IMPROVING EUCALYPTUS PULP AND PAPER QUALITY USING GENETIC SELECTION AND GOOD ORGANIZATION

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INTERACTIONS AMONG RESEARCH, FORESTRY, PULP MILL, SALES, AND THE CUSTOMER ARE VERY IMPORTANT. RESEARCH CAN BE THE BOND AMONG THE VARIOUS GROUPS IN DEVELOPING NEW PRODUCTS.

Eucalyptus kraft pulps began to appear on the world markets in the mid-1960s. Over less than a decade, eucalyptus pulps evolved to become important raw materials for a wide range of printing and writing papers, specialty papers, and tissue papers.

It is interesting to analyze the general quality and market position of eucalyptus pulps today and how eucalyptus pulp products could be developed in the future. This paper focuses on opportunities to develop eucalyptus pulps through genetic selection both between and within species. Attention is also devoted to the need for close integration among research and operational people involved in the forest, mill, and sales organizations.

WHY DOES THE EUCALYPTUS PULP INDUSTRY USE SO LITTLE GENETIC VARIABILITY?

Consider the following points:

- Eucalyptus is a large genus of plants that includes about 700 species occurring naturally across wet and dry, and tropical and temperate environments of Australia (and in a few cases the islands to the north of Australia).
- Only a handful (less than 1%) of these 700 species seem to have been used for industrial purposes. The eucalyptus kraft pulp industry today is based largely on only two or three species, i.e., *Eucalyptus globulus* and *E. grandis* (and its hybrid with *E. urophylla*).
- Why does the industry use so little of what the remarkable genus known as eucalyptus may have to offer?

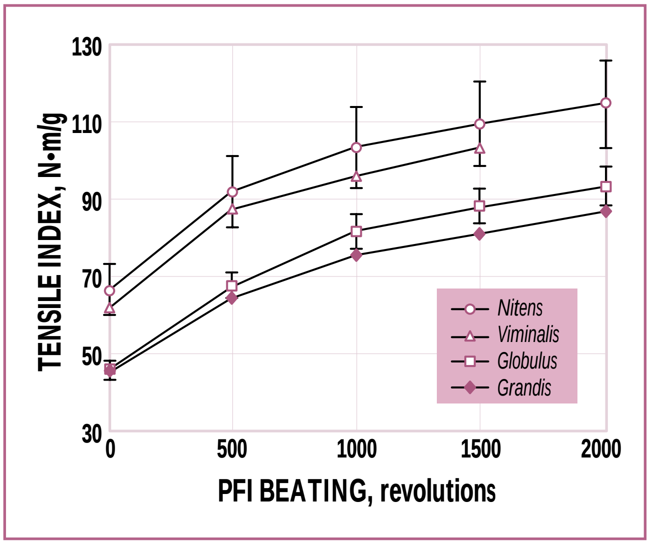
Why have foresters not established plantations using a wider diversity of eucalyptus species? This relative lack of diversity is surprising considering the worldwide increase in eucalyptus plantation area over the last decade. Why has the pulp industry been content with such a limited product range from eucalyptus?

The eucalyptus pulp industry has so far missed considerable opportunities by basing wood production on so few species of eucalyptus.

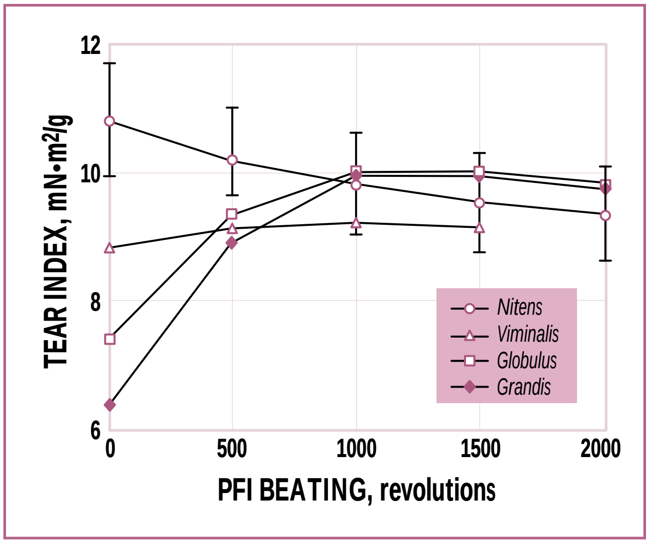
HOW MUCH VARIABILITY EXISTS BETWEEN DIFFERENT SPECIES OF EUCALYPTUS FOR WOOD AND PAPER PROPERTIES?

Field and laboratory studies

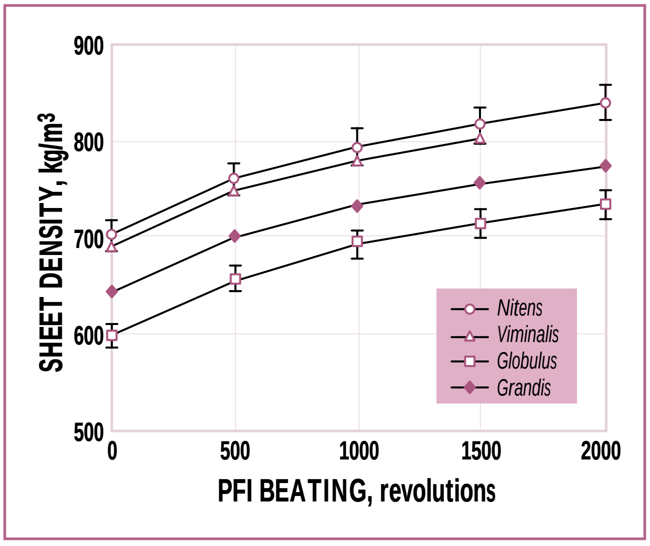
The following results are from a eucalyptus species trial established on one uniform site. Each of the species in the trial were represented by two to three different native provenances (populations) grown from seed collected in different regions in Australia. Cross-sectional wood discs were collected from 20–30 trees per species harvested at 10 years of age *(1)*. These wood discs were subjected to kraft cooking and chlorine bleaching sequences at Stora Corporate Research laboratories in Sweden *(2)*.



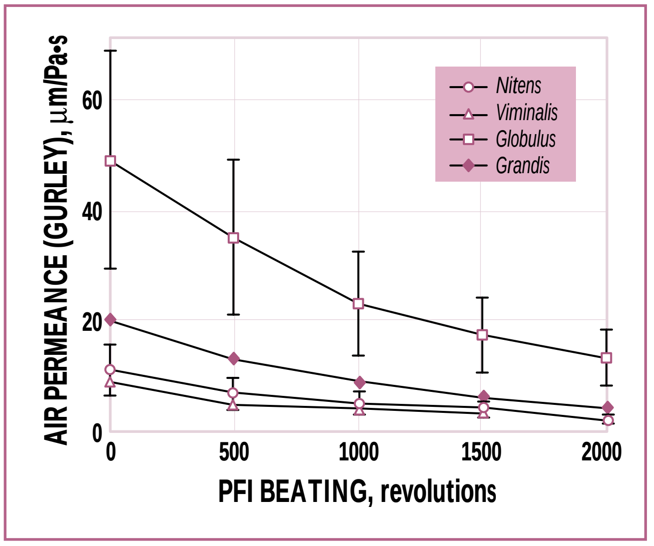
1. Means of different eucalyptus species for tensile index of paper across increasing levels of PFI refining in the laboratory. The error bars show the approximate range of the 2–3-provenance means that were used to calculate the mean for each species.



2. Means of different eucalyptus species for tear index of paper across increasing levels of PFI refining in the laboratory. The error bars show the approximate range of the 2–3-provenance means that were used to calculate the mean for each species.



3. Means of different eucalyptus species for paper sheet density (paper bulk is the inverse of paper density) across increasing levels of PFI refining in the laboratory. The error bars show the approximate range of the 2–3-provenance means that were used to calculate the mean for each species.

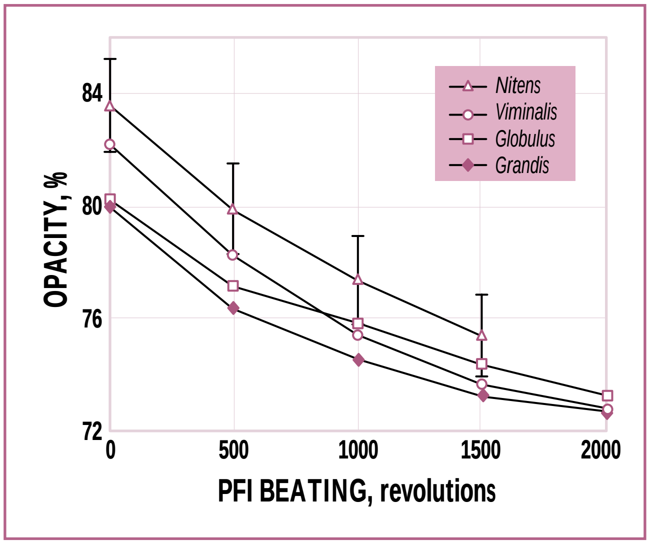


4. Means of different eucalyptus species for porosity (air permeance) of paper across increasing levels of PFI refining in the laboratory. The error bars show the approximate range of the 2–3-provenance means that were used to calculate the mean for each species.

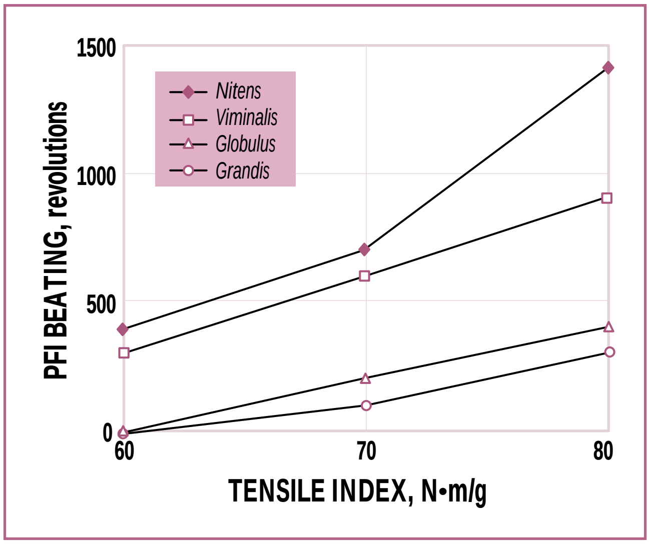
Species differences in paper properties across different refining levels

Figures 1–5 give paper properties plotted against increasing refining (PFI beating) levels for four different eucalyptus species, i.e., *E. globulus, E. grandis, E. nitens,* and *E. viminalis.* Also included in Figs. 1–5 are error bars that show the approximate range of the provenance means that were used to calculate each of the species means.

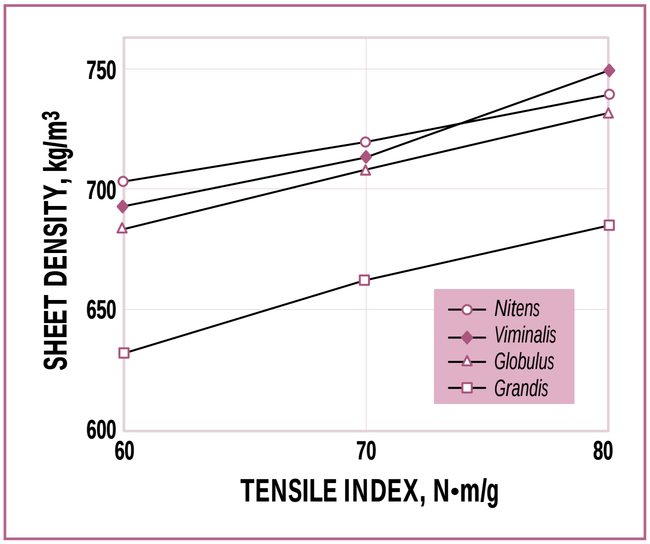
It is evident that bleached kraft pulp processed under laboratory conditions from *E. globulus* wood raw material produced paper sheets having very high porosity (Fig. 4) and rather low sheet density (or high sheet bulk) (Fig. 3) compared with the other eucalyptus species. Pulps from *E. nitens* and *E. viminalis* produced paper sheets having rather high tensile strength (Fig. 1), high sheet density (low bulk) (Fig. 3), and low porosity (Fig. 4). The *E. nitens* pulp had higher tear strength before refining



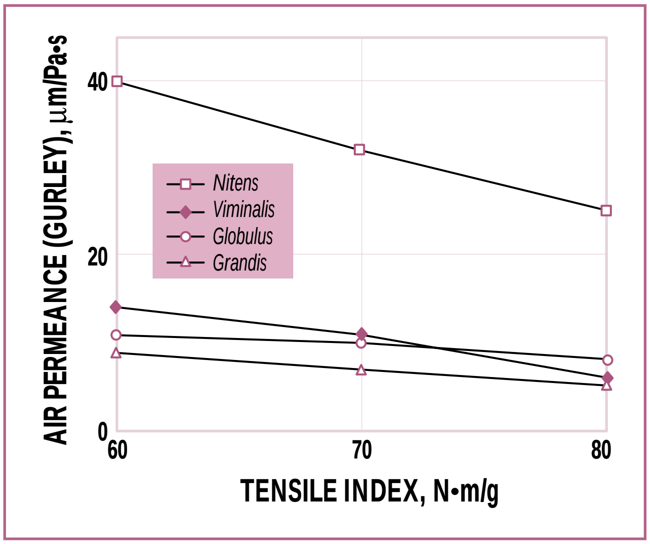
5. *Means of different eucalyptus species for opacity of paper across increasing levels of PFI refining in the laboratory. The error bars show the approximate range of the 2–3-provenance means that were used to calculate the mean for each species.*



6. *Means of eucalyptus species for the PFI refining of pulp required to reach different levels of paper tensile strength*



7. *Means of eucalyptus species for paper sheet density at different levels of paper tensile strength. Bulk is the direct inverse of sheet density.*



8. *Means of eucalyptus species for paper porosity (air permeance) at different levels of paper tensile strength*

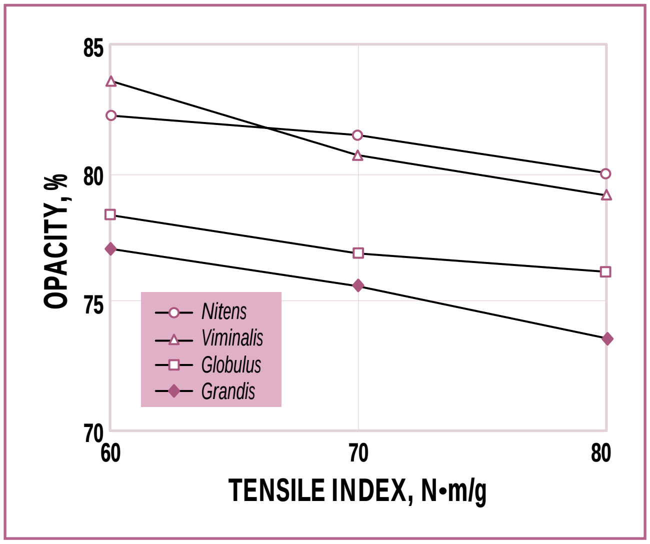
(Fig. 2). Pulp from *E. grandis* tended to be intermediate in sheet density and porosity.

The paper properties shown in Figs. 1–5 are based on trees grown under uniform conditions, harvested at the same age, and pulped and bleached in the same laboratory process. In the case of eucalyptus market pulps traded on world markets, there can be differences in properties that are due to different growing conditions of the forests, different harvesting ages, and different pulp mill processes. Such variations are not considered here.

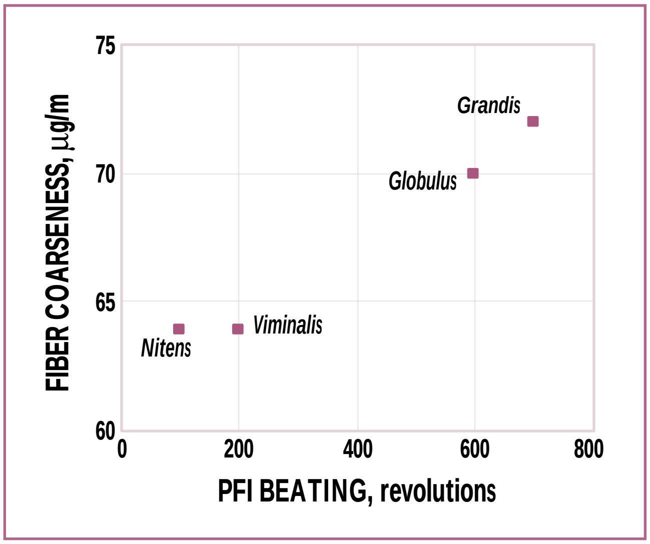
Populations within species

Figures 1–5 reveal substantial differences in paper properties that can occur between populations (provenances) within each of the different eucalyptus species. These populations represent different regions in Australia where the particular species occur naturally.

In the case of porosity, the species mean for *E. globulus* was 35 µm/Pa·s at a refining level of 500 PFI revolutions (Fig. 4). However, the two populations evaluated for *E. globulus* ranged from 21 to 48 µm/Pa·s. It is a simple matter to obtain seed from these different populations and use genetic differences at the population level for



9. Means of eucalyptus species for paper opacity at different levels of paper tensile strength



10. Means of eucalyptus species for wood fiber coarseness vs. means of the same species for PFI refining (beating revolutions) required to produce a 70-N·m/g constant-tensile-strength paper. Fiber coarseness is measured as the weight of 1 m of wood fibers laid end-to-end.

industrial forestry and pulping operations (discussed later). Substantial population differences are also evident for tensile strength (Fig. 1).

Species differences in paper properties across different tensile levels

Figures 6–9 compare the paper properties of different eucalyptus species at a constant tensile strength. Tensile strength is an important parameter commonly used by papermakers to define appropriate levels for refining pulps. A tensile index of approximately 70 N·m/g can be considered somewhat standard for many of the end-use applications of eucalyptus pulps.

It is apparent from Fig. 6 that *E. nitens* and *E. viminalis* required no more than 200 revolutions of PFI refining to reach a tensile index of 70 N·m/g. *Eucalyptus. globulus* and *E. grandis* require over three times more processing (600–700 revolutions) compared with *E. nitens* and *E. viminalis* to reach 70 N·m/g tensile strength.

These rather large differences between eucalyptus species in terms of the PFI refining to reach a certain level of tensile strength (Figs. 1 and 6) are an important finding. The energy input needed for refining is one of the major costs in paper manufacturing. Hence, the apparently high tensile-strength profiles of *E. nitens* and *E. viminalis* pulps (Fig. 1) and the relatively low refining requirements to reach a given tensile strength (Fig. 6) should be attractive to many papermakers.

The necessary refining of pulps is a major consideration for paper manufacturers, not only in terms of production costs but also because increased refining leads to a decrease in paper properties such as opacity (Fig. 5), porosity (Fig. 4), and bulk (Fig. 3). Many paper manufacturers are interested in minimizing the refining of pulps both to save cost and to improve quality features such as opacity.

When comparing paper properties of eucalyptus species at a constant tensile strength, it is evident that the lower refining levels required for *E. viminalis* and *E. nitens* (Fig. 6) give these pulps a substantial advantage in paper opacity (Fig. 9). In terms of other paper properties, such as bulk (Fig. 7) and porosity (Fig. 8) at constant tensile strength, the *E. nitens* and *E. viminalis* pulps appear to be comparable with the *E. grandis* pulp.

Eucalyptus pulps in different market segments

For more than two decades, the eucalyptus kraft pulp market has been almost completely dominated by wood raw material derived from (a) *E. grandis* and its hybrids known in the market as the Brazilian type of eucalyptus pulps or (b) *E. globulus* Iberian market pulps from Portugal and Spain. It is apparent from Figs. 1–9 that, under uniform conditions of tree growth and the same kraft cooking and bleaching processes, the Iberian and Brazilian market pulps can be expected to have the following profiles:

- *E. globulus* (Iberian)-type pulps at a given level of refining are characterized by relatively low paper sheet density (high sheet bulk) (Fig. 3) and high porosity (measured as high air permeance) (Fig. 4).
- *E. grandis* (Brazilian)-type pulps can be expected to produce paper with lower bulk and porosity compared with *E. globulus*.

Paper market segment	Paper end use for eucalyptus	Bulk	Porosity	Opacity	Tensile strength
Uncoated printing and writing papers (wood free)	Copy, inkjet, laser, offset, book, stationery	High	Low	High	High (long-fiber blend)
Coated printing and writing papers (wood free)	Light-, medium-, and high-coated, and art qualities	High	Low	High	High (long-fiber blend)
Packaging paper and board	Surface layer on liquid, art, and folding boxboard	•••	High	High	High (long-fiber blend)
	MG and envelope	High	High	High	High
Specialty papers	Decor laminate	High	High	High	High
	Cast coated	High	High	High	High
	NCR (top sheet)	Low	Low	High	High
	Photo (base)	High	•••	High	High
	Release paper	•••	Low	•••	High
	Label paper	High	Low	High	High
	Cigarette paper	High	High	High	High
	Filter paper	High	High	•••	High
	Security	High	Low	High	High
	Parchment	High	High	High	High
Tissue paper	Facial tissue	High	•••	•••	High

I. Main paper end uses for eucalyptus pulps and overall requirements for these end uses in terms of bulk, porosity, opacity, and tensile strength of the paper products

In the case of paper properties such as porosity and bulk, the difference between *E. globulus* and *E. grandis* pulps happens to be relatively large. However, in the case of other important paper properties, such as tensile index and opacity, the differences between *E. globulus*- and *E. grandis*-type pulps (compared under conditions of similar forest environment, harvest age, and kraft cooking) seem to be rather small. The relatively high tensile strength of *E. nitens* and *E. viminalis* pulps (Fig. 1), low refining requirements to constant tensile strength (Fig. 6), and high opacity at constant tensile strength (Fig. 9) should be particularly interesting features for many paper manufacturers.

Table I lists the important end uses of paper and classifies them according to the main paper-market segments. The requirements of the different paper end uses in terms of bulk, porosity, opacity, and strength are also given *(3)*. The characteristic high porosity *E. globulus* pulps fits well with production of the surface printing layer of liquid, art, and folding boxboard (Table I). The high bulk and high porosity of *E. globulus* also makes it suited to specialty papers such as decorative laminates, cast coated paper, photographic base paper, cigarette paper, filter paper, and parchment paper.

Eucalyptus species such as *E. nitens* and *E. viminalis* offer interesting possibilities in a range of paper end uses (Table I). In particular, the high strength, high opacity, and low porosity of *E. nitens* and *E. viminalis* pulps should make them very well suited to the important market segment of uncoated and coated wood free printing and writing papers (i.e., those using chemical rather than mechanical pulps). This market segment represents about 16% of the total production of paper and board in western Europe. The low porosity and high strength of *E. nitens* and *E. viminalis* pulps also should be well suited to some of the specialty end uses such as release paper and security paper.

The uncoated and coated wood free printing and writing papers are usually produced by blending up to 50% long-fiber softwood pulp with the short-fiber eucalyptus pulp. The long-fiber pulps are usually around US$ 50/ton (as a trend price) more expensive than eucalyptus pulps. It is interesting to speculate if the higher tensile strength of *E. nitens* and *E. viminalis* could be sufficient to substantially reduce the need for long-fiber and, hence, increase the amount of short-fiber eucalyptus in the pulp blends for printing and writing papers. Softwood long-fiber pulps are also used for strength in surface layers of board and many of the specialty papers. Consequently, the opportunities for high-strength eucalyptus pulps on the market could be quite significant.

Note that the results of the paper analyses shown in Figs. 1–9 are for only a very small sample of the approximately 700 eucalyptus species that nature provides. As previously mentioned, the opportunities seem endless.

Species differences in wood fiber properties

It is worthwhile to attempt to understand what morphological or chemical aspects of the wood of the different eucalyptus species are contributing to the different paper properties previously discussed. **Table II** gives wood morphological properties for *E. globulus, E. grandis, E. nitens,* and *E. viminalis.*

Eucalyptus globulus had by far the highest wood basic density relative to the other three species when grown on one particular site and harvested at a constant age of 10 years (Table II). *Eucalyptus nitens* and *E. viminalis* had a substantially lower wood basic density than *E. globulus* but higher density than *E. grandis.*

Species	Wood density, kg/m^3	Fiber length, mm	Fiber width, mm	Fiber coarseness, µg/m	Millions of fibers per g pulp
E. globulus	533	0.93	0.21	70	15
E. nitens	463	0.97	0.20	64	16
E. viminalis	462	0.83	0.20	64	19
E. grandis	446	0.87	0.22	72	16

II. Means of different eucalyptus species for wood basic density and fiber morphological characteristics. The wood is from trees grown on one site and harvested at a constant age of 10 years.

The high tensile strength of paper made from *E. nitens* and *E. viminalis* seems to be due largely to the lower fiber coarseness of these species. [The coarseness was 64 µg/m for *E. nitens* and *E. viminalis* compared with 70–72 µg/m for *E. globulus* and *E. grandis* (Table II).] Low fiber coarseness is usually associated with wood fibers having thin walls relative to fiber width and, therefore, able to be collapsed more readily during refining to give more effective bonding surfaces in the paper sheet. The apparently more flexible and collapsible wood fibers of *E. nitens* and *E. viminalis* would contribute to the higher paper tensile strength.

In other respects, the wood fibers of *E. nitens* and *E. viminalis* appear to have little in common with each other. *Eucalyptus nitens* has relatively long (0.97mm) and thin (0.20mm) wood fibers by eucalyptus standards (Table II). This could explain the high tear strength of *E. nitens* at low levels of refining (Fig. 2). *Eucalyptus viminalis* has short (0.83mm) and thin (0.20mm) fibers, with a relatively large number of fibers (19 million) per unit weight of pulp (Table II).

Eucalyptus globulus and *E. grandis* had the highest fiber coarseness of the four species compared (Table II). The higher coarseness would normally be associated with quite rigid fibers, which require more refining to collapse and produce reasonable levels of tensile strength. **Figure 10** illustrates the strong association that exists between species means for fiber coarseness and paper tensile strength.

Species differences in wood chemistry properties

Table III gives wood chemical properties for *E. globulus, E. grandis, E. nitens,* and *E. viminalis. Eucalyptus globulus* had the highest cellulose content, highest pulp yield, lowest lignin content, and lowest wood consumption under kraft cooking of the four eucalyptus species considered. The high wood density of *E. globulus* (Table II) is an important factor in its low wood consumption. This low wood consumption of *E. globulus* makes it a very attractive species for pulp production. In the Iberian peninsula, where wood costs are relatively high, the low wood consumption of *E. globulus* has become an increasingly critical factor to the continued profitability of the local pulp industry.

Eucalyptus nitens had a high hemicellulose (glucuronoxylan acetate) content and low lignin content (Table III). The high hemicellulose content of *E. nitens* should tend to enhance PFI refining of the pulp. *Eucalyptus viminalis* had relatively high cellulose and lignin contents. *Eucalyptus grandis* had the lowest hemicellulose content and the highest lignin content of the four species considered.

A LOW-TECHNOLOGY APPROACH TO GENETIC IMPROVEMENT OF PULP QUALITY AND PRODUCT DEVELOPMENT

So far, we have discussed the wood, pulp, and paper properties of four of the 700 different eucalyptus species that exist in nature. We have looked at the wide genetic variability that occurs both between and within this small sample of four different species.

The obvious question is: How can the pulp and paper industry exploit the wide genetic variability of eucalyptus? The answer is simply to establish plantations with a wider selection of species and populations within species. For most soil and climatic environments in temperate and tropical regions of the world, the forester would normally have a choice of adapted eucalyptus species that are suitable for plantation establishment. It is perhaps a matter of investigating what species are possible to plant, not only copying what species others have grown in the past in similar environments. The forester must make sure that detailed investigations are made of the specific end uses of the wood that he or she is attempting to grow.

HIGH-TECHNOLOGY OPPORTUNITIES TO ENHANCE AND SPEED NEW PRODUCT DEVELOPMENT

In recent years, considerable advances have been made in biotechnologies such as quality-trait mapping, gene modification, and tissue culture. These advances, particularly when integrated with traditional tree breeding, open exciting opportunities to enhance and speed new product development from forest species. The integration of biotechnology and tree breeding can create unique opportunities to bring foresters, pulpmakers and papermakers, and researchers together.

Quality-trait mapping

Recent developments in molecular marker technology and quality-trait mapping should make it possible to correlate genes with particular characteristics of the wood. The characteristics of most interest to the pulp and paper industry are, of course, those wood fiber morphology and

Species	Wood cellulose content, % wt./wt.	Wood glucurono-xylan, % wt./wt.	Wood lignin content, % wt./wt.	Bleached kraft pulp yield, %	Wood consumed, m^3/ton bleached pulp
E. globulus	45	23	27	56	3.2
E. nitens	43	25	27	55	3.8
E. viminalis	44	22	29	54	3.8
E. grandis	43	21	30	53	3.9

III. Means of different eucalyptus species for wood chemical properties. Chemical properties are estimated by direct "wet" chemistry. The wood is from trees grown on one site and harvested at 10 years.

wood chemistry properties that determine key paper qualities such as refinability, strength, opacity, porosity, and bulk.

Today we have only a limited understanding of the key genes that are likely to influence the expression of wood morphological and chemical properties. We also have only a limited understanding of the mode of inheritance of these genes. Nevertheless, these genes offer an excellent target for biotechnological research that will broaden the understanding of wood characteristics and their control mechanisms.

Quality-trait mapping can have a number of important uses in the genetic improvement of pulp:

- Early selection. Knowledge of the location on the chromosome of genes influencing wood properties could be quite useful for early selection. Tree breeders could, for example, determine wood properties of seedlings by analyzing DNA taken from the leaves, thereby greatly speeding the selection process. In breeding *E. globulus* by traditional methods, it is necessary to delay genetic selection for most wood properties until the field trials are 4–6 years old.
- Identifying and modifying genes. An important step would be to identify and isolate the actual genes that control specific wood properties. These genes could then be used, together with traditional breeding programs, to produce new modified trees with specific combinations of wood, growth, and other characteristics.

An example of modifying genes

Genetic modification technology, together with tissue culture technology, opens opportunities to selectively enhance and control the behavior and reactivity of wood and pulp properties. An example is lignin content.

Changes to the content or structure of the lignin content of the wood should be quite attractive to the pulpmaker. The removal of lignin during kraft pulping and bleaching is a costly part of the process and an environmentally sensitive issue. A substantial amount of research is devoted to improving the pulping and bleaching processes to improve lignin degradation. However, insufficient research has been devoted to directly modifying the lignin structure or reducing the lignin content of the wood itself.

A relatively narrow variation in lignin content seems to occur within eucalyptus species. Therefore, modification by traditional breeding appears to be limited.

Genetic modification through genetic engineering offers an alternative way to alter the lignin content and lignin structure. A gene that influences the lignin biosynthesis pathways in plants has already been isolated. It, however, is still unclear what the consequence of reducing the activity of any of the candidate enzymes in the lignin biosynthesis pathway will be on the content and structure of lignin or, indeed, on other growth characteristics of the tree.

Clonal propagation

It is important to remember that the eucalyptus species, like most forest species, are heterozygous. This means that the progenies from genetically modified parents cannot be expected to express the modified characteristic at the precise level it was expressed by the parent. Progeny produced through clonal propagation, however, should express the modified trait at the precise levels required.

The application of genetic modification technology will be most rapid and efficient if tested clones of high commercial value (for characters such as growth) are selected for genetic modification. The insertion of new genes would further enhance the value of the clone. Commercialization of genetically modified eucalyptus would most likely have to be through clonal propagation by tissue culture or cuttings.

Future strategy

For the future, it seems important to concentrate on the following items:

- Knowledge. Increase our understanding of the relationship between genes and wood, and pulp and paper properties. Also learn more about the expression, function, and modes of inheritance of these genes.
- Identification. Identify specific genes that are influencing key wood fiber morphology and wood chemical properties of the tree.
- Modification. Take a step beyond traditional tree breeding. Modify existing genetically improved and commercially valuable clones by inserting new genes that will change or enhance wood properties *(4)*.

ORGANIZATION INTEGRATION

We know that research carried out in isolation usually achieves very little. The practical application of biotechnology and genetics in product development requires close cooperation between forest, mill, sales, customer, and research. In particular, the flow of decisions and operations from forest to mill to customer must be closely integrated.

It is interesting to consider what should happen in different parts of the forestry/mill/sales/research organization to develop new products or improve existing products.

Forest

Foresters are sometimes not able to "see beyond the trees." When the logs are being taken away to the pulp mill, the job of the forester is finished. Wrong! It is critically important for the forester to be well informed about the ultimate end-use of wood products. The forester must know the existing pulp and paper products and understand alternatives for the future.

The forester is usually the person who chooses the type of tree to be grown. Unless the forester is well informed about end-use products, the choice of forest species will be based on plantation parameters such as growth, survival, and tree form.

Mill

Pulp mill managers are sometimes not able to "see beyond the bale press" at the end of the production line. Like the forest manager, the pulp mill manager must be familiar with the ultimate end-use products of the paper industry.

There must be a close connection between the forest and the pulp mill. The mill process must take maximum advantage of what the particular wood raw materials have to offer. It is possible to make bad pulp out of good wood, but the converse is not true.

Mill design is an important factor to consider in product development. Some pulp mills are designed with too much emphasis on a particular species of wood. The pulp mills in the Iberian peninsula, for example, may be designed too tightly around the pulping of *E. globulus.* More flexibility in certain parts of the mill could give more possibilities to use and blend wood from other species.

Sales and customer

Sales personnel sometimes have an "all orders are equally attractive" approach. Customers sometimes have a "buy on price" approach.

One key to establishing better partnerships between suppliers and customers is for both parties to understand "value." To present the concept mathematically:

$$\text{Value} = (\text{Set of benefits}) - \text{Price}$$

where

Benefit 1 = \$ for the customer
Benefit 2 = \$ for the customer
Benefit 3 = \$ for the customer.

In pulp and paper, the price is determined by the market at a particular time and cannot be altered. However, if the customer understands the value that a particular pulp (relative to alternative pulps) brings in terms of dollars saved, the supplier should be able to share in the value added.

The connection between customer, sales, and production is vital. The customer must be able to say, "My key needs are. . . ." These are the benefits listed in the previous equation. The pulp salespeople must ask "What are the benefits of the products that we sell, and how can we turn those benefits into profit?" The mill production people must know, "What products can we make profitably?"

Research

The researcher is required to do more than just research. The researcher must be the "glue" that keeps the integration of forest, mill, sales, and customer together. When things appear to be falling apart, it can be the researcher who motivates and pushes the collaboration ahead.

CONCLUSIONS

In Europe, birch pulps tended to dominate the short-fiber market until the 1970s. Around this time, eucalyptus pulps from Iberia (*E. globulus*) and Brazil (*E. grandis*) began to substitute for birch because of the better overall quality of eucalyptus pulps for many important paper end-use segments.

What new pulps will come next? Figures 1–9 suggest that pulps produced from species such as *E. nitens* and *E. viminalis,* if available, could penetrate the existing market share of *E. globulus* and *E. grandis* in various paper segments. It is easy to imagine *E. nitens* market pulps being rather attractive to customers requiring high tensile strength at low refining levels, together with low porosity and high opacity. **TJ**

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