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Simulating wood quality in forest management models

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Abstract

The raw material properties of wood develop as the tree grows, laying down wood cells with specific properties, and forming the stem structure that is the basis of timber quality. This development is influenced by genetic and environmental factors and forest management practices. It is desirable in growth and yield models intended for the economic assessment of management practices to include some indication of wood quality and how it is affected by genetics, environmental factors and silvicultural measures.

In forestry, understanding the development and variation of wood quality is important for different management and planning problems which can be broadly classified under (1) management for harvest operations, and (2) long-term silvicultural planning. This paper reviews approaches and models that allow us to study these two problems in quantitative terms. We start the review by discussing the concept of «wood quality model», then classify the approaches on the basis of their complexity, underlying principle and intended application. We illustrate three advanced dynamic quality models and their applications with example case studies. These include empirical, hybrid, and mechanistic models applied to predictions of both sawn timber and fibre properties. Finally, we consider the current challenges for wood quality modelling in connection with forest management.

Key words: wood quality; mixed models; empirical models; hybrids models.

Resumen

Simulación de la calidad de madera en los modelos de gestión forestal

Las propiedades de la madera se desarrollan cuando crece el arbol, estableciendose las células de la madera con propiedades específicas, y formandose la estructura del tronco que es central para la calidad de la madera. Esta desarrollo se ve influido por factores genéticos y ambientales y por las prácticas de gestión forestal. Es deseable incluir en los modelos de crecimiento y producción destinados a la evaluación económica de las prácticas de gestión una indicación de la calidad de la madera y cómo se ve afectada por factores genéticos y ambientales y por las medidas silvícolas.

En el sector forestal, la comprensión del desarrollo y la variación de la calidad de la madera es importante en distintos programas de gestión y planificación que se pueden clasificar en (1) la gestión de las operaciones de cosecha, y (2) la planificación silvícola a largo plazo. Este artículo discute los principales enfoques y modelos que nos permiten estudiar estos dos problemas en términos cuantitativos. Comenzamos la revisión discutiendo el concepto de «modelo de calidad de madera», y luego clasificamos los enfoques sobre la base de su complejidad, el principio subyacente y el uso previsto. Mostramos tres modelos dinámicos avanzados de calidad y sus aplicaciones con estudios de casos. Estos incluyen modelos empíricos, híbridos y mecánicistas aplicadaos a las predicciones tanto de la madera aserrada como a las propiedades de la fibra. Por último, consideramos los retos actuales para el modelado de la calidad de la madera en relación con la gestión forestal.

Palabras clave: calidad de madera; modelos mixtos; modelos empiricos; modelos híbridos.

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Introduction

Wood is used as raw material for sawmills, pulpmills, panel production, and now also increasingly for bioenergy. In each end-use, some specific properties of the raw material determine the expected value recovery and the particular end products that the raw material is best suited for (Fig. 1). These end-use-specific properties of the raw material are collectively referred to as «wood quality». It is evident from this definition that wood quality is not a uniquely defined concept and should therefore always be specified in context.

For sawmills, the strength, stiffness, dimensional stability, durability and appearance of a piece of timber are important determinants of its quality and end use (*e.g.* boards, studs, pieces of furniture) (*e.g.* Usenius, 2002; Kliger *et al.,* 2003). These factors largely depend on stem structure, some key indicators being the size and type of knots, the amount of heartwood and sapwood, and the distribution of annual rings inside the marketable log (Thörnqvist, 1996). Factors such as wood density, stem form, spiral grain and occurrence of reaction wood also affect the yield of sawing. Pulpwood quality is largely determined by fibre properties, including fibre dimensions, chemical composition (*e.g.,* the content of lignin, cellulose and extractives) and microfibril angle (Zobel and Buijtenen, 1989). From the perspective of wood processing industries, the variability of these properties within a tree is an important issue (Lundqvist, 2002, Usenius, 2002). In bioenergy production, important quality indicators include moisture content, and some element contents in wood ash. The energy value from wood is largely independent of species.

The raw material properties of wood develop as the tree grows, laying down wood cells with specific properties, and forming the stem structure that is key for timber quality. This development is influenced by genetic factors, environmental factors and forest management practices (Fig. 1). It has long been understood in qualitative terms that forest management influences wood properties through a causal chain where manipulating stand structure influences crown development, and this is further reflected in the formation of stem structure (Larson, 1962). Wider spacings give rise to larger crowns with a larger number of thicker branches and consequently, as a result of a greater photosynthetic area, wider growth rings, larger stem diameters, more pronounced taper, and different distributions of fibre properties, such as density, microfibril angle, and stiffness. In addition, the final yield quality and quantity also depend on the actual harvesting, bucking, sorting, transport and storing of the logs.

In forestry, understanding the development and variation of wood quality is important for several different management and planning problems. From the point of view of modelling wood quality, two broad categories of problem can be identified. Firstly, there is the problem of **harvest and transport**, when wood processing industries acquiring raw material from a catchment area need to assess wood quality and its variation between and within the potentially harvestable stands at the time of harvest (Fig. 2a). Furthermore, information is needed about the impacts of bucking,

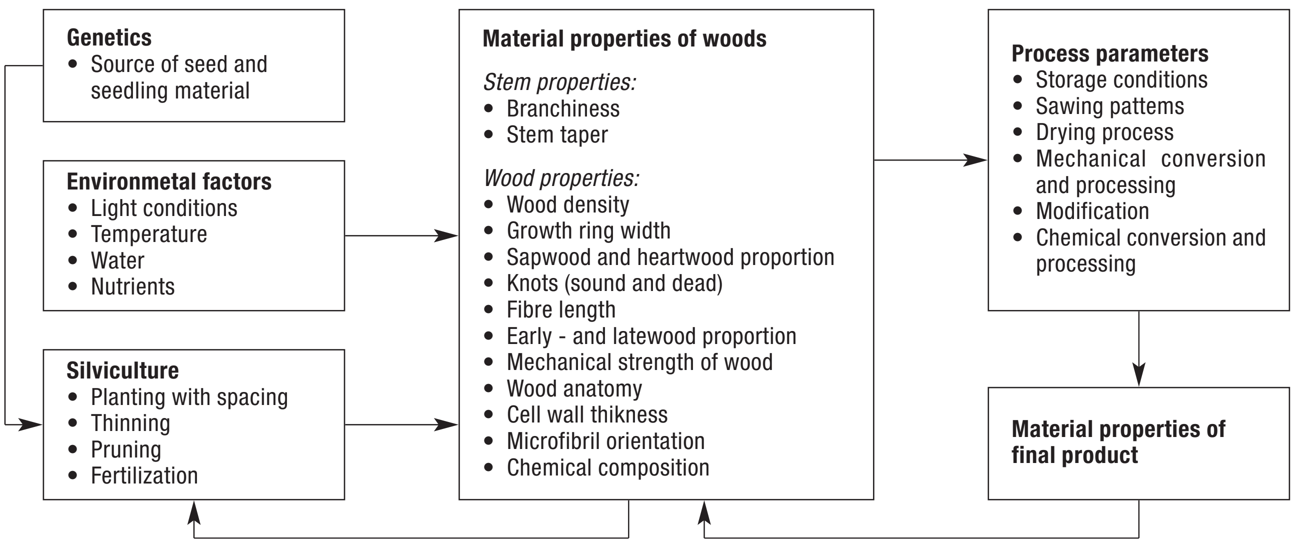

Figure 1. Interrelation of wood properties and product properties (Teischinger, 2003).

logging and storage on the properties of the raw material, such that wood quality is not impaired in transit from the forest to the manufacturing site. The models needed at the different stages of this process should be able to predict the relevant raw material properties related either to stands, stems or logs, directly from some *readily measurable input variables*.

Secondly, models of wood quality are needed in **long-term silvicultural planning**. Here, apart form selecting the genetic material at the time of planting, it is of particular interest to understand how wood quality can be influenced by measures such as planting density, timing and intensity of harvests, fertilisation and pruning, and what impact these measures may have on the economic return from the forest (Fig. 2b). The economics of stand management are typically studied using growth and yield models in an optimisation context. This requires that the models of wood quality can be linked to the growth and yield models through *input variables that are output from the growth model*.

The objective of this paper is to review approaches and models that allow us to study the above two types of problem in quantitative terms. The review does not intend to be comprehensive —a vast number of models

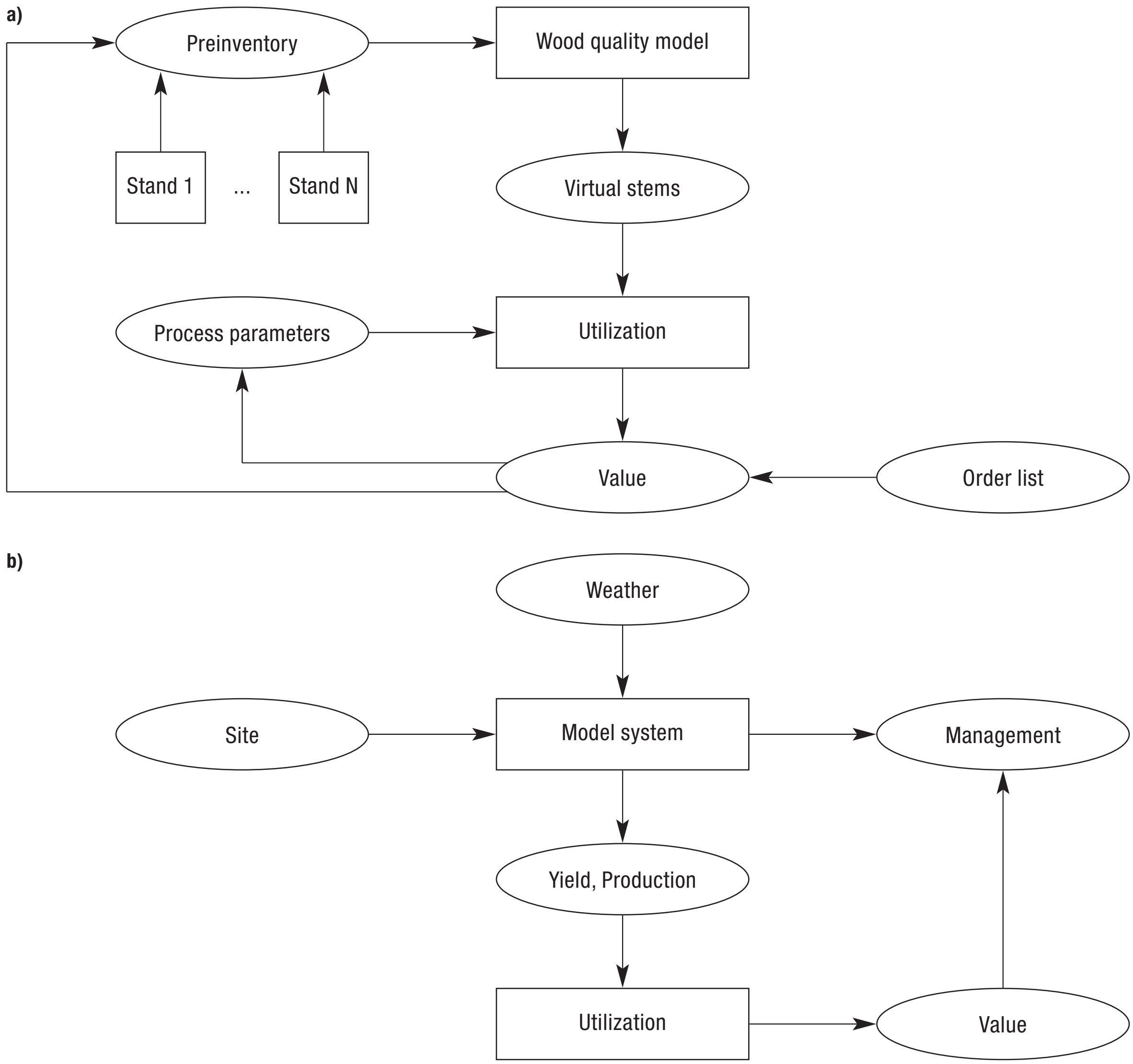

Figure 2. Schematic presentation of the two types of forest management problem requiring models of wood quality. a) The «harvest problem» consists of selecting stands for harvest so as to maximize the value recovery for a particular utilization process with set customer orders, and of selecting parameters for the utilization process, *e.g.,* sorting and bucking to fulfil an order matrix, sawing to measure at the sawmill, etc. b) The «silvicultural planning problem» consists of selecting the management measures that maximise the economic returns from the forest, calculated on the basis of the quantity and quality of the yield at a given site and environment.

related to various aspects of wood quality have been published in the scientific literature since the 1980s—but we aim at illustrating some key features of the different types of model, providing selected examples of each. We start the review by discussing the concept of «wood quality model», then classify the approaches on the basis of their complexity, underlying principle and intended application. Secondly, we illustrate some of the more advanced approaches through case studies, and finally, consider the current challenges for wood quality modelling in connection with forest management.

Review of existing models and trends

Concept of wood quality in models

Wood quality models aim at providing information about the variation in wood properties that affect the end-use of wood products. The variation relevant for the end-use has often been found to be larger within than between trees or even between stands (Zobel and Van Bujtenen, 1989; Zhang *et al.,* 1994, Moore *et al.,* 2009). Logging operations aim at bucking and sorting individual trees, and silvicultural practices are often defined at individual or at least at the diameter-class level. Therefore, although stand level studies and models also exist in the scientific literature (*e.g.,* Seeling, 2001; Malinen *et al.,* 2003), our focus here is on individual-tree scale models.

The unifying characteristic of all individual-tree wood quality models is **stem geometry.** The geometry of stems and logs is essential for the sawmill, which has traditionally been the end-use providing the largest economic returns. At its simplest, this is described by the taper of the stem, which determines the most profitable bucking and the setting of the saw blades, while more information about the distribution of knots and heartwood, for example, could prove useful in applications. It is therefore helpful to consider all quality models as **mappings of the actual stem geometry** to variables that summarise this complex information at an appropriate level. This level determines model complexity.

Model complexity

Because of the importance of geometry, modelling stem taper is of primary importance for all wood quality models (Tong and Zhang, 2008). The next level of complexity is provided by models that attach some **mean values of the property variation** to the stems, depending for example on their size and the position of the tree in the stand (Vestöl *et al.,* 1997; Wernsdorfer *et al.,* 2005). Further, some models provide the mean properties (Lundgren, 2000; Gobakken, 2000; Lemieux *et al.,* 2001; Sepúlveda *et al.,* 2002) or lumber grades (Prestemon, 1998; Petutschnigg and Katz, 2005; Benjamin *et al.,* 2007; Lyhykäinen *et al.,* 2009) of different **sections of the stem**, such as the butt, middle and top logs. These can reflect, for example, the maximum size of sound and dry knots (Todoroki *et al.,* 2005; Benjamin *et al.,* 2007), the proportion of juvenile wood (Lindström, 2002), or the mean basic density (Gobakken, 2000).

More flexible models are obtained if the distribution of mean properties is considered as **continuous with height** along the stem. The properties then represent means per whorl, or means from pith to bark as a function of height, allowing for the further derivation of respective means for any selection of logs. For example, Maguire *et al.* (1994, 1999), Moberg (2001) and Mäkinen and Colin (1998) modelled the vertical distribution of branch characteristics in Douglas fir, Norway spruce and Scots pine, respectively. Wilhelmsson *et al.* (2002) modelled the vertical distribution of basic density, latewood content, juvenile wood diameter, heartwood diameter and bark thickness, and how it varies with site and climate in stems of Norway spruce and Scots pine in Sweden. Several other researchers have developed models for the vertical distribution of various wood quality characteristics (Mäkinen *et al.,* 2003; Molteberg and Høibø, 2007).

An increasing number of models have been constructed that attempt to describe the full **three-dimensional distribution** of selected stem properties, and how it varies with tree size and the environment. These are sometimes called **virtual stems** (Fig. 3). It should be noted that many of the virtual stem models are actually two-dimensional at least in some characteristics, assuming cylindrical symmetry (Fig. 3b). Some of the first models of virtual stems were for radiata pine in New Zealand (Tian and Cown, 1996) and for Norway spruce in France (Leban *et al.,* 1996). These models included the height distributions of fibre properties in each growth ring in a cylindrically symmetrical trunk (*e.g.* Degron and Nepveu, 1996). Other similar models have provided the branch knot distribution in three dimensions (*e.g.* Grace *et al.,*

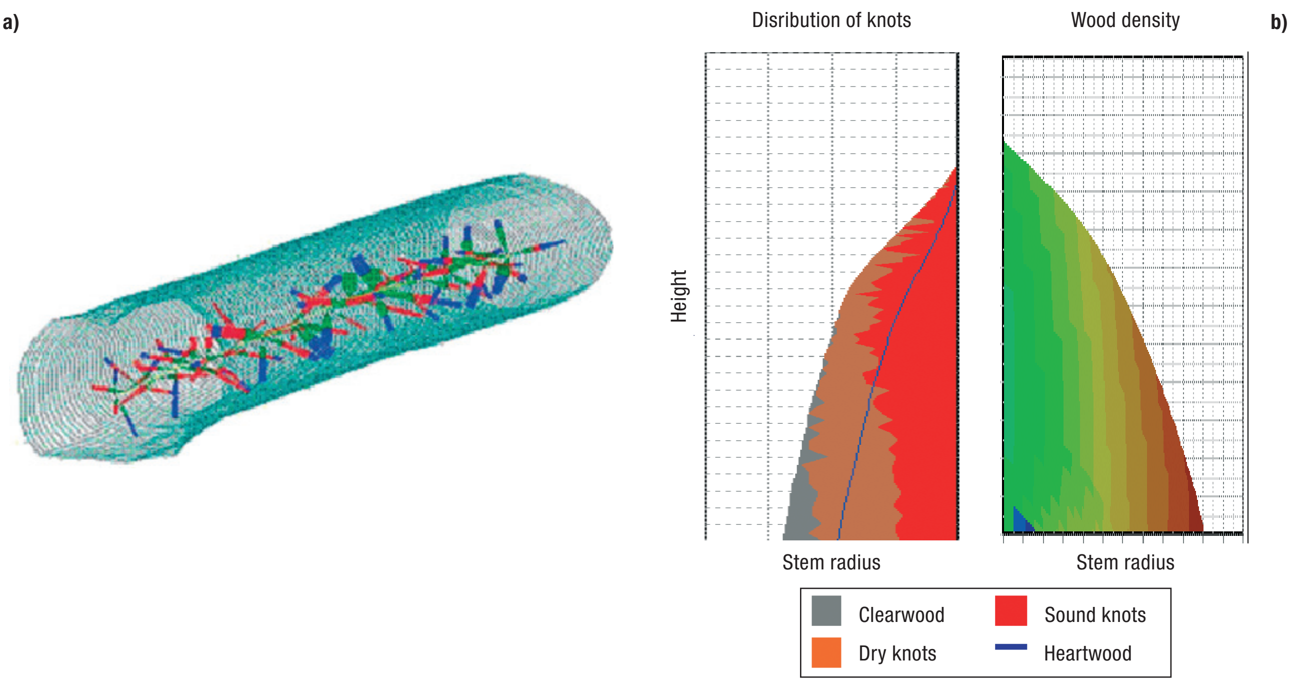

Figure 3. Virtual stem models provide a three-dimensional representation of stems with properties. a) Description of internal knots and the outer shape of the stem by the InnoSim simulator (Usenius, 2002; Song and Usenius, 2007). b) A two-dimensional projection of Norway spruce stems simulated by RetroSTEM (Kantola *et al.,* 2008). Whorl mean widths of zones defined by knot type presented as a function of height (a), wood density in rings assuming cylindrical symmetry (darker colours represent higher wood density) (b).

1998; Kellomäki, 1999; Mäkelä and Mäkinen, 2003; Weiskittel *et al.,* 2006; Kantola *et al.,* 2007). Some virtual stem models also consider the irregular shape of the stem profile, with the possibility of lean, warp (Moberg, 1999; Usenius, 2002; Hapca *et al.,* 2007) and asymmetrical circumference about the pith (Leban *et al.,* 2002). Defects such as resin pockets (Seifert *et al.,* 2010) and compression wood (Leban *et al.,* 2002) have also been included in some of the recent virtual stem models.

Modelling principles

The objective of wood quality modelling is to relate the quality characteristics, at the level of complexity chosen, to the variation in stem (*e.g.* ring width, diameter at breast height, crown length), stand (stand means of the stem variables) and site (*e.g.* site index, temperature sum) properties. This will allow us to make predictions of wood quality for different trees, stands and environments. Several different approaches have been taken, utilising different modelling principles and techniques.

The conventional modelling approach in wood quality models, like in other models in forest science, is **empirical-statistical**. The objective is to predict wood quality characteristics from measured stem, stand and site properties through equations fitted to data. This approach applies, in principle, to all levels of model complexity, and the inputs can also be created using a growth model. Examples include mean-tree property models (Vestöl *et al.,* 1997), height-distributed models (Maguire *et al.,* 1999, Wilhelmsson *et al.* 2002), and virtual stem models (Weiskittel *et al.* 2006; Ikonen *et al.,* 2008). However, because the relevant quality attributes largely depend on both the end-use of the raw material and the chain of forest operations applied, the number of empirical-statistical models predicting wood properties is large and application-specific.

A special type of empirical-statistical model is a three-dimensional virtual stem model developed from very detailed measurements of stem structure, obtained either from careful external measurements (*e.g.* Todoroki, 1990), destructive stem analyses (Usenius, 2002; Pinto *et al.,* 2003), or using X-ray (*e.g.* Lindgren and Lundqvist, 2000; Oja *et al.,* 2003) or NMR techniques (Morales *et al.,* 2004). These models are often little more than mathematical interpretations of the actual measured logs, but as such, can serve as input to sawing simulation, for example in AUTOSAW (Todoroki, 1990; Todoroki and Rönnqvist, 2002; Todoroki *et al.,* 2005), SIMQUA (Leban and Duchanois, 1990), Saw2003 (Chiorescu and Grönlund, 2000) or WoodSim (Usenius, 2002; Song and Usenius, 2007; Pinto *et al.,* 2003).

Some researchers have taken the view that wood quality models should make full use of what is known about the relationship between stem structure and tree growth (*e.g.,* Larson, 1962). In this **structural growth-quality** approach, instead of deriving stem structure directly from the measured final state of the tree, it is constructed dynamically along with the dimensional growth of trees. The basic logic of the approach is that if we follow crown development, we can keep track of many structural properties, especially diameter growth, heartwood formation and branch growth and mortality. Fibre properties can similarly be related to growth, especially to ring width and position. The branch models by Maguire *et al.* (1991) were among the first studies of this approach. Osawa *et al.* (1991) utilised the pipe model (Shinozaki *et al.,* 1964) in their profile theory, which predicts branchiness and stem shape from height growth and crown rise. Houllier *et al.* (1995) proposed a general method for deriving wood quality attributes, especially those related to properties of sawn timber, from height and diameter growth and the development of stem taper. Since then, a variety of empirical (Høibo *et al.,* 1997; Mäkinen, 1999; Weiskittel *et al.,* 2007) and theoretical (Mäkelä, 1997, 2002) studies have focused on the relationship between tree growth and stem structure, resulting in a number of 3-dimensional stem simulators (*e.g.* Win-EPIFN, Leban *et al.,* 1996; BLOSSIM, Grace *et al.,* 1999; 2006; RetroSTEM, Mäkelä *et al.,* 2002; Kantola *et al.,* 2008).

The structural growth-quality approach mainly focuses on how the mechanical properties of stems develop in relation to tree growth, while fibre properties are simply taken as statistical functions of ring width and position (*e.g.* Lindström, 1997; Mäkinen *et al.,* 2002; Ikonen *et al.,* 2008). Some modelling studies have approached the development of fibre properties in a **physiology-based approach**, following the process of how cells are laid down in the course of time and how this depends on the environmental factors and the availability of carbohydrates (Fritts *et al.,* 1999; Deckmyn *et al.,* 2006, 2008; Drew *et al.,* 2010; Hölttä *et al.,* 2010). Deleuze and Houllier (1995, 1997) considered the development of stem taper using a physiological carbon transport model. Eder *et al.* (2009) reviewed the interaction between mechanical stresses and xylem properties. Several other aspects of the physiology of wood formation have been the focus of modelling studies (*e.g.* Booker and Sell, 1998; Kramer, 2001, 2002; Forest and Demongeot, 2006; Schulgasser and Witztum, 2007), but though important in increasing understanding, few of these directly aim at developing management tools.

Another more theoretical approach with possible future applications involving management for wood quality is the so-called **structural-functional modelling**. These models describe whole-tree growth in 3 dimensions, as driven by environmental factors in a process-based framework. Some of these models, such as AMAPpara (Reffye *et al.,* 1997), LIGNUM (Perttunen *et al.,* 1998) and the models by Kellomäki *et al.* (1999) and Ikonen *et al.* (2003), can produce descriptions of ring width and taper, sapwood and heartwood, and the distribution of knots, and some have been applied to demonstrate the development of wood quality in sawn timber (Ikonen *et al.,* 2003).

Models and simulators applicable to the harvest problem

As described above, the «harvest problem» is related to estimating the potential value of different forest stands as raw material sources for specified end-uses of wood. Here, the value is most naturally assessed from the point of view of the industries utilising the wood. Many applications of wood quality models deal with the development of pre-harvest inventory procedures and the utilisation of the data collected in estimating the value of the forest resource.

Taper models serve as a basis for many pre-harvest inventory systems, allowing for the bucking of stems to different assortments for sawmills, pulpmills, fuel wood and waste (Tong and Zhang, 2008). Systems have been developed where pre-measurements of height and diameter are converted to taper curves using empirical models, and these are further utilised by crosscutting simulation programs to optimise the bucking procedure (*e.g.* Nieuwenhuis, 2002). The taper curves can be amended by pre-inventory information of wood quality, *e.g.* such as the occurrence of various defects (Pavel and Andersson, 2009).

When the growth-quality models are applied to the harvest problem, they construct the current virtual stems using pre-harvest inventory data and backward dynamic calculation of the stem internal structure. The French Win-EPIFN simulator (Leban *et al.,* 1996) was among the first pre-harvest information systems based on growth-quality models. On the basis of measurements of tree height, age and diameter, it uses a chain of models to produce virtual stems with shape, branching pattern and several wood properties. The virtual stems can be sawn into logs and boards which are graded and valued. The Win-EPIFN model has also been incorporated in other decision support systems (*e.g.* Catchpoole *et al.,* 2007).

The Atlas Cruiser (Gordon *et al.,* 2006) is another example of a decision-support tool for characterising forest stands to estimate their potential value. Features such as tree size, branching characteristics and stem form are assessed during a forest inventory. The system applies different models that together characterise wood quality properties, including the branch cluster model BLOSSIM (Grace *et al.,* 1999, 2006) and descriptive models for taper and wood density (Gordon *et al.,* 2006). These data, together with a set of log grades and prices are then used to estimate potential stand value. Kantola *et al.* (2009) demonstrated the potential applicability of the RetroSTEM model (Mäkelä *et al.,* 2002; Kantola *et al.,* 2008) in combination with the InnoSim sawing simulator to solving similar problems related to decision-making about harvests.

The use of detailed three-dimensional virtual stem models/images has not become routine practice at sawmills or pulpmills to date, but several simulation studies applying such models in combination with sawing simulators have demonstrated that if detailed on-line descriptions were available about individual stem geometry, they could considerably increase the value recovery of the sawing process (Todoroki and Rönnquist, 2002; Oja *et al.,* 2003; Poukka *et al.,* 2003; Nordmark, 2005). This would require either on-line scanning of logs or virtual stem models that could reliably reproduce images of individual stems using feasible external measurements.

Long-term silvicultural management

The methods described above for predicting the wood quality of an existing raw-material resource are also readily applicable to assessing the value of stands treated with different silvicultural regimes. Pre-measurements are taken from the stands for creating virtual stems with internal properties; these may then be input to sawing simulators or inventory analysis systems to assess the value of the raw material. For example, the Atlas software system (Gordon *et al.,* 2006) was recently used to assess the value of different silvicultural regimes within a radiata pine trial (Grace, unpublished data). The AUTOSAW simulator has been applied to such comparisons in several studies (*e.g.* Weiskittel *et al.,* 2006; Lowell *et al.,* 2008). Kantola *et al.* (2009) compared the revenue from stands treated with different thinning intensities using the RetroSTEM model combined with the WoodSim industrial simulator.

While comparisons of measured stands are useful for gaining insights into the impacts of silviculture on economically relevant wood properties, they are usually restricted to a few different cases only. More systematic comparisons of the economics of silvicultural methods can be done using **stand growth models** for either creating selected management scenarios (Deckmyn *et al.,* 2008) or optimising over a continuous range of options (Hyytiäinen *et al.,* 2004).

Several **empirical growth and yield models** have been equipped with a wood quality sub-model. For example, the Win-EPIFN model (Leban *et al.,* 1996) has been combined with a system of models for height and diameter growth in different environments and with different silvicultural treatments (*e.g.* Meredieu *et al.,* 1999). The TASS growth simulator is based on the structural growth of individual trees in a spatial arrangement (*e.g.* Mitchell, 1988), and has been amended with a submodel for branch and stem properties that follows a logic very similar to the growth-quality models described above (Goudie, 2002). The SILVA model includes a semi-dynamic reconstruction for branch diameters, accounting for crown plasticity in relation to competition (Seifert and Pretzsch, 2002; Seifert, 2003). Similarly, BWINPro has a dynamic description of crown development and branch growth (Schmidt, 2001, 2004; Schmidt *et al.,* 2006), and in the Sylview simulator the knot zones inside stems are determined on the basis of crown rise (Scott, 2006). Todoroki and Carson (2003) used AUTOSAW to determine log characteristics that increased profitablity and efficiency when sawing pruned logs and then used the stand growth model within the STANDPAK modelling system (Whiteside, 1990), to investigate forest management options that would yield such logs.

Fewer **process-based growth models** include the possibility of wood quality prediction. Mäkelä (1997, 2002) considered the development of stem structure in combination with a carbon balance model, and this approach was further developed in the PipeQual model (Mäkelä and Mäkinen, 2003; Kantola *et al.,* 2007). A rather similar approach is used in ANAFORE (Deckmyn *et al.,* 2008), but in addition, ANAFORE also includes a process-based description of the formation of xylem cells, with their properties depending on the growth conditions. Economic optimisation has been carried out using PipeQual to determine the optimal thinnings and rotation lengths for Scots pine (Hyytiäinen *et al.,* 2004) and to consider alternative uses of Norway spruce by sawmills and pulpmills (Cao *et al.,* 2008).

Summary and trends

A vast amount of data has been collected and a large number of models have been developed to describe wood quality in existing forest stands and for model projections of future stands under different silvicultural regimes. Currently, techniques are available for very detailed, three-dimensional representations of virtual stems with various wood properties and defects. However, there are still problems regarding the reliable creation of such virtual stems from either pre-inventory measurements or growth model simulations.

For industrial purposes, the development of on-line scanning techniques would probably reduce the need for detailed stem property predictions and move the focus towards more flexible sawing simulation. On the other hand, efficient methods will still be required to assess the value of the resource before stems have been transported to the mill. The trend in forest inventories is towards lidar scanning, which will mean that a change is to be expected in the pre-inventory variables available to any models. From this perspective, the growth-quality approach seems the most flexible, as it does not only rely on some pre-defined measurements, but utilises more general information about the dynamics and development of tree structure.

When the value of the forest resource is assessed in a dynamic growth-quality modelling system with the objective of finding the optimal silvicultural regime, the quality information that can be used in the economic assessment will necessarily be less detailed than in the evaluation of current resources for actual industrial production. Firstly, growth models can only deal with expected stems and their distributions, not actual individual stems (even if the model was on an invididual basis). Secondly, the grading in the future projections cannot usually be based on very specific industrial grading rules, because these may be unknown at the present time. The key issue here is the connection between management, growth, and wood quality. Models that include this connection either empirically or on the basis of eco-physiological processes therefore seem to have the greatest potential for applications in silvicultural planning.

Case studies

In this section, we present example applications of three different advanced wood quality models based on the growth-quality approach. Our objective is to demonstrate how this basic approach can be connected with either empirical or process-based growth models at different levels of detail, and how these models can be applied to variable forest management questions. TreeBLOSSIM (Grace *et al.,* 1998; Grace *et al.,* 1999; Grace *et al.,* 2006) represents a fairly empirical, management-oriented approach while ANAFORE (Deckmyn *et al.,* 2008, 2009) is a physiologically-based model primarily developed as a research tool. PipeQual (Mäkelä and Mäkinen, 2003; Kantola *et al.,* 2007) is intermediate between these two, deriving growth from the carbon balance but using empirical growth-quality relationships for stem structure. RetroSTEM is a version of PipeQual where tree growth is calculated backwards with empirical functions (Mäkelä *et al.,* 2002; Kantola *et al.,* 2008).

BLOSSIM and TreeBLOSSIM

BLOSSIM is a branch growth model developed for radiata pine using the growth-quality approach described above (Grace *et al.,* 1998). It predicts the number and position of branch clusters within the annual height increment, the number and position (orientation) of branches and stem cones within these clusters and the development of the part of the branch that forms the knot at the end of the rotation (Fig. 4). BLOSSIM was designed to link with independently developed growth models, and by describing the location of branches in three-dimensions it includes sufficient detail to link

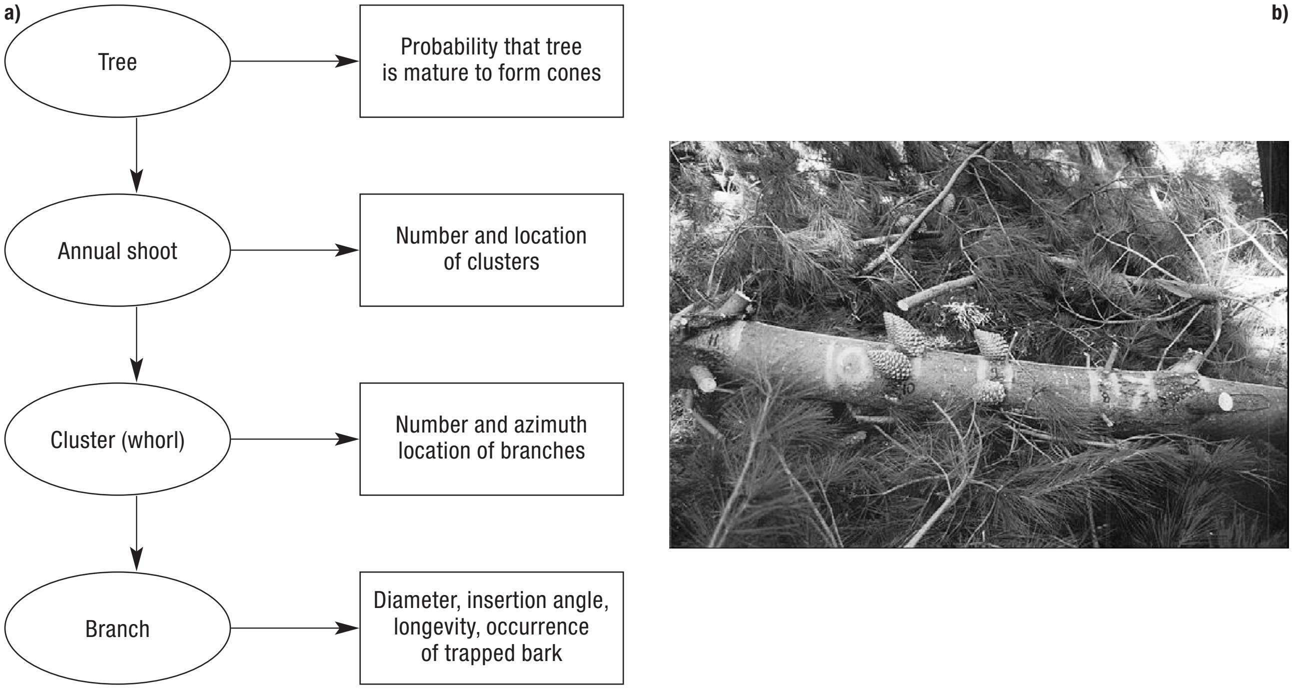

Figure 4. Branch architecture in BLOSSIM. a) Schematic presentation. b) A mature radiata pine annual shoot with 4 branch clusters, clusters 10, 9, 8 and 7. Photograph J. C. Grace.

with sawing simulators. A more recent addition was the development of functions to predict the mass and location of foliage for each branch as a function of branch growth rate and then predicting area and basic density for each growth ring from the mass and location of foliage within the crown (Pont, 2003).

BLOSSIM has several applications in practical forest management in New Zealand. It has been incorporated within ATLAS Forecaster and Atlas Cruiser software, where it provides estimates of branching patterns that affect the value of measured logs (http://www.atlastech.co.nz/atlas+suite.aspx). It has also been linked to the AUTOSAW sawing simulator (Pont *et al.,* 1999), and it has been combined with an individual tree – distance independent growth model in the TreeBLOSSIM simulator (Grace *et al.,* 1999; Grace *et al.,* 2006). TreeBLOSSIM predicts tree growth and the related development of the three-dimensional pattern of branching for the growing trees. Given a list of trees representing a stand it can predict the current branching structure by backwards simulation, and then predict future growth dynamically.

Pont *et al.* (1999) used BLOSSIM and AUTOSAW to investigate the influence of branching on visual grading for premium products such as clear and cuttings grades. The study indicated that variation in the number of clusters on a log showed the largest potential for affecting value. The next most significant effect resulted from varying the number of branches in each cluster. Although only small branches were added or removed there was a large effect, of the order of 7% to 9% in value, indicating the importance of knowing the number of branches and stem cones in a cluster. The structure of BLOSSIM is such that independent models predicting wood properties as a function of ring number and/or ring width can be overlaid.

The ability of BLOSSIM to predict the number of branch clusters and the diameter of the largest branch in each cluster has been evaluated for a wide range of genetically improved seedlots and site conditions using the TreeD methodology, a photogrammetric image-based dendrometry system (Brownlie *et al.,* 2007). These analyses indicated that trees occasionally had a very large branch that was not well predicted, and examination of the photographic images indicated that these most likely resulted from an incidence of stem damage, probably caused by wind (Grace *et al.,* 2009). Given that branch size is an important determinant of log grade (http://www.maf.govt.nz/forestry/statistics/logprices/specification.htm), this highlights the importance of understanding the influence of wind on tree development within forest ecosystems.

Table 1. Percentage loss in value due to the occurrence of stem damage and/or large branches

Site Index (mean top height at age 20 years)	Nominal final stocking (stems/ha)	Final stocking at age 27 years (stems/ha)	Loss in value (%)
29.9 m	360	366	36
29.4 m	130	113	28
44.4 m	130	113	9
43.7 m	360	267	0

A study has been initiated to determine the potential loss of value due to the occurrence of stem damage and/or large branches. The estimated value from a Cruiser inventory assessment was compared with the predicted value from using the BLOSSIM model within Atlas software system with the assumption of no stem damage (Table 1). The four sample plots considered were part of an experiment covering a range of site qualities on the eastern side of the North Island. The experiment was planted at 1,543 stems/ha, thinned to 600 stems/ha at a height of 6 m. These four plots were pruned to 6 m in three 2 m lifts leaving 7 m of crown at each lift, and thinned to their nominal final crop stocking at a height of 10 m. The results at age 27 years, using a specific set of log grades, indicated that around 30% of the potential stand value was lost due to stem damage and/or large branches in the plots with lower site quality, whilst less than 10% of the value was lost in the plots with higher site quality.

Future developments to BLOSSIM include (1) the prediction of the likelihood of stem damage and the crown's response, to enable better prediction of the larger branches that influence log grade, and (2) modifications to the functions to allow genetically improved seedlots with different branching patterns to be simulated.

PipeQual and RetroSTEM

PipeQual and RetroSTEM (Retrospective Stand and Tree Evaluation Model) are dynamic simulators of stem properties that are based on the same, growth-quality type model of structural development but use different «growth engines» that drive stem development (Fig. 5). The structural development applies ideas of the profile theory (Osawa, 1991) in combination with empirical sub-models for branch population dynamics (Mäkinen and Colin, 1998; Mäkinen, 1999). This allows for the description of stems as 3-dimensional objects with annual rings and knots. The latter are divided into sound and dry, and the rings have properties such as density and tracheid dimensions. The models have been parameterised and tested for Scots pine (*Pinus sylvestris* L.) (Mäkelä, 2002) and Norway spruce [*Picea abies* (L.) Karst.] (Kantola *et al.,* 2008) in Finland and Jack pine in Canada (Schneider *et al.,* unpublished work in progress).

PipeQual derives tree growth from the acquisition and allocation of carbon, and can be used for simulating the development of quality properties in combination with stand growth. PipeQual is therefore responsive to any treatments that might affect wood quality, such as stand density and thinnings. In contrast, RetroSTEM was developed to calculate stem structure at the time of harvest, to be applicable for example in combination with the InnoSim sawing simulator (Song and Usenius, 2007). It uses an empirical function for height growth

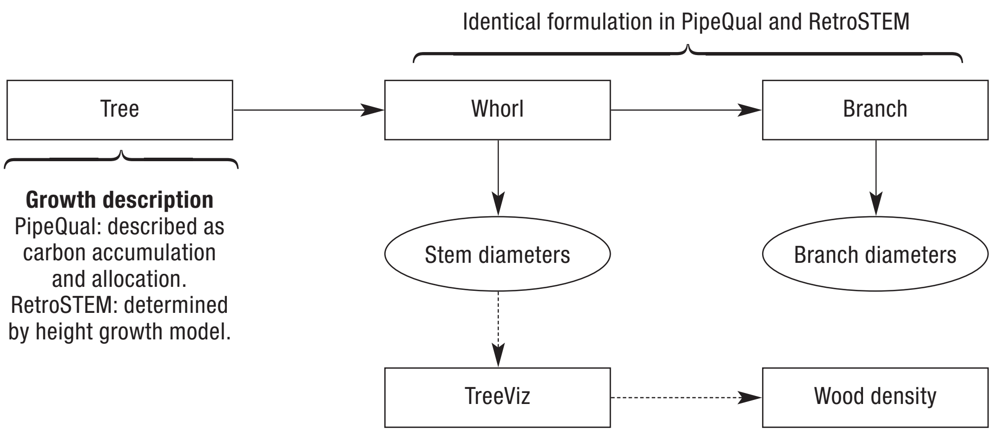

Figure 5. The structure of PipeQual and RetroSTEM.

and a related pattern for the height of the crown base to simulate stem growth backwards from the measured state at harvest.

Hyytiäinen *et al.* (2004) applied PipeQual to economic optimisations of thinnings and rotation times in Scots pine stands. The information about stem structure was utilised in bucking the stems into logs, fibre wood and waste, and further to grade the logs into quality classes on the basis of their knot size and distribution. The possibility of including this detailed information in the assessment of the economic returns of the alternative treatments was essential for the results, which differed from simulations where such information was not utilised. For example, it turned out to be profitable to conduct thinnings from above in older stands, leaving the intermediate trees to build up clearwood for a few more years after the removal of the larger trees (Hyytiäinen *et al.,* 2004).

Kantola *et al.* (2009) demonstrated an integration of the RetroSTEM model with an industrial process simulator, InnoSim (Song and Usenius, 2007). RetroSTEM was used for predicting the timber yield and quality distribution of sawn timber from the final felling of a Norway spruce stand with unthinned, normally and intensively thinned plots (Table 2). The underlying motivation for the study was to demonstrate how the combined model system could be utilised for assessing the value of different raw material sources for fulfilling a particular industrial order, however, it also gave information about the end-use value of timber from different thinning treatments.

Consistently with the Finnish thinning recommendations (Tapio, 2006), the study showed that the highest gross value of the product volumes (sawn timber, sawmill chips and sawdust) per log volume (€ log m^3) and total value per hectare (€ ha^{-1}) was achieved by using the normal thinning strategy, and the smallest value when no thinnings were used (Table 2). The differences were small in the unit value (€ per log m^3), but higher in the total value (€ ha^{-1}). The model system also allowed for a more detailed analysis of the dependence of the value on the price differences between timber grades (Fig. 6), indicating a larger relative difference if the A-grades (Nordic timber..., 1997) enjoyed higher price

Figure 6. The simulated sawn timber yield (centre goods, side boards and total volume) by quality grades for different thinning treatments (0 unthinned, 1 normal and 2 intensive thinning). Stack colours for quality grades from A (best sawn timber) to D (poorest) (Nordic timber …, 1997): A (white), B (grey), C (black) and D (stripes).

Table 2. Average tree dimensions (standard deviations) and the volume yield and value of sawn timber in the different thinning regimes

Characteristics	Unthinned	Normal	Intensive
Stem number (*n* ha^{-1})	805	682	456
DBH[a] (cm)	26 (*5.1*)	28 (*4.7*)	33 (*3.5*)
Tree height (m)	25 (*1.8*)	26 (*2.9*)	27 (*0.9*)
Crown ratio	0.5 (*0.1*)	0.6 (*0*)	0.7 (*0*)
Log volume[b] (m^3)	0.7 (*0.4*)	0.9 (*0.4*)	1.2 (*0.3*)
Log volume[b] (m^3 ha^{-1})	545	584	556
Sawn timber (m^3 ha^{-1})	289	314	299
Large boards[c] (%)	44	46	51
Small boards[d] (%)	56	54	49
Sawmill chips (m^3 ha^{-1})	152	159	154
Sawdust (m^3 ha^{-1})	83	89	81
Gross value[e] (€ log m^{-3})	131	135	134
Total value[f] (€ ha^{-1})	71,351	79,055	74,338

[a] Stem diameter at breast height. [b] Sawn logs. [c] Thicknesses 50, 63, 75 mm. [d] Thickness 19, 25, 32, 38 mm. [e] The value of sawn timber, sawmill chips and sawdust per log volume. [f] The value of sawn timber, sawmill chips and sawdust.

Table 3. Data of the 5 homogeneous and even-aged oak stands used for this Bayesian parameterization

Stand	age	Density Trees ha^{-1}	DBH cm	Height m	Soil C pool kg C m^{-2}	Soil CN ratio	Litter g m^{-2} yr^{-1}
1	86	300	30	27	1.4	23-31	507
2	150	264	25	17	2.7	21	543
3	72	320	29	21	6.6	16	649
4	70	460	23	15	13.0	20	609
5	49	650	17	20	0.7	15-16	476

premiums. However, one should bear in mind that the model has a tendency of under-estimating the lower grades because defects other than knots are currently not included in the model.

ANAFORE

ANAFORE (ANAlysing FORest Ecosystems) is a mechanistic, stand scale forest model including a physiology-based sub-model for the development of earlywood (EW) and latewood (LW) width and density (Deckmyn *et al.,* 2008). These wood properties are derived from stem growth as a result of the allocation of carbon, which is modelled according to the pipe theory as refined by Deckmyn *et al.* (2006). In particular, transition from early growth (leaf and crown development) to late growth (emphasis on storage) is induced by soil water stress, or at a fixed date. The wood-quality aspects of the model are therefore fully integrated in the growth model and are responsive to the environmental drivers of the model. Consequently, the model system provides a scientific tool to explore the assumptions made about the development of wood properties and their links with whole-tree physiology. If adequately calibrated against data, it can also be used for projections of the impacts of climate change on wood quality and growth. Here we describe an example of how the model can be used towards these objectives.

ANAFORE describes stands using stand-level total biomasses derived from detailed single-tree architecture. Stand growth is predicted from simulations of carbon, water and nitrogen fluxes, tree growth, and wood tissue development. ANAFORE follows a bottom-up approach: leaf level processes such as photosynthesis and transpiration are simulated at a half-hourly time step for sunlit and shaded leaves of crown leaf layers and implemented daily into a single tree architecture and carbon allocation module. For this example, the model was run using monthly climate data.

Because ANAFORE is a complex model with a high number of input variables, model simulations include high uncertainty in most cases (where limited data are available). The uncertainty can be reduced using Bayesian techniques that allow for model calibration with limited data. A Bayesian routine was included in the ANAFORE model (Deckmyn *et al.,* 2009), and model parameters were calibrated against forest inventory data collected in 1991 at 5 homogeneous, even-aged pedunculate oak stands (*Quercus robur* L.) in Belgium, on diverse soils (Muys 1993) (Table 3). The calibrated model was further validated against data from an experimental oak stand at Brasschaat (51°18’ N and 4° 31’ E) (Table 4). Additional datasets used for the validation were the earlywood (EW) and latewood (LW) width and wood density over the entire lifespan (Fig. 7).

Table 4. Measured (Curiel-Yuste *et al.,* 2005) and simulated (ANAFORE, this study) tree characteristics for the oak stand at Brasschaat (Belgium) in 2001 and 2003

	2001		2003	
	measured	simulated	measured	simulated
Stem production (kg C $tree^{-1}$ y^{-1})	2.96[a]	2.63	2.96[a]	3.13
Tree height (m)	17.2	19.2	17.8	20.2
Standing stem biomass (kg C $tree^{-1}$)	137	101	162	110
DBH (m)	0.30	0.23	0.31	0.24
Wood density (kg m^{-3})	n.m.	658	582	658

[a] Annual average for the measurement period 2001-2003. n.m.: not measured.

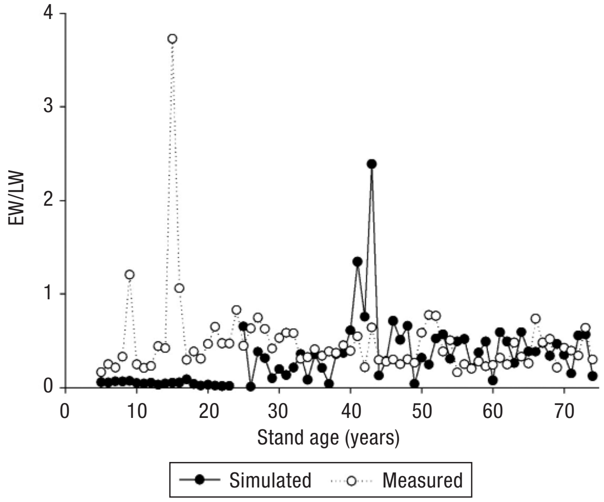

Figure 7. Simulated and measured EW/LW ratio in oak.

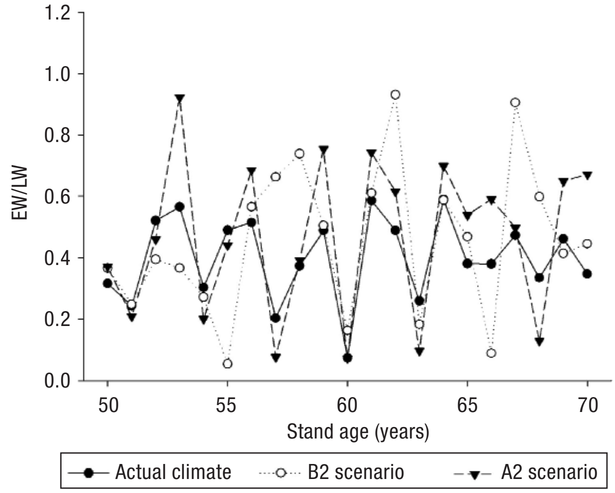

Figure 9. Simulated EW/LW ratio under 3 climate scenarios: actual climate, moderate (B2) and severe (A2) climate change.

The validation run was used for exploring the assumptions made about EW and LW development. The results suggest that wood volume was underestimated due to an overestimated simulated wood density and an underestimation of productivity of the stand (Table 4). As wood density is a function of productivity, a better simulation of the latter would improve the density simulation as well. However, the EW/LW ratio was predicted reasonably well in the older stand (Fig. 7). The early growth of the trees (both quantitatively and qualitatively) is quite poor. Many forest models have this problem, and seldom much attention is payed since young tree development is less important and data are scarce. Nonetheless, final wood quality is partially determined by the early growth (such as the development of the branch free stem) and these results show that our simulation of young tree development might not be adequate.

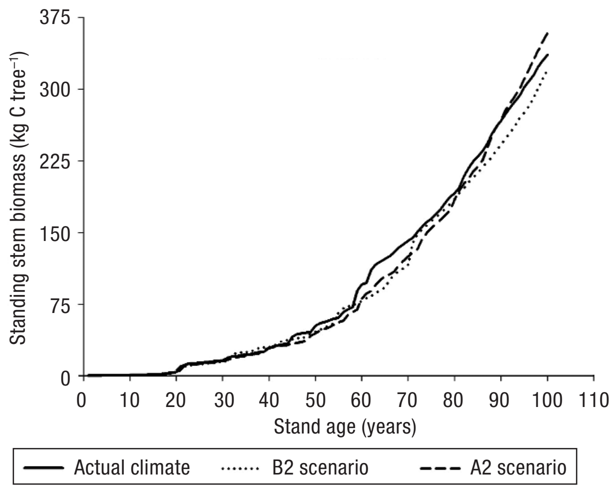

Figure 8. Simulated standing biomass development of pedunculate oak under 3 climate scenarios: actual climate, moderate (B2) and severe (A2) climate change.

As an example of the possibilities of the ANAFORE model we ran the model for the Brasschaat oak stand. We performed three runs: (i) a simulation of the life history of the forest from 1934 till 2008 with past meteorological data, (ii) a simulation of an oak forest with the same characteristics as the oak stand of Brasschaat (*i.e.* same soil, same planting and management) but planted in 2011 and growing under a moderate climate change scenario (B2, IPCC) and (iii) as the previous but with an extreme climate change scenario (A2, IPCC).

The results suggest final biomass which is lightly increased under climate change conditions (Fig. 8), as has been found in many studies. Concerning the effect on wood quality, although average EW/LW ratio and density are not influenced, the inter-annual variation increases considerably (Fig. 9). This could be explained by the increased number of drought periods under climate change conditions and results in a poorer wood quality.

Summary of the case studies

The three models reviewed in the above case studies represent different approaches to wood quality modelling within the structural growth-quality framework. They demonstrate that three-dimensional stem structure, including rings, knots, sapwood-heartwood zones and fibre properties, can be efficiently reproduced from pre-measurements and backward simulation when the development of stem structure is considered dynamically in connection with a tree growth model. The same models can also be used for predictions in forward simulation and therefore as tools for silvicultural planning.

The most empirically-based of the above models, TreeBLOSSIM, has already been incorporated in several simulation systems of practical value, while the main applications of the carbon-balance-based PipeQual seem to be in forward projections and silvicultural planning. ANAFORE, on the other hand, represents a more detailed analysis of the connections between wood quality and growth, focusing on the within-year variations of growth and how these affect the formation of xylem cells. While not readily applicable to *e.g.* industrial use at the moment, these types of models will be necessary for analysing the possible changes in the wood material resource under expected environmental change.

Challenges

Although much progress has been made in predicting stem form, branchiness and average fibre properties, especially for commercially important coniferous species, there are fewer advances in modelling hardwood species and other quality-related parameters as part of the growth system, even though there is a vast amount of research on individual wood properties, and their influence on wood performance (but see the ANAFORE example above). Importantly, these parameters include defects that contribute to the variability in wood properties within the stem, such as reaction (compression) wood, resin pockets, and the distribution of different types of knot (Leban *et al.,* 2002; Seifert *et al.,* 2010). Another important feature with impacts on wood quality are the mechanical stresses that develop in trees as they grow (Archer, 1987; Kubler, 1987; Eder *et al.,* 2009), causing crook and warp when released in utilisable timber.

Reaction wood is a response to external forces that tend to displace the stem from its vertical position, allowing the trees to adjust their mechanical properties through the addition of and the structure of new cells (Wilson and Archer, 1979; Timell, 1986). Reaction wood differs from normal wood in its chemical composition (*e.g.* Kibblewhite *et al.,* 2010), density, and cell structure, especially the microfibril angle. Both tree flexure (when the stem moves in response to wind and returns to a vertical position), and lean correction (which occurs when a stem has been «permanently» displaced from the vertical) contribute to varying cell structures around the stem (Telewski, 1989) and consequently different mechanical properties (Zipse *et al.,* 1998). Consequently, one might expect that occurrence of reaction wood would be greater in more windy situations and therefore after heavy thinnings that increase the wind force inside the canopy.

In radiata pine, studies have shown that percentage of compression wood in a stem-section increases for a few years following heavy thinning (Cown, 1974) and that ring average microfibril angle increases for a few years after heavy thinning (Grace, unpublished data). Tree structure has an influence on the response to increasing wind force, as trees with a high stem length to diameter ratio (*i.e.* suppressed trees) are mechanically less stable than dominant and co-dominant trees as they tend to sway at lower frequencies, which are closer to gust frequencies (Sellier and Fourcaud, 2009). Of course, this may also lead to stem breakage (see Gardiner *et al.,* 2008, for a review of mechanistic models).

Wood property distributions are also influenced by the presence of branches. In one study, the wood up to 20 cm below the branch tended towards compression wood with higher density, and shorter tracheid lengths. In another study basic density varied throughout an internode, being least at the mid-internode position and increasing towards the branch clusters (Nicholls, 1986). The orientation of the wood fibres in the vicinity of branches also leads to reduced strength and stiffness in the vicinity of knots (*e.g.* Philips *et al.,* 1981).

Mechanical stresses develop in trees as they grow (Archer, 1987; Kubler, 1987). They are important for ensuring adequate strength and stability of living trees and appear to be influenced by stand structure and silviculture treatment. Differences in growth stress between one side of a tree stem and the other enables it to bend into more favourable positions. The magnitude of the difference determines the amount of reorientation. While growth stresses are necessary in standing trees, they are undesirable when it comes to utilisation. Tree felling and cross-cutting of stems into logs will release longitudinal growth stresses near the cut. With large values of growth-stress, end-splitting can occur. When logs are sawn, growth stress release can cause lumber to warp and end-split. Growth stresses have been incorporated into a number of models. For example Fourcaud and Lac (2003) incorporated growth stresses in a model that predicts how a tree will grow and correct for stem lean. Growth stresses have also been incorporated in a model to investigate their influence on distortion of sawn timber (Ormarsson *et al.,* 2009).

The above review suggests that the development and occurrence of both reaction wood and growth stresses are strongly dependent on the mechanical forces influencing the tree, and hence on the tree and stand structure that cause or mediate those forces. The challenge is deciding how, and at what level of detail, the related mechanisms should be incorporated within modelling systems. It is considered that different levels of detail will be required for different end-users. It should also be borne in mind that an increasing level of detail may reduce the feasibility of model application by increasing the requirements for input and computational capacity.

Stand, site or tree-specific *quality indicators* could be developed based on empirical analysis of the occurrence of defects in trees of different structure and in stands treated with different types of thinning (*e.g.* Cown, 1974; Grace, unpublished data). Such empirical models could be appropriate for general silvicultural recommendations, but they would be less useful from the perspective of the timber processing industries,where the variability of wood properties within a tree is an important issue. While the prediction of the exact 3-dimensional variation of properties within individual stems seems unrealistic, the 3-dimensional *dynamic stem simulators* could conceivably incorporate the expected mechanistic impacts of stem movements under external forces, provided that they described the structural aspects of stands and trees that influence these forces (*e.g.* Skatter and Kucera, 2000; Ancelin *et al.,* 2004). It seems that such models would necessarily have to be spatially explicit and allow for the description of crown asymmetry as well.

Other, more general challenges for wood quality modelling are the same as for any growth models: the implications of climate change and changing management practices need to be incorporated. Current empirical growth models may not continue to provide sufficiently accurate predictions of long-term growth. Development of process-based, hybrid and or mechanistic models that incorporate an understanding how tree physiological processes influence the development of individual cells will be important. Such models require more input and knowledge from the end-user, and are often not user-friendly. One approach would be for the developers of detailed models to run a series of simulations and synthesise the results in an easy to understand form.

From a forest management perspective, an important question is whether the patterns of variation in wood properties that cause problems for the processing industry are influenced more by forest management practices, or the day to day/season to season variability in climatic factors. Here knowledge of the causes of variability and the results from field trials may be equally applicable as models for making decisions on future silviculture regimes. The importance of long-term experimental trials for both knowledge and model development cannot be underestimated.

Forest management practices are also changing with a shift from even-aged plantations to continuous cover and mixed species forests. This requires a different approach to modelling as tree age will not necessarily be known. While some age-independent growth models have been developed (*e.g.* Tomé *et al.,* 2006), there are many challenges in developing such models where there is little or no available data. Also incorporating wood property functions within such a framework is a challenge that has not been tackled.

There will be a need to extend the modelling techniques discussed above to a wider range of species. Few models have been developed for deciduous trees. For example Knoke (2003), Knoke *et al.* (2006), Bouriaud *et al.* (2004) have developed models for beech; Le Moguédec and Nepveu (2004) have developed models for sessile oak; and Makinen *et al.* (2003) have developed branching models for silver birch. The ANAFORE model discussed above has also been applied to beech and oak (*e.g.* Deckmyn *et al.,* 2009).

Conclusions

In summary, the key requirements for models applicable to forest management in terms of wood quality are (1) to predict the distribution of wood quality characteristics among trees from adequate pre-inventory measurements, (2) to predict the responses of quality characteristics to forest management and site, and (3) to provide information about the intra-stem variation of those characteristics.

A lot of progress has been made in developing models to meet these requirements in the last decade, with the most advanced models simulating 3-dimensional stems (mainly stem form and branching for some important conifer species) in connection with growth models, and being readily applicable to some specific management questions. However, several challenges remain that call for further development of tree models with wood quality components. These models need to be further developed to include a wider range of quality-related parameters, such as reaction wood, growth stresses, and resin pockets. Describing heterogeneity in stand structure may prove important for the mechanistic modelling of these aspects.

The structural models need to be extended more widely to angiosperm species, where the variable branching patterns are a challenge as compared with the branch clusters, or whorls, in conifers. Angiosperms also have more variable wood cell structures than conifers.

As regards models of fibre properties, most advance to date has been made in empirical models. For future applications under a changing climate, it would be very useful to develop more mechanistic models of the development of cell properties in combination with tree growth. Such mechanistic models might also simulate important changes in management more adequately than empirical models.

Emphasis in the future should be on those quality characteristics that are used in wood industry, and on the main management options (mixtures, uneven-aged stands, species conversion, etc.) encountered in the field. Increased interaction between the end-users, model developers, and different scientific disciplines is needed. This could lead to increased understanding of the factors driving tree development, and would ensure that models developed incorporated the appropriate level of detail to adequately represent reality while being simple enough from the end-use perspective.

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