/English) and the type of subscriber (private/commercial), but sales have not been very successful. In order to make the software available to more users, a web-based freeware is now being developed. In the future, a portal or databank administrated, e.g., by IUFRO for these kinds of environments and tools (including a model archive of process-based models) could be very helpful for the developers and users of these learning and expert environments.

The future aims of developing PuMe are twofold. Firstly, we are interested in gaining more experience of the use of PuMe by different users in different countries, in order to improve our understanding about the pedagogical aspects of virtual learning environments. We hope this will allow us to improve the system as a powerful learning tool. Secondly, we will expand the knowledge base of PuMe by incorporating information about additional species in wider areas of application, as well as additional features for the current species. Improved model versions will be incorporated as soon as they become available. In this way, PuMe will also serve the modellers as a test bench and a link between model developers and potential model users.

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INTERNET SOURCES

LIGNUM WEB PAGE: http://www.metla.fi/metinfo/kasvu/lignum/index-en.htm [26.5.2005]

DOWNLOAD PAGE OF PuMe: http://www.joensuu.fi/ktl/saima/pume_downloads1.htm [26.10.2005]

EXAMPLE OF PuMe EXERCISE: http://www.joensuu.fi/ktl/saima/pume_exercise.htm [15.1.2006]