TECHNICAL ARTICLES

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USING TREE PHYSIOLOGY TO BETTER UNDERSTAND THE EFFECT OF ENVIRONMENTAL FACTORS ON WOOD FIBRE PROPERTIES

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ABSTRACT

In recent years, the emphasis of forest management has shifted from growing maximum volume towards managing the plantation in order to provide adequate quantities of fibres with properties appropriate to the manufacturing process and the final product produced by the mills. The ability of any management strategy to achieve this goal depends to a large extent on the understanding of the factors that determine the properties of the fibres. Understanding the physiology of xylem (fibre) development provides a powerful tool to enhance forest management in this way. A number of empirical studies have been conducted in the last few decades that have attempted to relate a variety of site and forest management factors to observed wood properties. Although these studies have been immensely valuable contributors to our understanding of the effect of environment on xylem development, they also highlighted the amount of variation in fibre properties that could not be understood by simple cause–effect relationships, and many studies provided conflicting results, even within a single species. A number of authors in the middle and later decades of the 20th century conducted valuable research into the physiology of xylem development, and the importance of their findings has come to light in a renewed wave of physiological research in forestry. The further development and application of this understanding provides exciting opportunities to influence tree growth in forest stands so that they provide precisely the kinds of fibres that are required, as well as accurate estimates of the properties that can be expected.

INTRODUCTION

The sustained production of high quality products is dependent largely on availability of raw materials used in the process. In order to stay competitive in global markets, forest–based manufacturing industries need access to the best possible raw materials. The raw material from the forest, wood, is the product of the plant's ability to convert sunlight, water, carbon and a variety of nutrients into this complex tissue. In order to provide materials of high quality, the forestry industry must harness advances in the biological sciences (Lucier *et al*., 2001). Forest managers, in South Africa and abroad, are becoming increasingly aware of the need to manage not only for increased yield, but also for wood quality (Sandercock *et al*., 1995; Wimmer *et al*., 2000; Downes *et al*., 2000; Harvett, 2001; Turner, 2001). Already, forestry managers have access to a number of tools, developed through years of research and experience, to manipulate and predict growth and, increasingly, wood quality. In South Africa, the CSIR Forestry and Forest Products Research Centre (FFP) has, for the last seven years, been actively involved in research with Sappi and Mondi to evaluate the effects of site quality and environment on wood properties. This work has clearly shown the impact of a number of site quality-related parameters (particularly site index) on wood quality, but it has also revealed that site index does not explain all of the variation. The outputs of this research are powerful tools to use to manage for wood quality, but there is scope to improve it further. This paper considers the possibilities and potential of the science of plant physiology as an instrument in the forest manager's toolbox, designed to accurately control and predict the quality of material destined for the pulp mill.

THE TREE, THE ENVIRONMENT AND WOOD PROPERTIES

The physiology of woody tissue production

Plant physiology is in essence the study of the way in which plants grow and develop, which is fundamentally determined by the biological processes that occur within the plant organism and deals with plant function (Kramer and Kozlowski, 1979; Salisbury and Ross, 1985). The environment to which a tree is exposed is a function of climate, as well as a number of soil–related and biological factors (Kramer and Kozlowski, 1979; Mitchell *et al*., 1992; Nambiar, 1995; Landsberg and Gower, 1997). This influence exerted by environment on the development of a tree occurs within the bounds of the genetic make-up of the individual however. The properties of its tissues and organs are fundamentally a product of its genotype and its environment (Kramer and Kozlowski, 1979; Kozlowski *et al*., 1991).

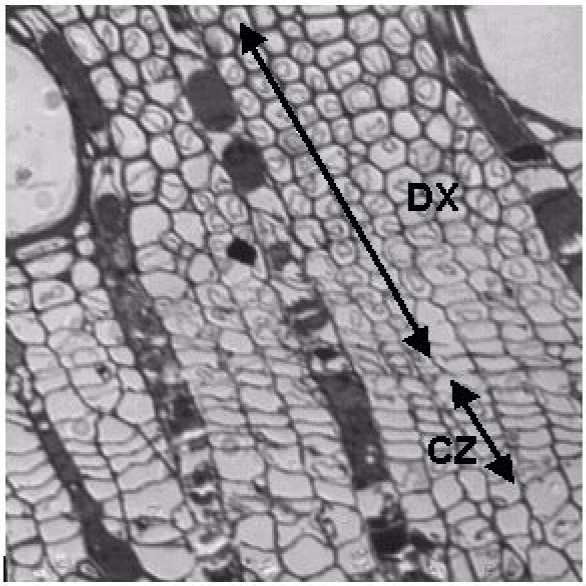

Figure 1: The cambial zone (CZ) and differentiating/recently differentiated xylem fibres (DX) in a Eucalyptus grandis x urophylla *clone in Zululand, South Africa. This sample was prepared for research currently being conducted into the factors affecting how xylem develops in commercial clones in South Africa.*

The functioning of the cambium (wood producing tissue consisting of so-called fusiform and ray initials, see figure 1) and the rate at which cells divide and develop, ultimately determines wood properties (Creber and Chaloner, 1984; Larson, 1991; Lachaud *et al*., 1999; Catchpoole *et al*., 2000) (figure 2). This is inextricably linked to the interaction of both direct and indirect environmental effects (Fritts, 1976; Denne and Dodd, 1981; Fritts *et al*., 1998) (figure 3). Indirect effects of climate on wood production, explainable only by understanding plant physiology, are in many cases more important determinants of xylem characteristics than direct effects (Larson, 1969 and 1991; Fritts, 1976).

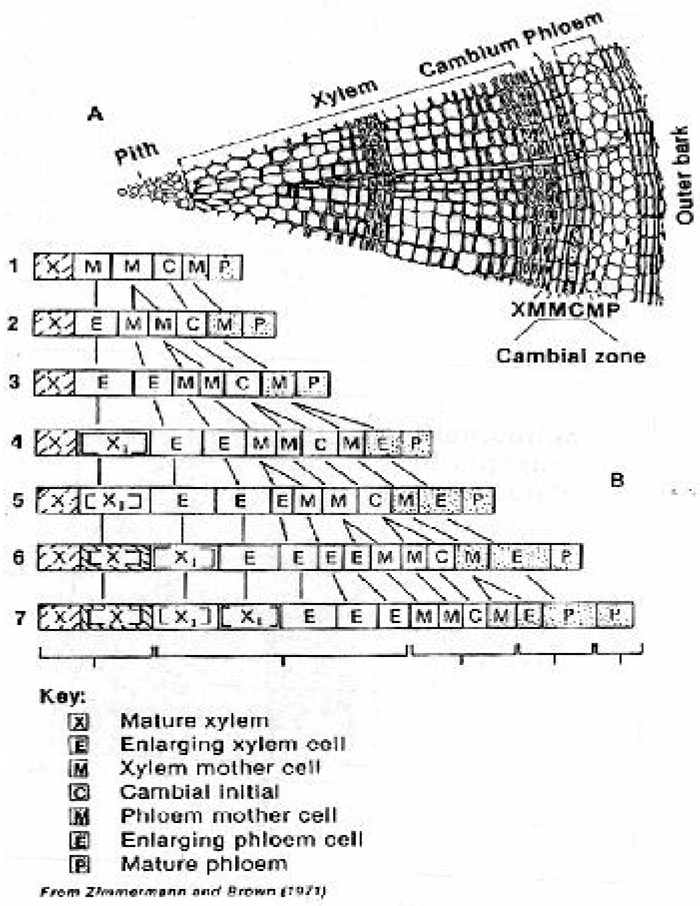

Figure 2: The development of woody tissue: Cambial initials divide and daughter cells are progressively "deposited" where they differentiate into mature xylem (Haygreen and Bowyer, 1982).

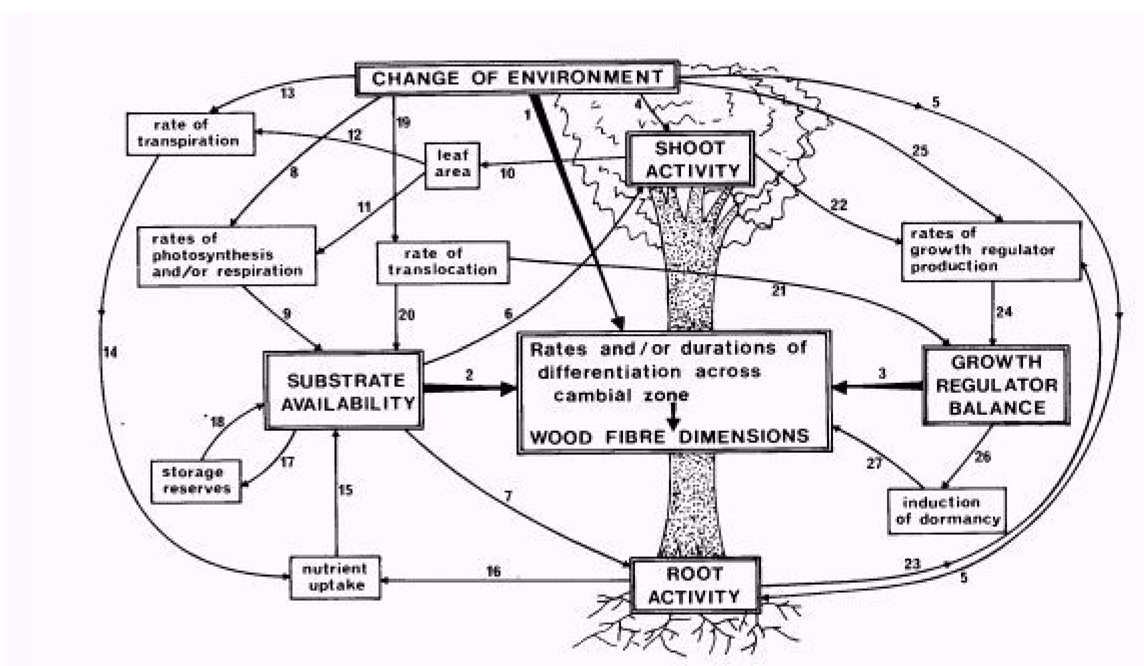

Figure 3: Simplification of the basic processes involved in determining xylem cell development and subsequent wood properties in a growing tree (Denne and Dodd, 1981)

Fundamental Determinants of the Physical and Chemical Properties of Wood

Genotype exerts a strong influence on a number of wood properties in most forest species in South Africa (Malan, 1988 and 1991; Denison, 2001) and tree breeding programmes have had great success in improving the wood quality of South African forest species (Denison, 2001). Certain environmental factors, particularly climatic factors, also play an important role in affecting wood properties, over and above the variations which can be explained by genotype alone (Downes *et al* ., 1997; Clarke *et al*., 1999). These relationships are complex, however, and it is not always possible to explain the observed variation in terms of empirical correlations and relationships.

Observed Relationships Between Environment, Forest Management and Wood Quality

A large amount of work has been undertaken in South African forestry to understand site and its effect on wood properties, including research by Malan (1988, 1991, 1993, 1996), Schutz et al. (1990), Clarke *et al* . (1999), Clarke (2000) and Megown *et al*. (2000). In general, it has become quite clear that understanding site quality and the environmental variables affecting it, is a very powerful means by which to predict and manipulate wood properties. Research work on *Eucalyptus grandis* which has recently been completed by FFP in collaboration with Sappi and Mondi, has established that site index explains a large part of the variation seen in many wood properties of importance to the pulping process (Turner *et al.* , 2001). There is great scope for applying this information to the management of the forest resource and the results of empirical research such as this are immensely valuable applied in situations similar to those in which the observations were made. However, it is often difficult to reliably use them in situations too far removed from those in which data was measured (Deleuze and Houllier, 1995; Landsberg and Gower, 1997, Battaglia and Sands, 1998). In South Africa and abroad, research in this field has generated conflicting results, even with a single species (Denne and Dodd, 1981; Zobel and van Buijtenen, 1989; Malan, 1991; Sandercock *et al*. 1995; Downes *et al*. 1997).

To overcome these difficulties, more needs to be known about the production and differentiation of wood physiologically, a process that occurs via the cambium, in order to lay out the mechanisms by which desirable structures, and therefore desirable properties, may be reached (Preston, 1981; Whetten and Sederoff, 1991; Ridoutt and Sands, 1994 & 1995; Sands, 1995; Chaffey, 1999a and 1999b; Catchpoole *et al*., 2000; Wimmer *et al*., 2002). Downes *et al*. (1999 and 2000) concluded that there is a need to understand weather-by - climate interactions at the level of whole tree physiology in order to fully understand the effect of weather on cambial activity and therefore stem increment and wood properties. This approach is the means by which to further explain wood property variation and improve the accuracy with which the quality of the fibre resource can be predicted and managed.

USING PLANT PHYSIOLOGY AS A TOOL TO BETTER UNDERSTAND HOW ENVIRONMENT AFFECTS WOOD QUALITY

The progress and status of research in this field

Larson (1964) published the opinion that an understanding of the fundamental principles of tree growth would provide the opportunity for researchers to develop new approaches to manipulating wood yield and quality in forest stands. This was consistent with the sentiments of several other workers who were making great advances in this field at that time, including Wilson (1964), Skene (1969 and 1972) and Denne (1971 and 1976). More recently, the interest in this field has been rekindled, as its potential to more fully understand wood quality variation is understood.

Ridoutt and Sands (1993 & 1994) considered the variation in xylem development and anatomy in *Eucalyptus globulus* at different heights in the stem. Mature fibre length and diameter were found to be significantly different at two heights in the stem. This was explained by variations in the developmental processes at these positions according to availability of hormones and substrates from the photosynthetic tissues in the crown. Downes *et al* . (1999) used electronic dendrometers as a highly precise means of assessing diurnal changes in stem radius and relating changes in environment to stem growth and rates of wood production. They found that this was related to a large extent to rainfall, but that the determining factors varied between species and throughout a growing season. Limiting factors were the most important determinants of growth, where temperature was only found to affect increment in irrigated trees where water availability was not limiting. Using the same approach of installing dendrometers, but as indicators of time of cell formation (see figure 4), Wimmer *et al*., (2002) were able to pinpoint, with an exceptionally high degree of precision, changes in microfibril angle in relation to environmental conditions and stem growth. They found that the rate of stem increment (a function of rate of cell division and cell enlargement) and the period of growth in study trees were significantly correlated to MFA. Water availability played an important role in determining MFA by this mechanism. Wind was directly correlated with MFA. In addition to these studies, other researchers are busy with work in this field on a number of softwoods including Zwiefel *et al*. (2001).

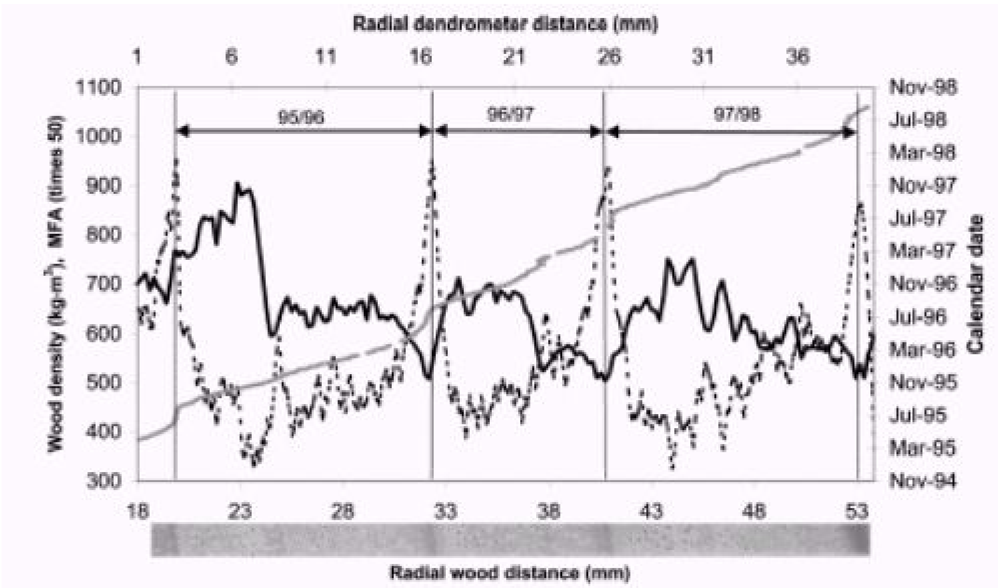

Figure 4: Using radial stem growth as a mechanism by which to determine time of cell formation. By this means, it is possible to relate wood properties (in this case wood density and microfibril angle) to environmental and physiological conditions in the tree (diagram from Wimmer et al., 2002).

Potential for Applying Tree Physiology in Managing the Forest for Wood Quality

Process – based models of biological systems, including forests, are the result of the integration of the physiological processes involved in growth into a logical system that can be manipulated and harnessed to understand the way in which the plant works. The use of process –based approaches to model stand growth and development is not new, but more recent models such as *3PG* (Landsberg and Waring, 1997) and *ProMod* (Battaglia and Sands, 1997) and the hybridisation of these with empirical models have enhanced the accuracy and versatility that models of this kind provide when simulating forest growth and development (Landsberg and Gower, 1997; Battaglia and Sands, 1998; Battaglia *et al*., 1999). Although these models do not explicitly provide estimates of xylem development, they are indicative of the improvement in this mechanistic approach to modelling the biological systems in forest trees. Two process–based models have been developed specifically for xylem growth and development of woody tissue (Deleuze and Houllier, 1995 and 1998, and "TreeRing" by Fritts *et al*., 1998) (figure 5).

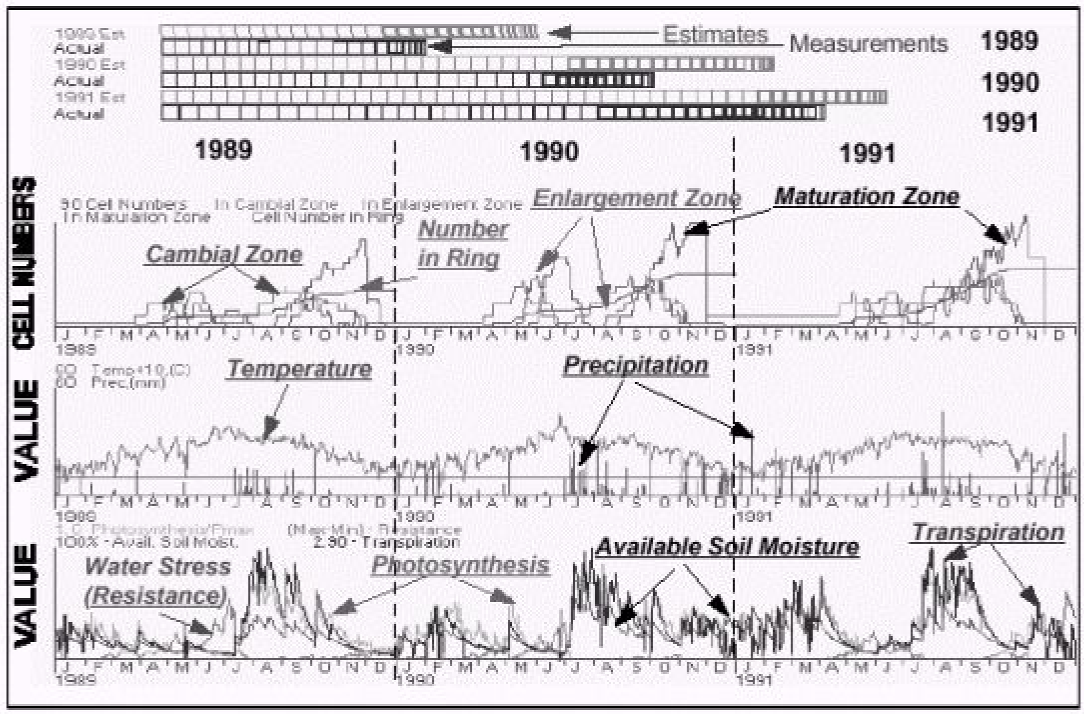

Figure 5: Outputs from the TreeRing model. The model provides estimates of the number of cells produced, as well as of changes in dimensions and wall thickness. This simulation is driven by climatic and physiological variables (Fritts et al., 1998).

Although these models remain very much in development, they have great potential to become very useful tools for modelling xylem development (Fritts *et al*., 1998; Sands, 1995; Downes *et al*., 2000) in the same way as models like *3PG* have become great tools for modelling forest stand growth and development. These models have not yet been able to capture many of the processes involved in xylem development because of the deep complexity of the system, and they have not yet been modified for use with hardwoods. Research is ongoing to improve the models, and work is also being undertaken in Australia to develop a module for hardwoods (personal communication, G. Downes (CSIRO Forestry and Forest Products), 2001). Research such as the cutting edge work being conducted in Australia at present is set to provide answers to many of these questions that are still unresolved, which will ultimately enhance the accuracy of the process-based approach and improve our ability to develop highly accurate and useful models.

In South Africa, physiological research into the development of woody tissue needs to be specifically focused on understanding the processes involved in determining fibre properties of particular importance to the pulp mill, such as cell wall thickness and tracheid diameter, as well as microfibril angle (MFA) and chemical characteristics, such as lignin content. The work recently completed by Downes *et al.*, (1999) and Wimmer *et al.*, (2002) on *E. globulus* and *E. nitens* provides the first of a powerful suite of results that can be integrated into a process - based approach appropriate for predicting a number of wood properties across a wide-range of conditions and for more than one species. The particular importance of water availability in these studies is of importance to South African conditions, where water is frequently limiting to growth, and therefore wood properties. Specific research into the physiology of wood formation in South African plantation species is needed in order to generate the information required to implement an accurate and powerful process-based approach to making management decisions on the basis of desirable wood properties.

Already, FFP is actively involved in advancing this broad area of research. The cooperative research program between Sappi, Mondi and CSIR is the platform for an increasing amount of research into the usefulness of "bioclimatic modelling" of wood, pulp and paper properties. This area of research considers the use of indices of climate that are most appropriate to understanding the biological phenomena that ultimately drive wood properties. At a finer level , a project is underway on two important Mondi and Sappi *Eucalyptus* clones to quantify the changes in fibre properties that can be expected as a result of genetic differences and drought. An example of the material studied in this work is presented in figure one. In addition, a valuable project to validate and test the spatial–data–linked forest growth model *3PGs*, was recently completed for the Water Research Commission (WRC), undertaken with the assistance of Mondi (Dye *et al*., 2001). This work has advanced the understanding of applying remotely sensed data (LANDSAT multispectral images) to process–based forest growth and water use modelling. In addition, the CSIR forestry research group in Pietermaritzburg is deeply involved in an extensive research project to improve the already powerful model *3-PG* for much wider use in commercial forestry. Results of work conducted on *Pinus patula* and *Eucalyptus grandis* have already shown the potential of this model in plantation management.

The work being undertaken at CSIR in general and at FFP in particular at present is well positioned to fit into the wealth of research that exists, and provide a robust basis for the future development and improvement of process-based models in South African plantations.

CONCLUSION

Biotechnology and tree physiology are key mechanisms by which to increase the potential of trees to produce more wood of a higher quality (Lucier *et al*., 2002). Both of these areas of research harbour great potential as immensely powerful management tools (Sands, 1995). It is necessary to advance and focus forest management in order to optimise resource quality and quantity. One of the key opportunities lies in taking an integrated, process-based approach, providing the ability to more deeply understand the fundamentals of what drives woody tissue production. The way forward for this kind of research will be guided by findings of research already underway in South Africa at FFP and in countries like Australia and the USA, where similar research programs are in various stages of advancement. The approach presented here is to harness the power of explanation provided by these integrated techniques according to the needs of the pulp mills, and in such a way provide a quicker, more accurate forest management approach which is designed to provide only the best quality fibre, all the time.

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