Integrating plantation health surveillance and wood resource inventory systems using remote sensing

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Summary

Commercial softwood growers in Australia are keen to improve the efficiency and precision of resource inventory underpinning their timber supply commitments.

At the same time, they also need to implement forest health strategies which contribute to their environmental management systems and certification process. For example, the Australian Forestry Standard requires forest managers to identify, assess and prioritise any potential damage agents that may impact on forest ecosystem health and vitality. These health programs, however, are often run parallel with, and independently of, resource inventory programs. While most large growers maintain a health surveillance program, their capacity to quantify the impact of damaging agents on stand productivity and wood volume is often limited. Quantification of productivity losses due to biotic and abiotic agents would significantly improve decisions associated with resource scheduling and allocation of resources for pest control and stand amelioration.

This paper discusses how remote sensing technologies can provide spatially-explicit data that permit the integration of plantation inventory and health assessments. The emerging diversity of sensor capabilities on both satellite and airborne platforms enables the development of hierarchical monitoring programs that can be customised for individual regions. For example, the coarse-scale sensor MODIS can provide very cheap coverage suitable for frequent temporal condition monitoring (thus identifying areas requiring more detailed attention in a timely manner), whereas the new generation of high-resolution sensors are facilitating a shift from manually mapped stand polygons (e.g. those from aerial sketchmapping and aerial photographic interpretation — API) to pixel and object-based digital analysis techniques suitable for both crown and stand-level inventory and canopy health assessment on a continuous, broad-scale basis. The application of these new technologies and associated spatial analyses permits the integration of plantation inventory and health assessment, thus providing forest managers with a holistic and cost-effective approach to timber production.

Keywords: plantations; health; surveillance; forest inventories; remote sensing; *Pinus radiata*

Issues with current management practices

Wood resource assessment

All timber plantation companies have in place an inventory framework with supporting documentation (e.g. inventory field manuals). Typically, strategic and pre-harvest inventory programs require assessment at key points in the rotation which can include survival counts after establishment (Year 1), at canopy closure (near Year 10), post first thinning (T1), post second thinning (T2) and just prior to final harvest. Decision support systems often depend on tree and stand attributes obtained from field inventory plots. Inventory programs are implemented by either in-house or contract crews who locate the plots and record a mix of measured and visually estimated attributes on either hardcopy proformas or more commonly electronic data loggers. Plot-based sampling intensity is often low (e.g. 1 plot per 4 ha) and this can influence how representative the data may be of the targeted stratum, particularly as the spatial variation within the planning unit can vary with site factors, past silviculture and health status.

Forest health surveillance

Many plantation growers also implement forest health strategies which form part of their environmental management and certification systems. These health programs, however, are often run parallel with, and independently of, resource inventory programs. While most growers maintain a health surveillance program, their capacity to quantify the impact of damaging agents on stand productivity and wood volume is often limited. In fact, very few studies in Australia have quantified the impact of biological agents on radiata plantation growth. May and Carlyle (2003) examined the effect of partial defoliation associated with *Essigella californica* on the growth of mid-rotation *Pinus radiata* in the Green Triangle. For 1999–2000, they calculated productivity losses ranging from 0% to 12%, with a cumulative growth reduction from March 1999 until September 2001 amounting to 12.8% (3.0 m^3 ha^{-1}). These levels of defoliation are routinely estimated in other radiata regions of Australia. For example, in the Hume region of NSW during 2006, about 36% of the estate was estimated to be affected by *Essigella* defoliation (A. Carnegie; NSW Dept. Primary Industries, Forest Health

Surveillance Unit; *pers. comm.*, March 2007). More recently, significant tree mortality has been observed in drought-stressed stands which have also succumbed to attack by the bark beetle, *Ips grandicollis*. Quantification of actual tree numbers killed by *I. grandicollis* has commenced in a research study located in the Green Hills State Forest (S.F.), near Batlow, the Hume Region of NSW, using remote sensing technologies (Fig. 1; http://www.crcforestry.com.au/RP1.htm).

The incorporation of canopy or crown damage symptoms in empirical and process-based volume prediction models has commenced (e.g. the development of a Forest Health module for CABALA, L. Pinkard, CSIRO, Hobart, *pers. comm.*, March 2008). Once this is achieved, routine and accurate quantification of stand volume losses due to biotic and abiotic agents will significantly improve decisions associated with wood supply estimation and allocation of resources for pest control and stand amelioration.

While some softwood growers in Australia rely entirely on ground-based surveillance and plot monitoring programs for assessing plantation health, others combine aerial and ground assessments. Most state-based forestry agencies have aerial reconnaissance as an integral component of their forest health programs in order to stratify and prioritise their ground-based assessments (Stone and Coops 2004; Carnegie *et al.* 2008).

The most common approach to aerial surveillance of plantation health in Australia involves aerial sketchmapping where a forest health expert flies over the estate and visually estimates the location of the affected stand, and records the damaged canopy extent, the tree incidence (i.e. proportion of affected trees), the severity of crown damage and the type of damage symptom (e.g. needle chlorosis, necrosis, dead tops, etc.) (e.g. McConnell *et al.* 2000; Carnegie *et al.* 2008; Phillips 2008; Wotherspoon 2008). This information is typically drawn directly onto hardcopy maps. More recently this information is being captured digitally using a stylus on a computer tablet incorporating a customised global positioning system (GPS) linked with geographic information system (GIS) software (e.g. Geolink software, USDA Forest Service, Johnson and Wittwer 2008). These systems can also import background images into the airborne tablet such as GIS vector files, aerial photographs and satellite imagery, which greatly assist survey navigation and increase the speed and accuracy of the aerial sketchmapping process. The real-time digitised information can later be downloaded into a geospatial database for further analyses. However, although this new technology can greatly improve efficiency, manual sketchmapping remains a highly subjective technique and the accuracy of results can vary significantly depending on the knowledge, experience and skill of the sketchmapper (Stone and Coops 2004).

The need for manual interpretation by a forest health expert, coupled with the associated high costs of aircraft-based surveys, means that forest health surveillance programs are relatively expensive and are usually conducted only on an annual basis, or after significant canopy health symptoms are noticed from the ground. In addition, the stratification used in annual health surveys is usually reliant on past experience and local knowledge rather than any objective quantification of current canopy condition. If surveys are undertaken only annually, the likelihood of early detection of any new disorders is reduced. Aerial sketched maps, even when digitised, cannot be easily statistically analysed due to the qualitative nature of the attributes collected, and hence the levels of uncertainty are rarely determined. However, samples of satellite or airborne imagery could be used to calibrate aerial sketchmapping and provide approximate levels of uncertainty associated with the visually estimated damage categories. Although aerial photography is currently used for a wide range of forest management practices, as a rule it is not routinely used for forest health assessment in Australia.

Integration benefits

Remote sensing has the potential to simultaneously collect digital information related to both health and stand structure within the same unit area (e.g. at the tree or stand level). Many growers acquire imagery on an annual basis for a wide range of forest activities (e.g. inventory assessment, boundary and road mapping, fire damage assessment, etc.). Combining as many forestry applications as possible can only increase the use and value of remotely sensed data, improving its cost effectiveness.

Key advantages in linking inventory and health assessment activities include:

- All remote sensing requires some ground-based validation. However, field plot surveys are expensive, major costs being associated with getting to and locating each plot. Assessing both damage symptoms and inventory attributes at the same time would improve sampling efficiencies and facilitate the integration of important health attributes in existing inventory software packages.
- The incorporation of health modifiers in existing resource modelling systems would provide a means of quantifying damage losses and potential impacts on yield scheduling and long-term wood flow.

Available remote sensing options

Numerous airborne instruments and satellite sensors with a wide range of capabilities now operate commercially in Australia. Passive optical sensors measure the amount of electromagnetic energy reflected and or emitted from ground-based surfaces and objects within a series of wavebands. The spectral resolution refers to the number, spacing and width of separate wavelength bands that a sensor records. The greater the number of discrete wavelength bands, the greater the potential to discriminate features with varying reflectance properties. The smaller the pixel size, the greater the chance that individual pixels will cover just single objects (e.g. single tree crowns).

Spectral information is a useful tool for canopy and tree health assessment. This is because spectral reflectance, in the range of about 0.45 μm to 2.5 μm, is influenced by the biophysical properties of vegetation including foliar biochemistry, internal and external leaf structure, the three-dimensional arrangement of the vegetation (e.g. canopy leaf area and spatial arrangement), and the presence of non-vegetative components (e.g. branches and underlying soils) (e.g. Baret *et al.* 2007; Blackburn 2007). Any damaging agent or process that directly alters these vegetative attributes can be quantified through analysis of reflectance data. In addition to the quantification of tree deaths, the two key

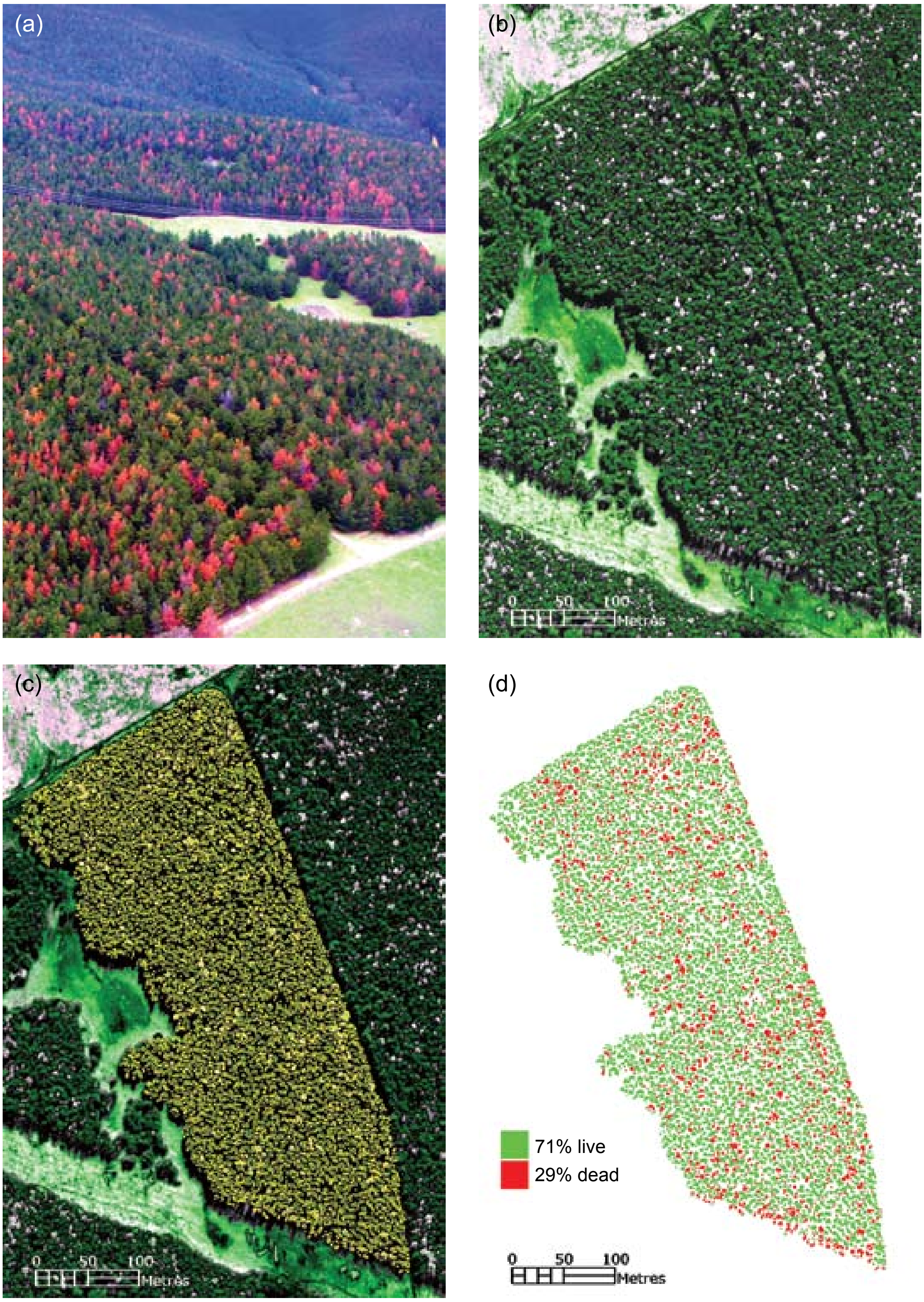

Figure 1. (a) An oblique aerial photograph of a 20-y-old, unthinned stand of *Pinus radiata* showing tree mortality associated with drought and *Ips grandicollis* (photo by A. Carnegie, NSW Department of Primary Industries, Forest Health Surveillance Unit); (b) A composite image of a digital photograph of the same area as (a) taken with a digital airborne Leica ADS40 camera; (c) An automated crown map overlayed on the composite image in (b); (d) Classification of live and dead trees using the image in (c).

canopy or crown damage symptoms assessed in ground-based assessments are foliar discolouration (in particular due to loss of chlorophyll) and defoliation (reduction in foliar biomass or effective leaf area index — LAI). Both these attributes have been successfully mapped and classified using remote spectral sensors (e.g. Bonneau *et al.* 1999; Hall *et al*. 2003; Moskal and Franklin 2004; Leckie *et al*. 2005).

Most spectral sensors are sensitive to different types of vegetation. This has advantages and disadvantages. On the one hand the capacity to map the presence of non-plantation vegetation (e.g. blackberries) can be advantageous, but on the other it is difficult to separate canopy health from understorey health and composition. The presence of weeds or understorey vegetation, however, generates the need to 'mask out' all vegetation components that are not of interest. This can be particularly difficult in unhealthy, defoliated stands where the understorey can dominate the reflectance signal or where a 'carpet' of necrotic or chlorotic abscised leaves or needles on the forest floor can influence the overall spectral signal.

The range and diversity of optical digital sensors (carried onboard either aircraft or satellites) is constantly expanding. It is difficult to predict the cost of individual products because they tend to be scale- and task-dependent, but larger projects are usually relatively cheaper per unit area than small discrete projects. Overall, fine-resolution data tend to be more expensive than coarse-resolution imagery, and there are usually trade-offs between spatial, spectral and temporal information.

MODIS

Images from the moderate-resolution imaging spectroradiometer (MODIS) satellite sensor are acquired daily at a spatial resolution of between 250 m and 1 km, depending on wavelength. Moreover, MODIS data are available free of charge, and thus offer a low-cost option for frequent monitoring of forest plantations at broad scales. For these reasons MODIS can be expected to monitor changes related to growth and health of forested areas. An efficient regional-scale change monitoring approach may be one that considers a hierarchy of spatial scales from coarse to fine. In this strategy, coarse-scale analysis would be used as a 'first pass' filter to identify regions and the timing of major change activity. These areas would then be targeted for more detailed investigation using finer spatial resolution imagery or field surveys (Coppin *et al.* 2004).

The normalised difference vegetation index (NDVI), a normalised ratio of the near-infrared and red bands which is related to the amount of leaf area and photosynthetic capacity of the vegetation, is one of the standard products from MODIS. Past studies have demonstrated the potential of using NDVI to study forest disturbances (e.g. harvesting operations, defoliation, etc.) illustrating the value of using high temporal resolution for accurately detecting changes in forests (Jin and Sader 2005). Change captured by an NDVI time series of a *P. radiata* stand in Green Hills State Forest, NSW, is illustrated in Figure 2. It can be seen that the NDVI time-series contains a trend and seasonal information which is related to changes in forest growth and health. For example, an intensive drought period in 2003 and an increase in tree deaths due to *I. grandicollis* at the end of 2006 caused a clear decline in NDVI.

Hyperspectral sensors

Hyperspectral sensors are capable of dividing the electromagnetic spectrum into numerous narrow bands. For example, the airborne hyperspectral sensor, HyMap, can record up to 128 bands covering the 0.44–2.5 µm spectral region while the Hyperion sensor on board the EO-1 satellite has a spectral range of 0.4–2.5 µm in 220 bands. The availability of a large number of bands enables detailed analysis of vegetation spectral properties and therefore hyperspectral sensors are very sensitive to plant physiological stress and nutritional status of foliage.

Fine spatial resolution sensors

Traditionally, aerial photography has been the dominant form of fine-resolution imagery used in Australian forest management. Aerial photographic interpretation (API) provides the GIS framework for many other forest operations. API has been extensively used to manually digitise silvicultural treatment boundaries; roading; non-harvestable areas; topography and drainage, etc. Aerial photographs can also be scanned and digitised.

Airborne digital cameras that have either a frame array or a push-broom scanner are now operational in Australia and it is expected that these sensors will soon completely replace conventional aerial analogue film. The newest digital mapping cameras (e.g. Vexel UltraCamD and Leica ADS40) have high photogrammetric spatial accuracy, four multi-spectral bands (red, green, blue and near infrared), stereo 3D, and a highly automated processing capacity. These new cameras can be used to classify live and dead crowns in plantations, making them a powerful tool for forest health and inventory assessments (Fig. 1). Image analysis techniques are now being developed for digitised aerial photography including stem density, individual tree crown delineation and stand top height estimates (Zagalikis *et al.* 2005; Wijanarto and Osborn 2007). Importantly, these attributes can be used to derive wood volume estimates.

Another airborne sensor available in Australia is the digital multi-spectral imager (DMSI). While more expensive than digital camera imagery, it can be fitted with four narrow-band filters to target specific wavelengths that are known to be sensitive to specific canopy symptoms, including needle necrosis and chlorosis (Goodwin *et al.* 2005).

Several high-resolution multi-spectral satellites with a spatial resolution of a few meters or less are now commercially available. These include IKONOS II (0.82–1 m), Quickbird (0.61–0.72 m), ALOS (2.5 m panchromatic and 10 m multi-spectral) and SPOT5 (2.5 m panchromatic and 10 m multi-spectral). The Australian

Figure 2. A normalised difference vegetation index (NDVI) time-series derived from the MODIS satellite sensor between 2000 and 2007 of a *Pinus radiata* stand planted in 1987 and unthinned during the period of observation, in Green Hills S.F., Hume Region, NSW. The tick marks on the *x*-axis indicate 1 January in each year.

company GeoImage Pty Ltd (www.geoimage.com.au) can provide specific information related to the products available from these commercial satellites. The cost competitiveness of imagery acquired from these satellites compared to airborne cameras depends on the configuration and area of the plantations to be covered. Recently, the costs of acquisition from both types of platforms, airborne and satellite sensors, have significantly declined. Satellites, however, have some advantages over airborne instruments including a more stable viewing platform and predictable acquisition specifications (e.g. time of overpass and spatial resolution) for multi-temporal analyses.

Airborne laser scanners

Unlike passive optical remote sensors, airborne lasers such as lidar (an acronym for light detection and ranging) actively emit high-repetition, short-duration laser pulses at a target and measure the return reflection time to gauge target distance and bearing (Dubayah and Drake 2000). The simplest systems are laser rangefinders and total station surveying instruments used in field surveying. As active sensors, lidar systems are independent of natural sunlight and therefore can operate day or night, or under cloud cover (e.g. Patenaude *et al.* 2004). A major strength of lidar systems is the ability to directly measure the three-dimensional distribution of canopy components as well as sub-canopy topography and understorey vegetation. Total scene estimates of height, volume and biomass at the stand and tree scale have been demonstrated with high levels of accuracy (e.g. Roberts *et al.* 2005; Turner 2006; Donoghue *et al.* 2007; Popecsu 2007).

The presence of understorey may impede the ability of lidar to estimate tree height and ground elevation (Roberts *et al.* 2005). However, many weed species have seasonal leaf phenology and this can be used to minimise this effect. For example, if blackberries were an issue, then lidar acquisition during winter would reduce the influence of this understorey weed on tree crown assessment. Ground-based laser scanners are also developing rapidly, permitting precise measurement of multiple forest attributes including understorey structure (e.g. the ECHIDNA®, CSIRO). This information could be used to calibrate the synoptic lidar data as well as to provide accurate information on stem quality.

Lidar sensors are unequalled in their capacity to measure stand structure and in particular tree height, which means these sensors offer a powerful tool for wood resource assessment. The new generation of airborne laser scanner systems also incorporates synchronous multispectral or hyperspectral sensors which combine the structural detail of lidar with the spectral capacity to detect live and dead crowns. The data-fusion capabilities of these new systems may provide the breakthrough needed to cost-effectively merge future health and inventory programs.

Remote sensing analysis approaches

Remote sensing data are quantifiable, spatially accurate and fully compatible with commercial GIS software used by forest managers. The commercial availability of fine-resolution spatial imagery is generating a shift from the production and manipulation of visually interpreted polygons to the production and analysis of pixel and object-oriented image segmentation and classification techniques. A pixel is defined as a two-dimensional picture element that is the smallest non-divisible element of a digital image, whereas an image object (or polygon) is a relatively homogenous patch or segment.

Pixel-based analysis

Fine spatial resolution sensors such as airborne lidar, digital cameras and some satellites can generate enormous data sets which demand high processing capacity. Most image classifications techniques operate at the individual pixel level, and similarly classified pixels are later aggregated into larger groups. One approach for extracting both stand structure and canopy health variables is to use image texture analysis (e.g. Haralick 1979; Moskal and Franklin 2004; Kayitakire *et al.* 2006). This is particularly applicable where stand-scale attributes and not tree-scale measurements are the most appropriate approach. Although crown size, shape and uniformity can affect image texture, so too do tree spacing and understorey vegetation, and this must be accounted for when undertaking texture analysis (e.g. Moskal and Franklin 2004).

Other raster-based modelling techniques also exist, such as spectral analysis of radiometric fractions (e.g. Levesque and King 2003; Goodwin *et al.* 2005; Coops *et al.* 2006a). The optimal modelling solution can often be a combination of approaches, for example spectral indices, textural variables and spectral mixture analysis (Sims *et al.* 2007). Once classified and a digital map produced, this spatial information can be added to climatic and terrain-based spatial data sets to provide quantitative insight into the spatial behaviour of a forest health disorder (e.g. hazard rating maps) (Coops *et al.* 2006b; Stone and Haywood 2006).

Object-based analysis

Object-orientated image analysis involves grouping pixels into discrete units prior to extracting spectral properties for classification. Specialist software packages (e.g. Feature Analyst® (Visual Learning Systems Inc., Missoula, Montana) and Definiens Developer v.7® (formerly eCognition®), Definiens®, Germany) which enable automated object recognition and feature extraction from digital imagery are now available. This software could be used to automate the initial processing of high-resolution imagery through the identification and masking out of unwanted features, for example pasture, native vegetation and roads, before commencing analysis of just the plantation pixels.

A form of object-orientated image analysis that has received attention in forest applications has been individual tree crown mapping. Leckie *et al.* (2003) argue that because of the many combinations of stand attributes present in plantations, automated image analysis must operate at the individual crown level to ensure a robust and accurate stand inventory assessment. In particular, isolation of individual tree crowns allows for both individual tree inventory and crown health classification.

Algorithms now exist to semi-automatically delineate individual crowns from both spectral and lidar fine resolution imagery to extract individual crown spectral signatures for modelling and classifying against ground-based tree attributes (e.g. Culvenor 2002; Leckie *et al.* 2003; Gougeon and Leckie 2006; Turner

2006). Leckie *et al.* (2004) demonstrated that for crown health classification the spectral information extracted from the most sunlit portion of the crown is the most useful. Once individual crown attributes are classified, these small units can be regrouped and aggregated to provide stand and cohort statistics for each specific forest application.

For conifers, stem counts can be estimated through the detection of local reflectance maxima in optical imagery which correspond to tree tops (e.g. Hirschmugl *et al.* 2007). Tree crown dimensions can also be obtained by a combination of local maxima and crown edge-finding through a range of arithmetical techniques (e.g. Gougeon 1995; Culvenor 2002). The increasing radiometric range of new satellites and digital cameras will enhance the capacity of these algorithms to successfully detect the full extent of crowns (Pouliot *et al.* 2002). Lidar crown delineation has added advantages over reflectance-based delineations in that it is unaffected by sun angle and cloud cover, and operates on actual tree height data (Turner 2006).

Obviously fine spatial resolution is required when applying tree detection and delineation algorithms to very young trees compared to post-thinned mature trees (Pitt *et al.* 1997). Local case studies will be essential to optimise the specifications for any delineation algorithm. For example, detection filter kernel sizes will differ for different age classes and 'look up' tables matching filter sizes to age cohorts may be required to improve segmentation results. Also, delineation of unhealthy crowns is more difficult than that of healthy crowns, especially for suppressed trees or where intra-crown variation is high. The latter is likely to be more of an issue for broad-leaved trees than for relatively compact conifers. For optical sensors the influence of understorey vegetation, shadow and soil also increases as the severity of defoliation increases (Hall *et al.* 2003; Goodwin *et al.* 2005).

Individual crown delineation offers the capacity to undertake whole-crown spectral classification for chlorotic or necrotic properties and then to aggregate results to the desired management scale. For example, dead radiata trees can be successfully delineated, classified and quantified using fine-resolution digital camera imagery (Fig. 1). By examining the relationships between the stand volume-related variables of stem density and tree height and the crown damage symptoms, the potential impact of the damaging process can be calculated (Leckie *et al.* 2005; Coops *et al.* 2006c). Spatial modelling techniques can also be used to identify the site and stand characteristics associated with a higher likelihood of damage from specific damaging agents (e.g. stand susceptibility ratings) (Coops *et al.* 2006b).

Traditionally, stand volume biometrics are based on stem diameter measurements from which allometric relationships to tree height can be derived (and vice versa) (e.g. Baker 1984). Several researchers, however, have advocated that remotely sensed estimates of LAI could become the cornerstone in future forest monitoring (e.g. Solberg *et al.* 2006; Baret 2007). Recently both canopy LAI and foliar chlorophyll content have been retrieved through the use of remotely sensed data and the inversion of canopy radiative transfer models (e.g. Fang *et al.* 2003). These mechanistic optical models are less sensitive to the daily conditions of acquisition (e.g. solar or sensor geometry, soil moisture, etc.) than the traditional spectral vegetation indices. They also have the potential to be directly coupled to stand growth process-based models (e.g. 3-PG, Rodriguez *et al.* 2002; CABALA, Battaglia *et al.* 2004). These are encouraging findings and the suitability of these models for the Australian plantation industry should be trialled.

Implementation impediments and opportunities

Facilities for processing and analysing imagery from airborne and satellite sensors are constantly improving. A major impediment to operational use of remotely acquired imagery, however, is the lack of operational procedures for handling, processing and analysing such spatial data. This places pressure on current GIS/API units and foresters to maintain access to training and education to keep up with these advances. In addition, high-resolution imagery generates enormous data sets that require improved data archival and processing capacity.

Sometimes the spatial resolution of the fine-resolution sensors is too detailed to match the spatial scale of current yield biometrics. Although numerous 'smoothing' algorithms are available, this is often viewed as suboptimal use of the available data. Full utilisation of this technology will require the generation of more spatially explicit definitions of site quality and associated yield tables.

There is continuing pressure to reduce costs associated with time spent assessing and monitoring plantations. A system that used a hierarchy of spatial resolution would optimise the efficiency and precision of any stratification process. That is, detailed surveys or plot assessments would be guided by reconnaissance-level information collected from cheaper, coarse-level imagery to refine and possibly reduce ground-based sampling intensity (Coops *et al.* 2006c). However, the acquisition of remotely sensed imagery will never replace the need for some ground-based assessment. While imagery acquired from multispectral sensors (about seven bands or less) may be used to accurately map classes of canopy damage, it will always have a limited capacity to identify the actual damaging agent or process. There will be a continuing requirement for forest health diagnosticians. Similarly, the synoptic perspective of the imagery will limit its capacity to detect suppressed trees and to measure stem quality directly. Log product yield predictions will still require some ground-based stem quality estimates. The capacity for crown-scale classification, however, will lead to improved efficiencies and precision of inventory plot design, possibly operating at an individual-tree level. The field location of individual trees will of course require very accurate geo-registration techniques including the use of differential GPS instruments.

Current GIS information is typically derived from API and LANDSAT imagery. This includes the land cover and digital elevation model (DEM) terrain information that underpins environmental management spatial data. Lidar produces significantly more accurate DEMs at higher resolution than those available commercially. These accurate DEMs enable the correction or optimisation of road networks, correcting API-derived drainage networks and identifying slope exclusions (Turner 2006).

Estimates of stocking and basal areas of entire planning units would significantly improve estimation of the uniformity of the planning unit, selection of appropriate yield tables and adherence to thinning prescriptions. Sampling errors derived from the estimates of basal area based on assessment of all (or most) of the trees in a planning unit would be significantly less than those based on a much smaller, plot-based assessment. This would not only improve inventory precision but also has important implications related to carbon sequestration estimates. The so-called '70% rule' associated with the NSW Greenhouse Gas Abatement Scheme provides a strong incentive to improve the accuracy of estimates of carbon stock change (http://www.greenhousegas.nsw.gov.au).

Currently most state forest agencies are trialling a range of remotely sensed data. The most cost-effective missions are the larger-scale projects (> 100 000 ha), and these often arise from cost-sharing collaboration on multi-functional projects involving neighbouring forest management companies or agencies, for example, the acquisition of lidar for both water catchment management and forest production objectives.

At present, most plantation growers would not be convinced that the routine acquisition of fine-resolution imagery is a cost-effective alternative to traditional approaches to plantation resource and health assessment. Case studies are therefore needed to compare the costs and benefits of these new systems against traditional planning, inventory survey and health surveillance methods.

Conclusion

To be widely accepted by the plantation sector in Australia, remotely sensed products need to be cost-competitive with current assessment methods, provide equivalent or improved estimates of tree or stand inventory and health parameters, and be available for integration with existing planning and resource assessment programs in a timely manner. Recent advances in the capacity and range of airborne and satellite sensors, and improved image processing and analytical software systems, in parallel with reducing costs of acquisition, mean achieving the first two requirements is a realistic possibility. A conceptual model illustrating how remotely acquired data could be integrated with existing plantation management systems is presented in Figure 3. A means of deriving standard inventory and canopy health attributes from remotely acquired data for input to existing plantation information management systems software is shown in this figure. Although this is achievable, the challenge for companies is to support the research required to customise the numerical relationships linking these processes.

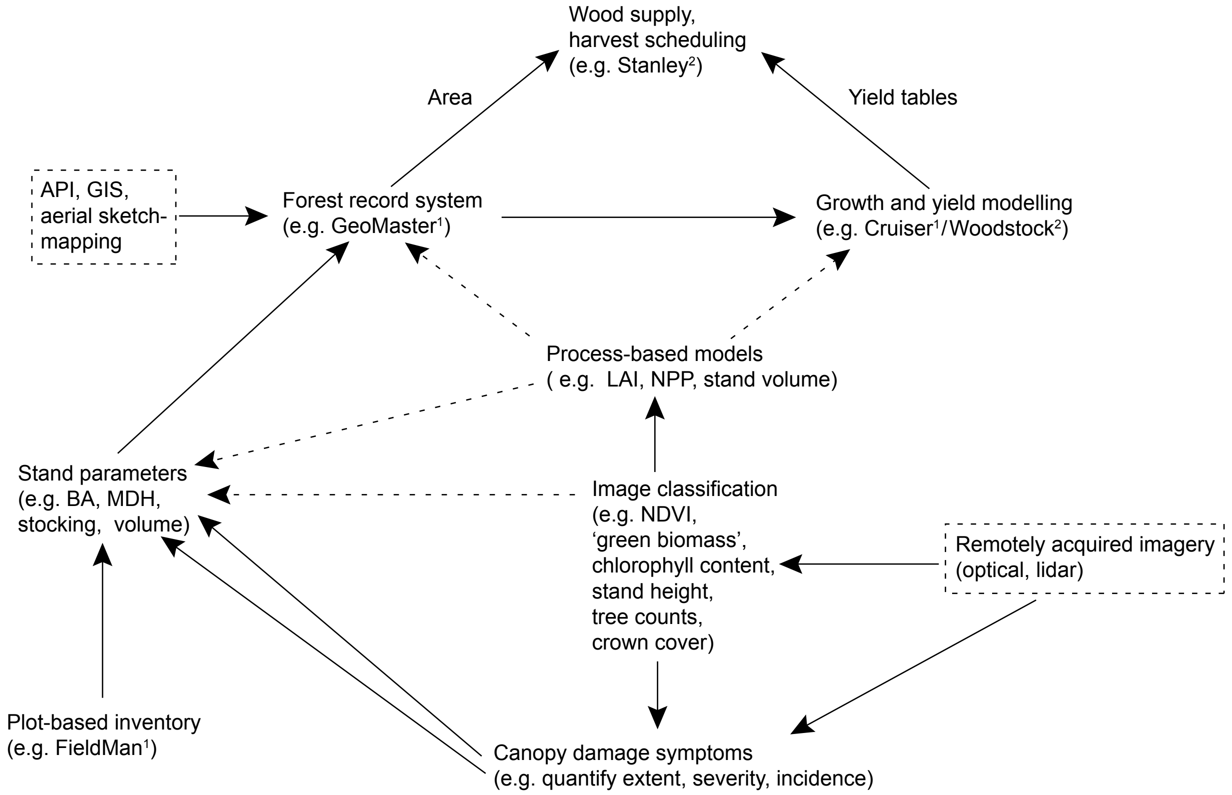

Figure 3. A conceptual model illustrating how remotely acquired spatial data, including canopy health imagery, could be integrated in existing softwood plantation information management systems. The superscripts refer to commercial software packages produced by ^{1} = Atlas Technology (SCION, New Zealand) and ^{2} = Remsoft Inc. (Canada). Dashed boxes represent sources of data. Dashed arrows indicate that further research and development is required.

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