# NEAR INFRARED SPECTROSCOPY: A RAPID, NON-DESTRUCTIVE METHOD FOR MEASURING WOOD PROPERTIES AND ITS APPLICATION TO TREE BREEDING

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# NEAR INFRARED SPECTROSCOPY: A RAPID, NON-DESTRUCTIVE METHOD FOR MEASURING WOOD PROPERTIES AND ITS APPLICATION TO TREE BREEDING

ABSTRACT

Near infrared (NIR) spectroscopy provides a rapid, non-destructive method for the routine estimation of wood properties. NIR spectroscopy is increasingly being used to replace traditional methods of wood property assessment providing a wealth of information to tree growers, tree breeders and manufacturers of forest products. The technology is particularly well suited to tree improvement programs where large numbers of samples must be analysed but it can be utilised in any forestry application where the rapid provision of wood property data is required.

The application of NIR spectroscopy to samples ranging in size from milled chips representing whole trees, to sections of wooden strips cut from increment cores and, at the smallest scale, wafers cut from the tangential face of cores is examined. Studies that have utilised NIR spectroscopy for tree breeding purposes are emphasised. Some limitations of the technology and obstacles to wider acceptance are also examined.

**Keywords:** Near infrared spectroscopy, *Eucalyptus globulus*, *Eucalyptus nitens*, *Pinus radiata*, *Pinus taeda*, tree breeding, wood properties.

## Introduction

The following review is not intended to be a thorough examination of all the wood - near infrared (NIR) spectroscopy literature. Rather it is a review of selected articles that relate to the estimation of pulp yield, and properties related to pulp yield, by NIR spectroscopy. The review will also describe how NIR spectroscopy has been used for the estimation of wood properties of increment cores and how data provided by NIR analysis has been used for the estimation of genetic parameters. Extensive reviews of NIR spectroscopy and its application to wood and forest products are provided by Schimleck & Workman (2004), So *et al.* (2004), and Tsuchikawa (2007).

NIR spectroscopy is a relatively new analytical technique that has been utilized for the prediction of product properties since the 1960's. Prior to the 1960's spectrophotometers were available that could measure NIR spectra, however the NIR region of the electromagnetic spectrum was rarely utilized as it was considered that it contained no relevant structural information (Barton 2004). Burns & Margoshes (1992) describe many of the problems encountered by spectroscopists who wanted to work with the NIR region, these included: an absence of sharp peaks, an abundance of overlapping and shoulder peaks, a dramatic loss in sensitivity (2 to 3 orders of magnitude relative to the mid infrared) and the difficulty of making band assignments owing to the presence of numerous overtone and combinations bands.

The earliest analytical applications of NIR spectroscopy were reported in the early 1960's by Karl Norris of the U. S. Department of Agriculture (Barton 2004). For example, Ben-Gera & Norris (1968ab) utilised NIR spectroscopy to determine the moisture, crude protein and oil concentrations of cereal grains and oil-bearing seeds. By the early 1990's the analytical applications of NIR spectroscopy were widespread with many different industries (agriculture, food, paper, petro-chemical, polymer and textile) utilising the technology (Ciurczak 1992).

The rapid growth of the technology can be attributed to the emergence of high-precision spectroscopic instruments with very high signal to noise ratios to detect minute differences in the reflectance spectra and high-speed computers to carry out the complex calculations involved in multivariate analysis (Norris 1989). In addition NIR spectroscopy has several advantages compared to traditional laboratory techniques, including:

- rapid speed and reliability of determinations;
- rapid and easy sample preparation;
- multiplicity of analysis with one operation;
- operation by unskilled personnel; and
- analysis is non-destructive (Norris 1989; Schultz & Burns 1990).

## Origin of near infrared spectra

The infrared region of the electromagnetic spectrum ranges from 700 to $10^6$ nanometers (nm) (10 to 14300 $cm^{-1}$) and is divided into near, middle and far infrared. A summary of each region is given in Table 1 (Osborne *et al.* 1993). The most useful region for qualitative analysis by reflectance in the near-infrared is 1200 to 2500 nm (8333-4000 $cm^{-1}$). For wavelengths below 1200 nm the weak absorption bands make reflectance measurements difficult and for those above 2500 nm the bands become too strong (Norris 1989). Spectra that occur in the near-infrared region largely consist of overtone and combination bands of the fundamental stretching vibrations of O-H, N-H and C-H functional groups (Osborne *et al.* 1993; Shenk *et al.* 1992).

**Please insert Table 1 near here please**

## The rapid estimation of pulp yield by NIR spectroscopy

Despite the numerous advantages that NIR spectroscopy presents its utilization for the estimation of wood properties has a relatively short history, with the earliest work being reported as recently as the late 1980's. Preliminary studies concentrated on the feasibility of NIR spectroscopy to predict wood chemistry, specifically pulp yield, and two wood components (cellulose and lignin) that together have a large influence on pulp yield (Birkett & Gambino 1988; Schultz & Burns 1990; Wright *et al.* 1990; Michell 1995; Olsson *et al.* 1995).

A long-term objective of tree breeding programs has been to improve the pulp yield of plantation grown trees as pulp yield is an important factor in determining plantation profitability (Dean *et al.* 1990; Borralho *et al.* 1993; Greaves *et al.* 1997). However, traditional assessment of pulp yield is time consuming and expensive limiting the number of trees that can be analysed (Downes *et al.* 1997; Raymond & Schimleck 2002). In addition, it is destructive because trees identified for assessment must be felled. Hence, the rapid estimation of pulp yield, by NIR spectroscopy, was particularly important as a rapid, non-destructive method had long been sought for this purpose.

These studies were generally based on whole-tree wood property data (cellulose, lignin, pulp yield etc.) and NIR spectra collected from milled chips that were usually a subsample of the chips used to provide the wood property data. The composite chip sample could have represented a whole-tree or multiple trees and was obtained from either chipped billets or discs from several different heights. A regression equation, based on multiple linear regression or Partial Least Squares (PLS) regression, was then obtained using the available wood property data and corresponding spectra. The calibration was then used to predict the wood property for a set of validation samples based on the NIR spectra of these samples.

It was quickly established that NIR spectroscopy could be used to predict pulp yield, cellulose content and lignin content, albeit with variable accuracy, which could be related to the quality of the laboratory data used to develop the calibrations and the wood property variation present in the calibration and prediction sample sets. However, without exception the validation samples were drawn from the same population (pseudo-validation) as the calibration samples and from a practical viewpoint several questions were raised, for example:

- Is it possible to have multiple-species, or multiple-site calibrations?
- Could a calibration for one site be used to accurately estimate the wood properties of samples from a different site (a truly independent validation)?
- Can whole-tree wood properties be estimated using NIR spectra from cores?

The following sections examine attempts to answer these questions.

## Multiple-species, multiple-site calibrations

Multiple-site, multiple-species calibrations are common in agriculture where extremely large spectral databases, containing in excess of one thousand spectra per commodity have been created over many years (Dardenne 2004). In an extreme case Berzaghi *et al.* (2002) reported the development of multiple-site forage calibrations based on a set of 20,000 plus samples from Australia, Belgium, Canada, Germany, Italy, Sweden and the USA.

The scale of this work has yet to duplicated with wood and this can be attributed to several factors; including the short history of wood – NIR research, the failure of NIR spectroscopy to replace traditional methods of wood property determination on a large-scale (in comparison NIR spectroscopy has replaced many traditional methods of analysis in the agricultural industries) and the difficulty and cost of determining properties such as pulp yield. Another problem with a property such as pulp yield is that laboratories are not consistent with the pulping methods that they employ making it impossible to share characterised samples between laboratories, unlike the work described by Berzaghi *et al.* (2002).

Garbutt *et al.* (1992) provided an early example of cellulose and lignin NIR calibrations based on mixed species (13 eucalypts, 1 hybrid), while Michell (1995) reported excellent calibration statistics for a number of wood and pulp quality parameters using native forest grown *Eucalyptus globulus* from 10 locations in Tasmania. The sample set utilized by Michell (1995) is worth noting. The samples, representing up to 10 trees per location, were collected by Orme in 1976 (Eldridge *et al.* 1993) and were part of an extensive investigation into the genetic variation of Tasmanian *E. globulus* (Turner *et al.* 1983). The variation that the set represented was extreme with tree age ranging from 38 to 370 years and soda pulp yields ranging from 37.6 to 60.2% (Turner *et al.* 1983). The extreme variation that existed for this set explains the very high correlation coefficients reported by Michell (1995). Equivalent correlation coefficients cannot be expected for plantation grown woods as demonstrated by Michell & Schimleck (1998) and Schimleck *et al.* (2000) who reported examples of multiple-site kraft pulp yield calibrations (based on milled chips representing a whole-tree composite) for plantation grown *Eucalyptus nitens* from Tasmania and multiple-site *E. globulus* and *E. nitens*, also from Tasmania.

Recent studies have attempted to include more species from more locations. For example, Schimleck *et al.* (2006a) obtained calibrations for whole-tree basic density, lignin, pentosans, pulp yield and specific consumption using 7 different eucalypt species and 5 hybrids, sampled from 3 different locations in Brazil. Calibration statistics for pulp yield were poor, however the pulp yield data utilized by Schimleck *et al.* (2006a) had variable Kappa numbers (range = 16.7 to 18.8) and, therefore, was not directly comparable between samples, explaining the poor results.

Another study demonstrating the ability of NIR spectroscopy to provide multiple-site, multiple-species calibrations was reported by Hodge & Woodbridge (2004) who developed calibrations for lignin content using five species of tropical and sub-tropical pines (*Pinus caribaea*, *P. maximinoi*, *P. oocarpa*, *P. patula* and *P. tecunumanii*) grown in Brazil and Colombia. A lignin calibration based on the 5 species from both countries had a coefficient of determination ($R^2$) of 0.90. It should be noted that the calibration reported by Hodge & Woodbridge (2004) was based on small wedges cut from breast height disks that had been split into juvenile and mature sections and not whole-tree chips, the wedges were also used to determine lignin content.

Efforts to develop multiple-site, multiple-species calibrations for pulp yield continue as the development of a calibration that encompasses wide variation and does not require continual refinement has great appeal to many users. The most notable effort is at Ensis (a CSIRO Forestry and Forest Products and Scion joint venture) where a pulp yield calibration based on approximately 700 samples (a mix of milled individual whole-tree samples and composite chip samples of many trees) and including multiple eucalypt species from multiple sites in Australia has been developed (G. Downes pers. comm.) (Figure 1). At an average cost of several hundred Australian dollars per sample the calibration represents a sizable investment. It is important to note that NIR spectra for the calibration were obtained from milled chips representative of the chips from which the pulp data was obtained and, therefore, from the perspective of the calibration, it does not matter if the sample is from part of a tree, a whole-tree or multiple trees.

**Insert Figure 1 near here please**

Multiple-site, multiple-species calibrations are a desirable objective for breeding programs, particularly for a property such as pulp yield where the expense of laboratory measurements limits the number of samples that can be analysed, however as noted by Murray (2004), predictions made by such calibrations will not be as precise as those obtained using a single species, site specific calibration. Typically these broad-based calibrations are referred to as GLOBAL calibrations. An alternative that has not been investigated for the estimation of wood properties is the LOCAL approach (Shenk *et al.* 1997) which involves developing a specific equation to predict a given property for a new sample. The new calibration is obtained using samples selected from a large database on the basis of their similarity to the unknown sample (Pérez-Marín *et al.* 2005). Several studies have demonstrated that LOCAL calibrations provide smaller predictive errors than GLOBAL calibrations (for example Sinnaeve *et al.* (1994); Shenk *et al.* 1997 and Pérez-Marín *et al.* 2005). The advantage of the LOCAL approach is that it provides the benefits of using a GLOBAL strategy, i.e. a large database that encompasses the expected variation, with the accuracy of specific calibrations (Pérez-Marín *et al.* 2005). However, the establishment of a large database containing thousands of samples is critical (Pérez-Marín *et al.* 2005) explaining why the LOCAL approach has yet to be explored for estimating wood properties.

## Application of pulp yield calibrations to new sites

The vast majority of the NIR-wood studies reported in the literature test their calibrations by using them to predict the properties of a subsample from the same population (pseudo-validation). While this approach demonstrates that the calibration is applicable to the subset it doesn't provide any indication of how it will perform if applied to samples from a new population. When applying a calibration to samples from different sites, its performance can be expected to suffer owing to the myriad of differences that exist between the sites represented in the calibration and prediction sets. An example of what can be expected was provided by Schimleck *et al.* (2000) when they used a northern Tasmania *E. nitens* pulp yield calibration based on trees from several sites to estimate the pulp yields of 38 plantation grown *E. nitens* samples from southern Tasmania. It was found that the calibration overestimated the pulp yields of the southern Tasmania *E. nitens*, however the relationship between yields estimated by NIR spectroscopy and those determined using laboratory pulping was very good ($R^2$ = 0.87). Selection of the highest yielding trees based on laboratory pulping and NIR predicted yields were also compared and it was found that of the top 12 pulp yielding trees selected using laboratory data, 9 would have been selected using NIR predicted data. As noted by Schimleck *et al.* (2000) there would be little chance of missing an outstanding individual and if tree selection was based on families, rather than individuals, then it would be very unlikely that an outstanding family would be missed.

In a later study Schimleck *et al.* (2005a) applied a Tasmania-wide *E. nitens* pulp yield calibration to a set of 25 samples from a site in northern Tasmania (Gog). While a reasonable $R_p^2$ was obtained (0.70), prediction errors were large (SEP = 4.60%) as the Tasmania-wide calibration consistently underestimated the pulp yields of the Gog samples.

One approach to improving the predictive performance of calibrations, when applied to samples from a site not represented in the calibration, is to include a small number of samples from the new site in the calibration set (Guthrie & Walsh 2002). Schimleck *et al.* (2005a) found that the addition of 5 Gog samples to the calibration set greatly improved the performance of the calibration when it was used to predict the pulp yields of the remaining Gog samples ($R_p^2$ = 0.77, SEP = 1.03%). Figure 2 shows predicted yields (based on NIR spectra from whole-tree composites) before and after the addition of 5 Gog samples to the Tasmania-wide *E. nitens* pulp yield calibration.

**Insert Figure 2 near here please**

Schimleck *et al.* (2006b) showed that the addition of a single Gog sample to the Tasmania-wide calibration set was sufficient to greatly reduce predictive errors and that the inclusion of at least 3 Gog samples in the Tasmania-wide set was sufficient to give relatively stable predictive errors. The practical implication of these findings is that calibrations can be adapted to be directly applicable to new locations. However, concerns exist about the statistical robustness of a calibration if a relatively small number of samples can markedly change its performance.

## Estimation of whole-tree wood properties using NIR spectra of milled cores

The ability to accurately estimate whole-tree pulp yield based on NIR spectra collected from increment cores would greatly reduce the costs of plantation assessment and facilitate non-destructive sampling. In order to estimate whole-tree pulp yields from increment core NIR spectra, calibrations between whole-tree pulp yield (obtained from destructively sampled trees) and NIR spectra collected from increment cores need to be developed. Schimleck *et al.* (2006a) examined this approach in their study based on multiple eucalypt species and hybrids grown in Brazil. It was shown that wood property calibrations based on whole-tree data and NIR spectra collected from whole-tree composite chips and increment cores from 0.65 and 1.50 m provided similar calibration statistics (Figure 3) and also performed in a similar manner when applied to a separate test set. A possible reason for the similar performance of the 3 sets of calibrations is that the rankings of the trees would in a similar order, for example from highest to lowest yield, regardless of which set (whole-tree composite, 1.3 m core, 0.65 m core) was used, and for calibration purposes it is the relative order of samples that is important.

**Insert Figure 3 near here please**

In a similar study based on hybrid poplar, Schimleck *et al.* (2005b) also found that calibrations for whole-tree pulp yield and cellulose based on whole-tree chip and increment core NIR spectra provided similar calibration statistics (whole-tree spectra $R^2$ = 0.94 (cellulose, 5 factors) and 0.96 (pulp yield, 5 factors) and core spectra $R^2$ = 0.89 (cellulose, 5 factors) and 0.90 (pulp yield, 6 factors)). For the hybrid poplar examined by Schimleck *et al.* (2005b) a moderate relationship was found between whole-tree cellulose and core cellulose ($R^2$ = 0.65).

Alternatively, calibrations based on whole-tree chips can be used to estimate whole-tree yields, based on core NIR spectra, but it can be expected that errors obtained using this approach will be greater because a core will not represent a whole-tree in the same way as a composite chip sample and variation specific to cores has not been included in the whole-tree calibration. In their study based on *E. nitens* Schimleck *et al.*

(2005a) examined this approach and, in an unexpected result, found that predictive errors were actually lower (whole-tree $R_p^2 = 0.70$, SEP = 4.60%; cores $R_p^2 = 0.78$, SEP = 3.27%). Schimleck *et al.* (2005a) also found that the addition of 5 Gog cores greatly improved the predictive performance of the Tasmania-wide *E. nitens* pulp yield calibration when applied to the remaining cores from Gog ($R_p^2 = 0.76$, SEP = 1.04%).

The findings of these studies indicate that it is likely that a small number of trees would have to be destructively sampled and analysed to ensure variation unique to a particular site was included in the calibration. Regarding the selection of trees for destructive sampling it is preferred that the trees identified represent the variation in pulp yields (or wood chemistry in general), however this may not always be possible. Several different approaches exist and are briefly described.

- Select trees without any prior knowledge of wood chemistry, the trees selected may still represent different diameter classes, provenances, clones, site conditions etc.;
- Collect cores (for example 50) from trees at the new location, predict the pulp yields of the 50 samples using an existing pulp yield NIR calibration (assuming an existing calibration is available) and make selections to represent the range of yields; and
- Collect cores from the new location, collect NIR spectra from the cores and use spectral analysis methods to identify the most spectrally unique samples. Advantages of using this method is that it can be used to select a specified number of samples that best represent the new population in terms of the spectral information and an existing calibration is not required. Several methods exist for selecting samples based on their spectral characteristics. Many spectroscopists use the Center and Select method developed by Shenk and implemented in WinISI software (Infrasoft International 2000) which uses a neighbourhood concept to identify spectrally unique samples. Other options include the Kennard-Stone (Kennard & Stone 1969), Duplex (Snee 1977) and OptiSim (Clark 1997) algorithms.

Assuming that an existing calibration exists (and this may be a big assumption) and pulping facilities are available there are several options in the way that NIR spectroscopy can be used when estimating the pulp yield of trees from a new location, these options are summarized in Table 2.

**Please insert Table 2 near here please**

## Estimation of the wood properties of intact radial strips

An understanding of patterns of wood property variation from pith to bark with age, the effects of forest management practices on wood quality and the minimum age of early assessment for various wood properties are all important questions for a breeding program (Raymond 2002). Answers to these questions can only be obtained by the analysis of large numbers of increment cores and, until the recent development of the SilviScan instruments (Evans 1994, 1998), this was only practical for basic density on a large scale.

Recent studies (Schimleck & Evans 2002ab, 2003, 2004) based on NIR spectra collected in 10 mm sections from the radial-longitudinal surface of strips cut from *Pinus radiata* increment cores have demonstrated that NIR spectroscopy can be used to examine the pith to bark variation of a range of physical properties and tracheid morphological characteristics. Using calibrations based on SilviScan generated data a range of properties were predicted by NIR spectroscopy including air-dry density, microfibril angle (MFA), stiffness and tracheid coarseness, specific surface and wall thickness. It has also been demonstrated that wood chemistry (cellulose, extractives, lignin, wood sugars) and fiber length can be estimated using NIR spectra collected from intact radial strips (Schimleck *et al.* 2004a; Jones *et al.* 2006; Poke & Raymond 2006). These studies were based on a limited number of samples compared to the studies that utilised SilviScan data.

The same questions discussed for calibrations based on whole-tree composite chip samples apply for calibrations based on increment cores. Studies based on *Pinus taeda* have shown that multi-site calibrations (representing different site qualities and physiographic regions in Georgia, USA) could be obtained for the physical and morphological properties reported in the studies of Schimleck & Evans and that the calibrations could be successfully applied to cores from different sites (Jones *et al.* 2005ab). The development of multi-species calibrations has also been explored. Schimleck *et al.* (2001) obtained reasonable calibrations for air-dry density and stiffness using spectra collected from 54 different commercial species (both hardwoods and softwoods) from around the world.

The provision of wood property data in 10 mm increments makes it possible to examine radial variation and the estimation of core averages, however, it has limited utility for examining the variation of wood properties within rings, which is important if a goal is the estimation of genetic parameters of individual rings (Sykes *et al.* 2003). Increasing the resolution of NIR measurements to 2 mm would make the estimation of wood properties within rings possible but the findings of a recent study (Jones *et al.* 2007a) suggests that existing NIR spectrometers are not suitable for scanning radial strips at high spatial resolution. An alternative method for collecting NIR spectra at high spatial resolution is to obtain NIR spectra from the tangential surface of samples cut from increment cores or radial strips. Depending on the thickness of the tangential section, reflectance (relatively thick sections) or transmission NIR spectra can be collected. The first approach (reflectance spectroscopy) has been utilised by Schimleck *et al.* (2007a) to estimate earlywood and latewood MFA within rings using sections cut from *P. taeda* radial strips. The second approach (transmission spectroscopy, in the general range of 600-1900 nm) has been utilised by Yeh *et al.* (2004, 2005) and Sykes *et al.* (2005) who collected their spectra from thin wafers cut from *P. taeda* increment cores and estimated α-cellulose, lignin, and tracheid coarseness and length. Calibration statistics were relatively good and indicated that transmission NIR spectroscopy could provide a method for examining wood property variation at high spatial resolution within individual rings. Sykes *et al.* (2005) based their calibrations on the earlywood and latewood of two rings (ring 3 and 8) and found that ring 3 calibrations for α-cellulose and fibre coarseness predicted ring 8 properties with $R^2$ values of approximately 0.6, indicating the potential for early selection. It should be noted that for the work based on transmission NIR spectroscopy sample preparation was particularly intensive and limited the number of samples that could be analysed quickly.

Compared to the studies based on whole-tree composite samples the studies based on increment cores present an interesting contrast, particularly when SilviScan data is used for calibration development. SilviScan provides an abundance of data, making the development of calibrations based on thousands of spectra possible. In addition, SilviScan provides wood property data that has been measured by a machine, largely negating the human element and minimizing errors that can occur in wet chemistry data. Unlike a NIR spectrum collected from a whole-tree composite, a NIR spectrum collected from a section of a radial strip relates exactly to the wood property data available for calibration. In combination these factors provide calibration statistics for properties such as stiffness and MFA that are generally superior to those reported for calibrations based on whole-tree composites. However, there are also problems unique to working with NIR spectra collected from radial strips and SilviScan data. It is imperative that a NIR spectrum for a given section of a radial strip corresponds exactly to the wood property data. Mismatched data will provide poor calibration statistics, if this occurs for a small number of samples, the mismatched spectra are obvious and the problem can be rectified but if the problem is widespread little can be done. Similar problems can arise if the spectra and wood property data are slightly offset. The problem of mismatched or offset data may be relatively minor for spectra collected at a resolution of 10 mm but as the resolution of spectral measurements increases matching the two data sets becomes more problematic, in addition the number of spectra collected increases rapidly as resolution is increased, for example increasing the resolution from 10 mm to 2 mm gives a five-fold increase in the number of spectra collected, compounding the problem. Recently Schimleck *et al.* (2007b) have demonstrated for calibration development that it is unnecessary to use NIR spectra from every section of a core. A single spectrum per core is adequate provided that sections from other cores representing juvenile, mature and the juvenile/mature wood transition are included in the calibration set. Calibration and prediction statistics can be marginally improved by increasing the number of spectra per core to between 3 and 5, while the addition of further spectra is unnecessary. The practical implication of this finding is that the problems associated with creating calibrations based on radial strips scanned at high spatial resolution can be greatly reduced, as can the cost of SilviScan analysis.

## Field based NIR spectroscopy of wood properties

Increasingly NIR spectroscopy is being investigated as a field based measurement technique with the aim of providing data in real-time. In agriculture this has become a reality with NIR spectrophotometers being fitted onto harvesters for the estimation of forage quality (Haesler *et al.* 2002; Paul & Pfitzer 2004; Sinnaeve *et al.* 2004). Ideally the estimation of wood properties by NIR spectroscopy would also be conducted in the field in real-time and would reduce the need to collect increment cores. Efforts are underway to make this goal a reality but preliminary results for *P. taeda* (Jones *et al.* 2007b) have not been promising. These authors cited the difficulty of designing a suitable fiber-optic probe for NIR analysis and the performance of fiber-optic probe systems compared to bench-top NIR spectrometers as two obstacles. The high resin content of some softwood species is also problematic as it bleeds into the core hole, and will adhere to the fiber-optic probe (Jones *et al.* 2007b).

In a recent study, Acuna & Murphy (2006) used NIR spectra collected from chain saw chips in the laboratory to predict the basic density of *Pseudotsuga menziesii* stems. Calibration $R^2$ ranged from 0.89 to 0.95, while $R^2$ obtained on a validation set (0.56 to 0.85) were weaker. The authors concluded that their results indicated that NIR technology could be used by mechanical harvesters to segregate logs based on basic density.

## Estimation of genetic parameters based on NIR generated data

The focus of this review has largely been pulp yield and to a lesser degree increment core properties, but the range of properties that can be assessed and incorporated into a breeding program is not limited to the properties discussed as demonstrated by the work of Baillères *et al.* (2002), who examined a wide range of properties including extractive and lignin content, lignin composition (syringyl guaiacyl ratio), shrinkage (longitudinal, radial and tangential) and surface longitudinal growth strain.

Interest exists in using NIR spectroscopy for tree breeding purposes as it provides a rapid, nondestructive method for determining multiple properties for a large number of samples. As already discussed nondestructive sampling can be achieved by removing increment cores and NIR spectroscopy can be used to predict whole-tree pulp yield based on core spectra. For convenience breast height is generally used, however for young (5 to 9 years) *E. globulus* and *E. nitens* Raymond *et al.* (2001a) recommended that sampling heights of 1.1 m for *E. globulus* growing on all sites and 0.9 m for *E. nitens* growing on high quality sites be used (for *E. nitens* growing on poor quality sites cores were not good predictors of whole-tree yield). In later studies these sampling recommendations were followed and provided data that was used to estimate genetic parameters and genotype-by-environment interactions for pulp yield and pulpwood productivity, and genetic parameters for cellulose content, extractives, lignin content and susceptibility to decay in *E. globulus* (Raymond *et al.* 2001b; Raymond & Schimleck 2002; Poke *et al.* 2006).

The genetic gains in cellulose content for *E. nitens* have also been compared using cellulose content determined using wet chemistry and predicted by NIR calibrations based on different sampling intensities (Schimleck *et al.* 2004b). Cellulose content was examined as it is strongly related to pulp yield (Dillner *et al.* 1971, Wallis *et al.* 1996, Kube & Raymond 2002) and provides a low cost alternative for pulp yield improvement in a breeding program (Kube & Raymond 2002). It was found that genetic gains based on NIR predicted cellulose content were high and very similar to the gains achievable using a direct measure of cellulose. In addition, NIR predicted cellulose was found to be highly heritable with heritabilities comparable to direct measures of cellulose. Schimleck *et al.* (2004) also compared methods for selecting calibration samples (20, 40 and 60 samples based on pulp yields predicted using an existing calibration and samples selected on the basis of spectral variation). Calibrations based on samples selected for their spectral variation provided higher genetic gains (90% of the maximum possible gain) than were obtained using samples selected based on their predicted kraft pulp yields (Table 3 shows gains for a forward selection strategy, while Table 4 shows gains for a backward selection strategy). The study of Schimleck *et al.* (2004b) demonstrated that NIR spectroscopy can be used to provide estimates of genetic parameters that agree very well with those determined using data obtained with conventional laboratory techniques at a reduced cost.

**Please insert Tables 3 and 4 near here please**

## Conclusions

NIR spectroscopy provides a rapid alternative to traditional methods of wood property assessment and potentially has a very important role in the future of tree breeding programs. Many organisations have explored using the technology but few are using it on a regular basis. As discussed in this review there are many issues related to the analysis of wood by NIR spectroscopy that are shared with other research areas where NIR spectroscopy is commonly used and these have been overcome. One of the most important issues is the applicability of calibrations to new sites. Even with a multi-site calibration there is no guarantee that it will perform well when applied to samples from a new location and there is no way of testing if the calibration will perform adequately. Samples from the new location can be added to the calibration to improve its performance on the new site, but most NIR users do not want to continually update their calibrations. The generation of large spectral databases is underway with the aim of providing calibrations that can be applied to new locations with confidence, but for properties such as pulp yield, the expense associated with accurately determining it prohibits the analysis of thousands of samples. Possibly networks of users will be formed, similar to that in agriculture, and the sharing of calibration sets will become common, however this seems unlikely at present. Probably the best chance for the development of large spectral databases of characterised samples will be using samples analysed by SilviScan. The creation of large sets of spectra will also make it possible to explore the LOCAL approach for predicting wood properties.

In terms of commercialization NIR spectroscopy, as a technique for estimating wood properties, lags behind both SilviScan and the new generation of acoustic tools presently available. Recently Paprican and Analytical Spectral Devices announced that they will develop an instrument based on NIR spectroscopy to estimate Kappa number and pulp brightness (TAPPI 2007). For the commercialization of wood property estimation by NIR spectroscopy to become a reality on a large-scale, the issues regarding the application of existing calibrations to new sites must be overcome and the estimation of wood properties in the field by NIR spectroscopy must become a reality.

Important questions also remain relating to the best way to utilise NIR spectroscopy for the estimation of wood properties and how and by whom the analysis should be conducted. Expectations have consistently been over-optimistic about the estimation of wood properties by NIR spectroscopy and in many cases NIR predictions of wood properties have not been considered sufficiently accurate for practical purposes. If, for example, NIR spectroscopy was used to estimate the pulp yield of a single tree, then chances are it will provide an estimate that will disappoint the user. But if it is used to estimate population parameters based on a reasonably large sample set then it will provide excellent data. Likewise for the estimation of genetic parameters and identification of superior genotypes NIR spectroscopy is well suited owing to its ability to analyse large numbers of samples quickly and to predict multiple properties.

Presently several organisations and companies have investigated using NIR for research purposes and there has been considerable repetition of effort, hindering progress. For companies that do not want to continually update calibrations a possible alternative is to establish a collaborative research centre devoted to NIR spectroscopy where member companies contribute to an operating budget, develop research objectives and share research findings. Alternatively companies can continue to develop their NIR applications internally or pay to have samples analysed on a per sample basis by a research provider.

## REFERENCES

ACUNA, M.A.; MURPHY, G.E. 2006: Use of near infrared spectroscopy and multivariate analysis to predict wood density of Douglas-fir from chain saw chips. *Forest Products Journal 56 (11/12)*: 67-72.

BAILLÈRES, H.; DAVRIEUX, F.; HAM-PICHAVANT, F. 2002: Near infrared analysis as a tool for rapid screening of some major wood characteristics in a eucalyptus breeding program. *Annals of Forest Science 59*: 479-490.

BARTON, F.E. II. 2004: Progress in near infrared spectroscopy the people, the instrumentation, the applications. *In* Near Infrared Spectroscopy: Proceedings of the 11th International Conference, Córdoba, Spain. Edited by A.M.C. Davies; A. Garrido-Varo. NIR Publications, Chichester. pp. 13-18.

BEN-GERA, I.; NORRIS, K.H. 1968a: Determination of moisture content in soybeans by direct spectrophotometry. *Israel Journal of Agricultural Research 18*: 125-132.

______1968b: Direct spectrophotometric determination of fat and moisture in meat products. *Journal of Food Science 33*: 64-67.

BERZAGHI, P.; FLINN, P. C.; DARDENNE P.; LAGERHOLM, M.; SHENK, J. S.; WESTERHAUS, M. O.; COWE, I. A. 2002: Comparison of linear and non-linear near infrared calibration methods using large forage databases. Proceedings of the 10th International Conference, Kyongju, South Korea. Edited by A.M.C. Davies; R.K. Cho. NIR Publications, Chichester. pp.107-111.

BIRKETT, M.D.; GAMBINO, M.J.T. 1988: Potential applications for near-infrared spectroscopy in the pulping industry. *Paper Southern Africa November/December*: 34-38.

BORRALHO, N.M.G.; COTTERILL, P.P.; KANOWSKI, P.J. 1993: Breeding objectives for pulp production of *Eucalyptus globulus* under different industrial cost structures. *Canadian Journal of Forest Research 23*: 648-656.

BURNS, D.A.; MARGOSHES, M. 1992: Historical Development. *In* Handbook of Near-Infrared Analysis. Edited by D.A. Burns; E.W. Ciurczak. Marcel Dekker Inc., New York. pp. 1-5.

CIURCZAK, E.W. 1992: Analytical applications of near infrared spectroscopy. *Chemtech 22*: 374-380.

CLARK, R.D. 1997: OptiSim: an extended dissimilarity selection method for finding diverse representative subsets. *Journal of Chemical Information and Computer Sciences 37*: 1181-1188.

DARDENNE, P. 2004: Calibration transfer in near infrared spectroscopy. *In* Near Infrared Spectroscopy: Proceedings of the 11th International Conference, Córdoba, Spain. Edited by A.M.C. Davies; A. Garrido-Varo. NIR Publications, Chichester. pp. 19-26.

DEAN, G.H.; FRENCH, J.; MADDERN, K.N. 1990: Breeding eucalypts for manufacture of pulp and paper. *In* Proceedings 23rd Forest Products Research Conference, Nov. 1990, Clayton, Victoria. Vol. 2. Division of Forestry and Forest Products, Commonwealth Scientific and Industrial Research Organization, Clayton, Victoria. Paper 5/2.

DILLNER, B.; LJUNGER, Å.; HERUD, O.A.; THUNE-LARSON, E. 1970: The breeding of *Eucalyptus globulus* on the basis of wood density, chemical composition and growth rate. *Timber Bull. Eur. 23(Suppl. 5)*: 120-151.

DOWNES, G.M.; HUDSON, I.L.; RAYMOND, C.A.; DEAN, G.H.; SCHIMLECK, L.R.; EVANS, R.; MUNERI, A. 1997: "Sampling plantation eucalypts for wood and fibre properties". Commonwealth Scientific and Industrial Research Organization Publications, Melbourne, Australia. 144 p.

ELDRIDGE, K.G.; DAVIDSON, J.; HARWOOD, C.E.; VANWYK, G. 1993: "Eucalypt Domestication and Breeding". Oxford University Press, Oxford, UK. 308 p.

EVANS, R. 1994: Rapid measurement of the transverse dimensions of tracheids in radial wood sections from *Pinus radiata*. *Holzforschung 48*: 168-172.

EVANS, R. 1998: Rapid scanning of microfibril angle in increment cores by x-ray diffractometry. *In* Microfibril Angle in Wood. Proceedings of the IAWA / IUFRO International Workshop on the Significance of Microfibril Angle to Wood Quality, Nov. 1997, Westport, New Zealand. Edited by B.G. Butterfield, University of Canterbury Press. pp. 116-139.

GARBUTT, D.C.F.; DONKIN, M.J.; MEYER, J.H. 1992: Near infrared reflectance analysis of cellulose and lignin in wood. *Paper Southern Africa April*: 45-48.

GREAVES, B.L.; BORRALHO, N.M.G.; RAYMOND, C.A. 1997: Breeding objective for plantation eucalypts grown for production of Kraft pulp. *Forest Science 43*: 465-472.

GUTHERIE, J.A.; WALSH, K.B. 2002: Assessing and enhancing near infrared calibration robustness for soluble solids content in mandarin fruit. *In* Near Infrared Spectroscopy: Proceedings of the 10$^{th}$ International Conference, Kyongju, South Korea. Edited by A.M.C. Davies; R.K. Cho. NIR Publications, Chichester. pp. 151-154.

HAEUSLER, A.; RODE, M.; PAUL, C. 2002: Compositional analysis by near infrared diode array instrumentation on forage harvesters. *In* Near Infrared Spectroscopy: Proceedings of the 10th International Conference, Kyongju, South Korea. Edited by A.M.C. Davies; R.K. Cho. NIR Publications, Chichester. pp. 345-347.

HODGE G.R.; WOODBRIDGE, W.C. 2004: Use of near infrared spectroscopy to predict lignin content in tropical and sub-tropical pines. *Journal of Near Infrared Spectroscopy 12*: 381-390.

INFRASOFT INTERNATIONAL 2000: ISI Windows Near Infrared Software, WinISI II. Version 1.50. Port Matilda, Penn., USA.

JONES, P.D.; SCHIMLECK, L.R.; PETER, G.F.; DANIELS, R.F.; CLARK, A. 2005a: Nondestructive estimation of *Pinus taeda* L. wood properties for samples from a wide range of sites in Georgia. *Canadian Journal of Forest Research 35*: 85-92.

______2005b: Nondestructive estimation of *Pinus taeda* L. tracheid morphological characteristics for samples from a wide range of sites in Georgia. *Wood Science and Technology 39*: 529-545.

______2006: Nondestructive estimation of wood chemical composition of sections of radial wood strips by near infrared spectroscopy. *Wood Science and Technology 40*: 709-720.

JONES, P.D.; SCHIMLECK, L.R.; SO, C.-L.; CLARK, A.; DANIELS, R.F. 2007a: High resolution scanning of radial strips cut from increment cores by near infrared spectroscopy. *IAWA Journal* (accepted).

JONES, P.D.; SCHIMLECK, L.R.; DANIELS, R.F.; CLARK, A.; PURNELL, R.C. 2007b: Comparison of *Pinus taeda* L. Whole-tree wood property calibrations using diffuse reflectance near infrared spectra obtained using a variety of sampling options. *Wood and Fiber Science* (submitted).

KENNARD, R.W.; STONE, L. A. 1969: Computer aided design of experiments. *Technometrics 11*: 137-148.

KUBE, P.D.; RAYMOND C.A. 2002: Prediction of whole tree basic density and pulp yield using wood core samples in *Eucalyptus nitens*. *Appita Journal 55*: 43-48

MICHELL, A.J. 1995: Pulpwood quality estimation by near-infrared spectroscopic measurements on eucalypt woods. *Appita Journal 48*: 425-428.

MICHELL, A.J.; SCHIMLECK, L.R. 1998: Developing a method for the rapid assessment of pulp yield of plantation eucalypt trees beyond the year 2000. *Appita Journal 51*: 428-432.

MURRAY, I. 2004: Scattered information: philosophy and practice of near infrared spectroscopy. *In* Near Infrared Spectroscopy: Proceedings of the 11th International Conference, Córdoba, Spain. Edited by A.M.C. Davies; A. Garrido-Varo. NIR Publications, Chichester. pp. 1-12.

NORRIS, K. H. 1989: Introduction. *In* Near Infrared Reflectance Spectroscopy (NIRS): Analysis of Forage Quality. United States Department of Agriculture, Agriculture Handbook No. **643**. Edited by G.C. Marten; J.S. Shenk; F.E. Barton II. Govt. Pr., Washington, D.C. pp. 6.

OLSSON R.J.O.; TOMANI P.; KARLSSON K.; JOSEFFSON T.; SJÖBERG K.; BJÖRKLUND C. 1995: Multivariate characterisation of chemical and physical descriptors in pulp using NIRR. *Tappi Journal 78(10)*: 158-166.

OSBORNE, B.G.; FEARN, T.; HINDLE, P.H. 1993: "Practical NIR Spectroscopy with Applications in Food and Beverage Analysis", 2nd Edition. Longman Scientific and Technical, Singapore. 227 p

PAUL C.; PFITZNER, C. 2004: Analytical use of NIR diode array spectrometers on forage harvesters. *In* Near Infrared Spectroscopy: Proceedings of the 11th International Conference, Córdoba, Spain. Edited by A.M.C. Davies; A. Garrido-Varo. NIR Publications, Chichester. pp. 333-338.

PÉREZ-MARÍN, D.; GARRIDO-VARO, A.; GUERRERO, J.E. 2005: Implementation of LOCAL algorithm with near-infrared spectroscopy for compliance assurance in compound feedingstuffs. *Applied Spectroscopy 59*: 69-77.

POKE, F.S.; RAYMOND, C.A. 2006: Predicting extractives, lignin, and cellulose contents using near infrared spectroscopy on solid wood in *Eucalyptus globulus*. *Journal of Wood Chemistry and Technology 26*: 187-199.

POKE, F.S.; POTTS, B.M.; VAILLANCOURT, R.E.; RAYMOND, C.A. 2006: Genetic parameters for lignin, extractives and decay in *Eucalyptus globulus*. *Annals of Forest Science 63*: 813-821.

RAYMOND, C.A.; SCHIMLECK, L.R.; MUNERI, A.; MICHELL, A.J. 2001: Non destructive sampling of *Eucalyptus globulus* and *E. nitens* for wood properties III. Predicted pulp yield using near infrared reflectance analysis. *Wood Science and Technology 35*: 203-215.

______2001: Genetic parameters and genotype-by-environment interactions for pulp yield and pulp productivity in *Eucalyptus globulus* predicted using near infrared reflectance analysis. *Forest Genetics 8*: 213-224.

RAYMOND, C.A. 2002: Genetics of *Eucalyptus* wood properties. *Annals of Forest Science 59*: 525-531.

RAYMOND, C.A.; SCHIMLECK, L.R. 2002: Development of near infrared reflectance analysis calibrations for estimating genetic parameters for cellulose content in *Eucalyptus globulus*. *Canadian Journal of Forest Research 32*: 170-176.

SCHIMLECK, L.R.; RAYMOND, C.A.; BEADLE, C.L.; DOWNES, G.M.; KUBE, P.D.; FRENCH, J. 2000: Applications of NIR spectroscopy to forest research. *Appita Journal 53*: 458-464.

SCHIMLECK, L.R.; EVANS, R.; ILIC, J. 2001: Application of near infrared spectroscopy to a diverse range of species demonstrating wide density and stiffness variation. *IAWA Journal 22*: 415-429.

SCHIMLECK, L.R.; EVANS, R. 2002a: Estimation of wood stiffness of increment cores by near infrared spectroscopy: the development and application of calibrations based on selected cores. *IAWA Journal 23*: 217-224.

______2002b: Estimation of microfibril angle of increment cores by near infrared spectroscopy. *IAWA Journal 23*: 225-234.

______2003: Estimation of air-dry density of increment cores by near infrared spectroscopy. *Appita Journal 56*: 312-317.

______2004: Estimation of *P. radiata* D. Don tracheid morphological characteristics by near infrared spectroscopy. *Holzforschung 58*: 66-73.

SCHIMLECK, L.R.; WORKMAN, J.J., Jr. 2004: Analysis of timber and paper. *In* Near-infrared Spectroscopy in Agriculture, A Tri-Societies Monograph. Edited by C. Roberts; J.J. Workman; J. Reeves, American Society of Agronomy, Crop Science Society of America and Soil Science Society of America, Publishers, Madison, Wisconsin, 635-646.

SCHIMLECK, L.R.; JONES, P.D.; PETER, G.F.; DANIELS, R.F.; CLARK, A. 2004a: Nondestructive estimation of tracheid length from sections of radial wood strips by near infrared spectroscopy. *Holzforschung 58*: 375-381.

SCHIMLECK, L.R.; KUBE, P.D.; RAYMOND, C.A. 2004b: Genetic improvement of kraft pulp yield in *Eucalyptus nitens* using cellulose content determined by near infrared spectroscopy. *Canadian Journal of Forest Research 34*: 2363-2370.

SCHIMLECK, L.R.; KUBE, P.D.; RAYMOND, C.A.; MICHELL, A.J.; FRENCH, J. 2005a: Estimation of whole-tree kraft pulp yield of *Eucalyptus nitens* using near infrared spectra collected from increment cores. *Canadian Journal of Forest Research 35*: 2797-2805.

SCHIMLECK, L. R.; PAYNE, P.; WEARNE, R. H. 2005b: Determination of important pulp properties of hybrid poplar by near infrared spectroscopy. *Wood and Fiber Science 37*: 462-471.

SCHIMLECK, L.R.; REZENDE, G.D.S.P.; DEMUNER, B.J.; DOWNES, G.M. 2006a: Estimation of whole-tree wood quality traits using near infrared spectra collected from increment cores. *Appita Journal 59*: 231-236.

SCHIMLECK, L.R.; KUBE, P.D.; RAYMOND, C.A.; MICHELL, A.J.; FRENCH, J. 2006b: Extending near infrared reflectance (NIR) pulp yield calibrations to new sites and species. *Journal of Wood Chemistry and Technology 26*: 299-311.

SCHIMLECK, L.R.; SUSSENBACH, E.; LEAF, G.; JONES, P.D.; HUANG, C.L. 2007a: Microfibril angle prediction of *Pinus taeda* L. wood samples based on tangential face NIR spectra. *IAWA Journal 28*: 1-12.

SCHIMLECK, L.R.; TYSON, J.A.; JONES, P.D.; PETER, G.F.; DANIELS, R.F.; CLARK, A. 2007b: *Pinus taeda* L. wood property calibrations based on variable numbers of NIR spectra per core and cores per plantation. *Journal of Near Infrared Spectroscopy* (submitted).

SCHULTZ, T.P.; BURNS, D.A. 1990: Rapid secondary analysis of lignocellulose: comparison of near infrared (NIR) and fourier transform infrared (FTIR). *Tappi Journal 73*: 209-212.

SHENK, J.S.; WORKMAN, J.J., JR; WESTERHAUS, M.O. 1992: Application of NIR spectroscopy to agricultural products. *In* Handbook of Near-Infrared Analysis. Edited by D.A. Burns; E.W. Ciurczak. Marcel Dekker Inc., New York. pp. 385-386.

SHENK, J.S.; WESTERHAUS, M.O.; BERZAGHI, P. 1997: Investigation of a LOCAL calibration procedure for near infrared instruments. *Journal of Near Infrared Spectroscopy 5*: 223-232.

SINNAEVE, G.; DARDENNE, P.; AGNEESSENS, R. 1994: Global or local? A choice for NIR calibrations in analyses of forage quality. *Journal of Near Infrared Spectroscopy 2*: 163-175.

SINNAEVE, G.; HERMAN, J.L.; BAETEN, V.; SADAOUI, Y.; FRANKINET, M.; DARDENNE, P. 2004: Quality assessment of wheat and forage using diode array NIR instrument on the harvester. *In* Near Infrared Spectroscopy: Proceedings of the 11th International Conference, Córdoba, Spain. Edited by A.M.C. Davies; A. Garrido-Varo. NIR Publications, Chichester. pp. 319-325.

SNEE, R.D. 1977: Validation of regression models: methods and examples. *Technometrics 19*: 415-428.

SO, C.-L.; VIA, B.K.; GROOM, L.H.; SCHIMLECK, L.R.; SHUPE, T.F.; KELLEY, S.S.; RIALS, T.G. 2004: Near Infrared (NIR) Spectroscopy in the Forest Products Industry. *Forest Products Journal 54(3)*: 8-18.

SYKES, R.W.; ISIK, F.; LI, B.; KADLA, J.; CHANG, H.-M. 2003: Genetic variation of juvenile wood properties in a loblolly pine progeny test. *Tappi Journal 2(12)*: 3-8.

SYKES, R.W.; LI, B.; HODGE, G.; GOLDFARB, B.; KADLA, J.; CHANG, H.-M. 2005: Prediction of loblolly pine wood properties using transmittance near-infrared spectroscopy. *Canadian Journal of Forest Research 35*: 2423-2431.

TAPPI. 2007: NIR Brightness/Kappa Analyzer Being Developed by Paprican, ASD (3/20/2007), TAPPI Online Industry news, from http://www.tappi.org/s_tappi/doc.asp?CID=183&DID=554597.

TSUCHIKAWA, S. 2007: A review of recent near infrared research for wood and paper. *Applied Spectroscopy Reviews 42*: 43-71.

TURNER, C.H.; BALODIS, V.; DEAN, G.H. 1983: Variability in pulping quality of *E. globulus* from Tasmanian provenances. *Appita Journal 36*: 371-376.

WALLIS, A.F.A.; WEARNE, R.H.; WRIGHT, P.J. 1996: Analytical characteristics of plantation eucalypt woods relating to Kraft pulp yields. *Appita Journal 49*: 427-432.

WRIGHT, J.A.; BIRKETT, M.D.; GAMBINO, M.J.T. 1990: Prediction of pulp yield and cellulose content from wood samples using near-infrared reflectance spectroscopy. *Tappi Journal 73*: 164-166.

YEH, T.-F.; CHANG, H.-M.; KADLA, J.F. 2004: Rapid prediction of solid wood lignin content using transmittance near-infrared spectroscopy. *Journal of Agricultural and Food Chemistry 52*: 1435-1439.

______2005: Rapid prediction of wood chemical component variations using transmittance near-infrared spectroscopy. *Journal of Agricultural and Food Chemistry 53*: 3328-3332.

**Figure Headings**

FIG. 1-Relationship between measured pulp yield and NIR-estimated pulp yield for the Ensis pulp yield calibration.

FIG. 2-Relationships between measured pulp yield and NIR-predicted pulp yield based on whole-tree composite chip samples from Gog (a) predictions made using a Tasmania-wide pulp yield calibration and (b) predictions made using a Tasmania-wide pulp yield calibration after the addition of 5 samples from Gog. Note that the regression line has been plotted and that the thin broken line represents the line of equivalence in both figures.

FIG. 3-Co-efficients of determination ($R^2$) of calibrations for each trait developed using milled whole-tree chips, 0.65 m cores and 1.30 m cores.

**FIG. 1 (Ensis PY calibration)**

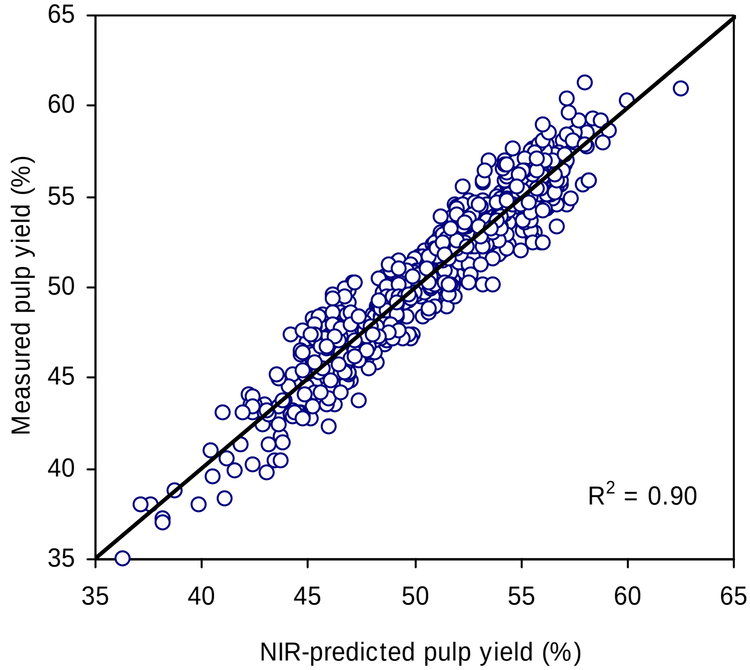


Figure 1 has been reproduced with the Permission of Dr. Geoff Downes, Ensis.

**FIG. 2 (Pulp yield predicted using a Tasmanian calibration)**

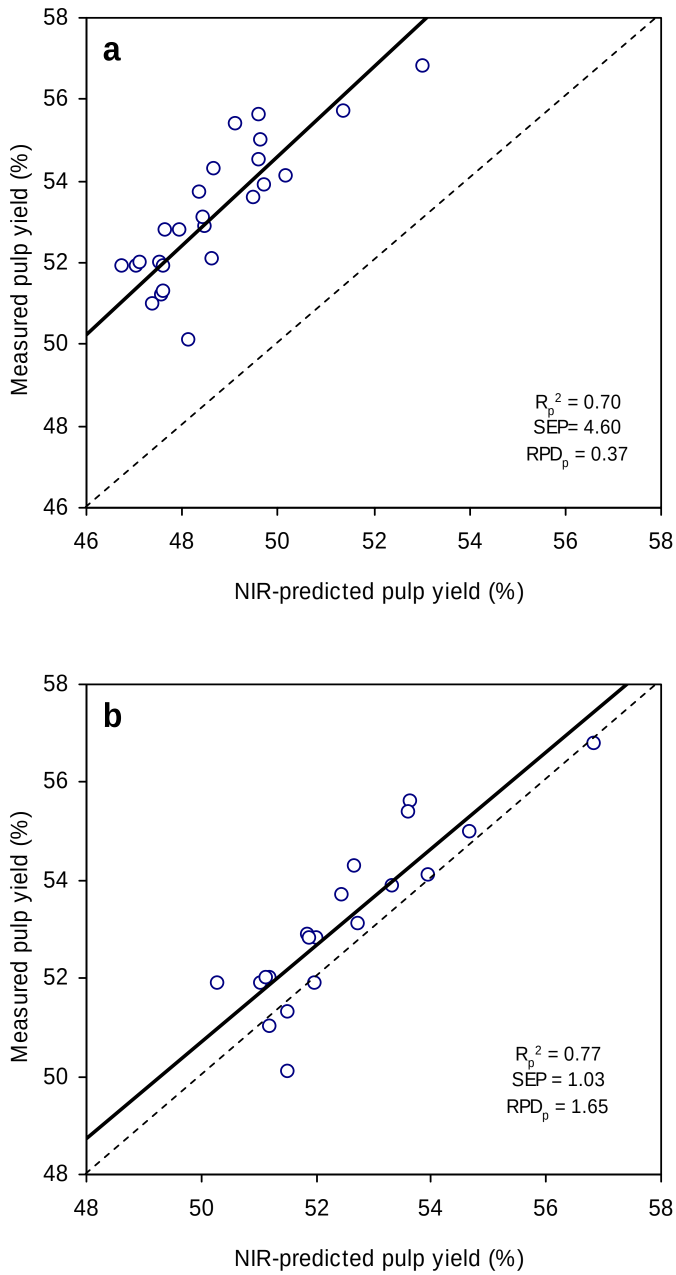


*Figure 2 originally appeared in SCHIMLECK, L.R.; KUBE, P.D.; RAYMOND, C.A.; MICHELL, A.J.; FRENCH, J. 2005: Estimation of whole-tree kraft pulp yield of *Eucalyptus nitens* using near infrared spectra collected from increment cores. *Canadian Journal of Forest Research 35*: 2797-2805, and has been reproduced with permission of the Canadian Journal of Forest Research.

**FIG. 3 (calibration $R^2$)**

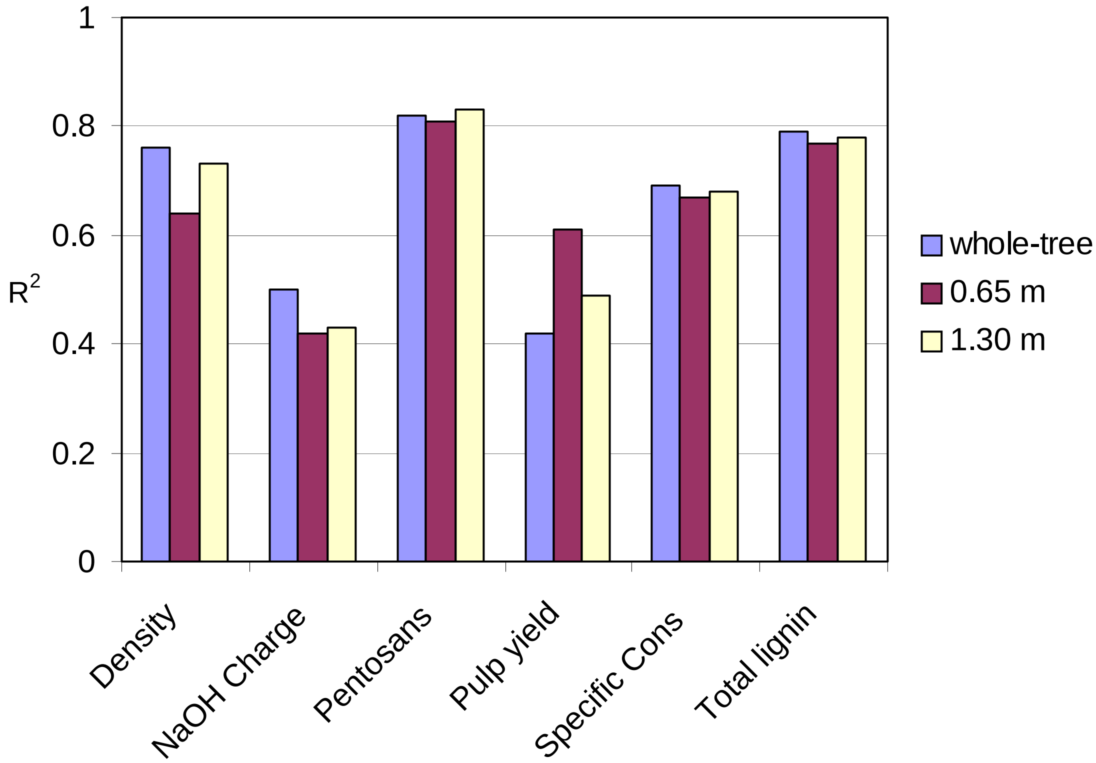


Figure 3 originally appeared in SCHIMLECK, L.R.; REZENDE, G.D.S.P.; DEMUNER, B.J.; DOWNES, G.M. 2006a: Estimation of whole-tree wood quality traits using near infrared spectra collected from increment cores. *Appita Journal 59*: 231-236, and has been reproduced with permission of the Appita Journal.

**Table headings**

TABLE 1-A summary of the infrared region of the electromagnetic spectrum.

TABLE 2-Advantages and disadvantages of each calibration option.

TABLE 3-Gain in cellulose content (%) with different NIR calibration methods using a forward selection strategy. Gain is expressed as a proportion of the gain that would be achieved by assessing every tree for cellulose content using wet chemistry methods.

TABLE 4-Gain in cellulose content (%) with different NIR calibration methods using a backward selection strategy. Gain is expressed as a proportion of the gain that would be achieved by assessing every tree for cellulose content using wet chemistry methods.

**TABLE 1 (Infrared region of the NIR spectrum)**

| Region | Characteristic transitions | Wavelength range (nm) | Wavenumber range ($cm^{-1}$) |
|---|---|---|---|
| Near-infrared (NIR) | Overtones, combinations | 700 - 2500 | 14300 - 4000 |
| Middle infrared (MIR) | Fundamental vibrations | $2500 - 5\times10^4$ | 4000 - 200 |
| Far infrared | Rotations | $5\times10^4 - 10^6$ | 200 - 10 |

**TABLE 2 (Advantages / disadvantages)**

| Option | Advantages | Disadvantages |
|---|---|---|
| Existing calibration | * Minimal cost as no additional pulping is required<br>* Rankings generally OK<br>* Able to identify majority of top trees | * Yield may be under or over estimated |
| Enhanced calibration | * Estimated yield closer to true yield<br>* Improved ranking and identification of top trees | * Some additional pulping required (minimal) |
| Site specific calibration | * Most accurate estimate of yield<br>* Most accurate rankings | * Maximal cost as all trees must be pulp tested |

Table 2 originally appeared in SCHIMLECK, L.R.; KUBE, P.D.; RAYMOND, C.A.; MICHELL, A.J.; FRENCH, J. 2005: Estimation of whole-tree kraft pulp yield of *Eucalyptus nitens* using near infrared spectra collected from increment cores. *Canadian Journal of Forest Research 35*: 2797-2805, and has been reproduced with permission of the Canadian Journal of Forest Research.

**TABLE 3 (Genetic gains – forward selection)**

| Type of calibration model | Selection of samples for calibration model | | | |
|---|---|---|---|---|
| | 20/site | 40/site | 60/site | WinISI [1] |
| Local site model | 73% | 83% | 88% | 89% |
| Off-site model 1 (Dial calibration) | 61% | 86% | 87% | 82% |
| Off-site model 2 (Gog calibration) | 64% | 73% | 70% | 83% |
| Off-site model 3 (Kamona calibration) | 80% | 90% | 91% | 91% |

1 The number of samples used by WinISI was 37 at Dial, 59 at Gog and 45 at Kamona.

Table 3 originally appeared in SCHIMLECK, L.R.; KUBE, P.D.; RAYMOND, C.A. 2004: Genetic improvement of kraft pulp yield in *Eucalyptus nitens* using cellulose content determined by near infrared spectroscopy. *Canadian Journal of Forest Research 34*: 2363-2370, and has been reproduced with permission of the Canadian Journal of Forest Research.

**TABLE 4 (Genetic gains – backward selection)**

| Type of calibration model | Selection of samples for calibration model | | | |
|---|---|---|---|---|
| | 20/site | 40/site | 60/site | WinISI [1] |
| Local site model | 93% | 94% | 87% | 100% |
| Off-site model 1 (Dial calibration) | 84% | 95% | 81% | 100% |
| Off-site model 2 (Gog calibration) | 83% | 97% | 79% | 100% |
| Off-site model 3 (Kamona calibration) | 90% | 91% | 89% | 99% |

1 The number of samples used by WinISI was 37 at Dial, 59 at Gog and 45 at Kamona.

Table 4 originally appeared in SCHIMLECK, L.R.; KUBE, P.D.; RAYMOND, C.A. 2004: Genetic improvement of kraft pulp yield in *Eucalyptus nitens* using cellulose content determined by near infrared spectroscopy. *Canadian Journal of Forest Research 34*: 2363-2370, and has been reproduced with permission of the Canadian Journal of Forest Research.