Chapter 1

High resolution remote sensing for native vegetation assessment and monitoring: an impact assessment approach

1 INTRODUCTION

1.1 Native vegetation assessment and monitoring

1.1.1 Background

Native vegetation assessment and monitoring is a fundamental requirement for a broad range of ecological and environmental studies. Initially, description of the vegetation – its structural and floristic characteristics – is required for inventory (e.g. Hnatiuk et al. 2009; Specht & Specht 2002). The vegetation inventory may be used for biodiversity assessment (Noss 1990, 1999), where either the species list (floristics) is a direct expression of biodiversity, or the vegetation characteristics are used as surrogates for a broader assessment (Margules et al. 2002). For example, the structural complexity and high abundance of tree hollows and logs in old growth forest provides a diverse range of habitat not present in immature or even-aged stands with similar species composition (Cork & Catling 1996; McElhinny et al. 2006). Vegetation studies are critical for fire risk assessment (Mutlu et al. 2008; NSW Rural Fire Service 2009) and fire plays a critical role in shaping vegetation floristics and structure (Clarke et al. 2005; Keith et al. 2007; Spencer & Baxter 2006). Vegetation studies are required for fields as diverse as resource management (Keith & Simpson 2008), pharmacology (Rates 2001) and ecosystems services (Fiedler et al. 2008).

Scientific vegetation assessment can focus on collection of individual plants (e.g. Botanic Gardens Trust 2009), although a more rigorous approach embodies the site concept where the range of species and their growth form is recorded in a systematic fashion (ESCAVI 2003; Hnatiuk et al. 2009). The site data may in turn be extrapolated to a larger area defined by traversing or air-photo interpretation (Gibbons et al. 2008a; Gibbons et al. 2009). Landscape-based approaches embody complementary information from multiple sites or vegetation patches, allowing both a broader and dynamic biodiversity assessment (Margules & Pressey 2000).

This thesis takes a remote sensing approach to native vegetation assessment, and focuses on mapping and structural assessment within a specific impact assessment framework, to be described in following sections. Key information requirements are baseline methods for monitoring the health of upland swamps within scrubby eucalyptus woodlands, as well as assessment of forest-woodland structural variation in a landscape context.

1.1.2 Remote sensing

While traditional, site-based vegetation surveys are critical to assessment and monitoring, they are limited by logistical concerns of accessibility and cost, as well as the inherent inability to assess variability beyond the site but within the vegetation patch the site purports to represent. A recent study (Gorrod & Keith 2009) has also shown that observer error is a critical factor in site assessment of vegetation structural attributes, indicating that other forms of quantitative or qualitative assessment are necessary. Remote sensing, defined as ". . . the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation" (Lillesand et al. 2007) has a long history of contribution to vegetation assessment, as it provides the means to extend the field study by mapping the boundary of contiguous vegetation, as well as allowing some quantification of variation within the defined area. Various forms of remotely-sensed imagery are available for vegetation mapping, from analogue vertical aerial photography, borne of military reconnaissance from WWI onwards (Lillesand et al. 2007) to digital satellite-based systems. Digital systems, in particular, are amenable to various forms of computer-based manipulation that may enhance the image's interpretability for a particular purpose (Canada Centre for Remote Sensing 2009; Jensen 2005). Four key features make remote sensing of vital importance to vegetation assessment:

1. Imagery can be repeatedly captured under similar, well defined conditions over a study area so that monitoring can be undertaken in a controlled manner, with imagery often accessed through publicly-held archives (Geoscience Australia 2009; National Library of Australia 2009; USGS).
2. Many digital sensors record spectral response from the near infrared (NIR: c. 700 nm – 900 nm), as well as visible light, encompassing the high foliar NIR reflectance and visible light absorption characteristics, thus enabling greater distinction between vegetation and other landcover types, such as soil, water and built environments (Datt 1998; Jensen 2005; Lillesand et al. 2007).
3. A wide variety of imagery is available, with different formats, resolution, extent, radiometric and spectral characteristics, so that a judicious choice of imagery can be made to match a particular analytical objective (Kerr & Ostrovsky 2003; Phinn et al. 2003).

4. Finally, imagery enables a synoptic view of whole landscapes, enabling the multi-scale fusion of data from different sources or processing streams.

A number of multispectral or hyperspectral satellite systems have made key contributions to vegetation assessment and monitoring (Jensen 2005; Lillesand et al. 2007) and new imaging satellites are regularly launched (ASPRS 2009). A summary of commonly-used systems is given Table 1.

Table 1 Selected, commonly used satellite image systems. B = blue, G = green, R = red, NIR = near infrared, SWIR = short wave infrared, TIR = thermal infrared (Jensen 2007).

Satellite System		Spatial Resolution	Spectral Resolution (nm)
QuickBird	Multispectral	2.4 m	(B) 450 – 520 (G) 520 – 600 (R) 630 – 690 (NIR) 760 – 890
	Panchromatic	0.6 m	0.45 - 0.90
Ikonos	Multispectral	4 m	(B) 450 – 520 (G) 520 – 600 (R) 630 – 690 (NIR) 760 – 900
	Panchromatic	1 m	450 – 900
Spot 5	Multispectral	10 m	(G) 0.50 - 0.59 (R) 610 – 680 (NIR) 790 – 890
	Panchromatic	2.5 m	480 – 710
Landsat ETM	Bands 1, 2, 3, 4, 5, 7	30 m	(B) 450 – 520 (G) 520 – 600 (R) 630 – 690 (NIR) 760 – 900 (NIR) 1550 – 1750 (SWIR) 2080 – 2350
	Band 6	120 m	(TIR) 10400 – 12500
	Panchromatic	15 m	
MODIS	Bands 1 and 2 only shown	250 m	(R) 620 – 670 (NIR) 840 – 880

Landsat (USGS 2009), in particular, has supported a wide range of vegetation studies over its 30+ year history (Cohen & Goward 2004). Applications are as diverse as condition assessment (Wallace et al. 2006), forest inventory and landcover change (Department of Natural Resources and Water 2007) and topo-climatic landform classification (Burrough et al. 2001). A range of change detection techniques have been applied and assessed (Coppin et al. 2004; Lu et al. 2004), with anniversary or near-anniversary imaging dates are commonly chosen, as this reduces the effects of variables such as solar illumination angle and shadow length as well a seasonal effects such as phenology (Lunetta et al. 2004). Landsat ETM spatial resolution (c. 30 m) is appropriate for distinguishing vegetation masses such as deciduous versus evergreen forest, or to give some indication of abundance where a small number of species are present (Nagendra 2001; Wulder et al. 2004), but has been less successful in discriminating forest from woody regrowth (Lucas et al. 2006; Lunetta et al. 2004), or species in more vegetatively diverse environments (Tickle et al. 2006). Many Landsat vegetation monitoring applications are, as a consequence, geared towards mapping wholesale changes to standing vegetation, whether for timber harvesting (Linke et al. 2009; Lunetta et al. 2004) or clearing for agricultural purposes (Department of Natural Resources and Water 2007).

1.1.3 High spatial resolution imaging systems

Recent advances in remote sensing include the launch of commercial, high spatial resolution (c. 0.5 m – 4 m) imaging satellites (DigitalGlobe 2008; GeoEye 2009) that offer a fundamental shift in vegetation assessment capability. Taking an individual tree as the definitive vegetation feature, the capability shift is due to relative pixel size compared to the feature investigated. With Landsat, a single 30 m multispectral pixel encompasses many tree crowns (c. 5 m – 10 m diameter), whereas multiple 2 m – 4 m multispectral pixels can image a single crown with the current imaging systems, meaning that changes and ecological function at the level of forest individuals can be assessed.

Relative pixel size has long been recognised as a key component in image interpretation (Woodcock & Strahler 1987), particularly with respect to the local variance present in the scene. For example, a Landsat forest view will have low local variance, due to the homogenising effect of a single pixel over highlighted and shadowed crown components, whereas a 2 m multispectral GeoEye image, for example, will have high local variance, due to individual pixels imaging shadowed and highlighted crown areas. Consequently, forest texture becomes an important characteristic for vegetation assessment and monitoring with high-resolution systems. This change in resolution means that variation within what is traditionally regarded as a homogenous vegetation unit, such as a stand of trees on a hillslope, are assessable. For example, the ecological effects of tree mortality resulting in gap formation and closure (Bugmann 2001; Shugart 1984) can now be evaluated. The increased resolution also means that topographic controls on vegetation character and distribution (Stephenson 1998; Swanson et al. 1988) can be assessed at finer scale.

The advent of high-resolution imagery means problems arise with some traditional remote sensing techniques, so that adaptations or new techniques are required for image classification and change detection. Problems include the use of per-pixel classifiers, which typically rely on features of interest having relatively homogenous pixel values (Jensen 2005). Paradoxically, forest structure is often better classified with low-resolution imagery since the spectral signals that identify structure – soil, understorey, shadow and crown illumination – are integrated so that structurally-distinct forest patches present an homogenous response (Wulder et al. 2004). For high-resolution imagery, some measure of inter-pixel diversity, such as semivariance, is required for structural assessment (Levesque & King 2003), meaning that combined spatial and spectral classification methods are required. Another problem arises from the off-nadir image capture capability of commercial high-resolution imagery. Off-nadir imaging introduces parallax-based geometric distortions in the image due both to topographic relief as well horizontal layover where above-ground features such as trees and buildings are displaced on the image plane from their vertically-projected position on the ground (Radoux & Defourny 2007; Toutin 2004) (Figure 1). This places additional requirements on image rectification, and is particularly important when pixel-to-pixel matching is required for digital, multi-temporal data assessment (Toutin 2004; Wulder et al. 2008). The presence of horizontal layover, as well as high spatial frequency, high contrast artefacts such as shadows, effectively precludes traditional change detection approaches for vertical features such as buildings and trees (Im & Jensen 2005).

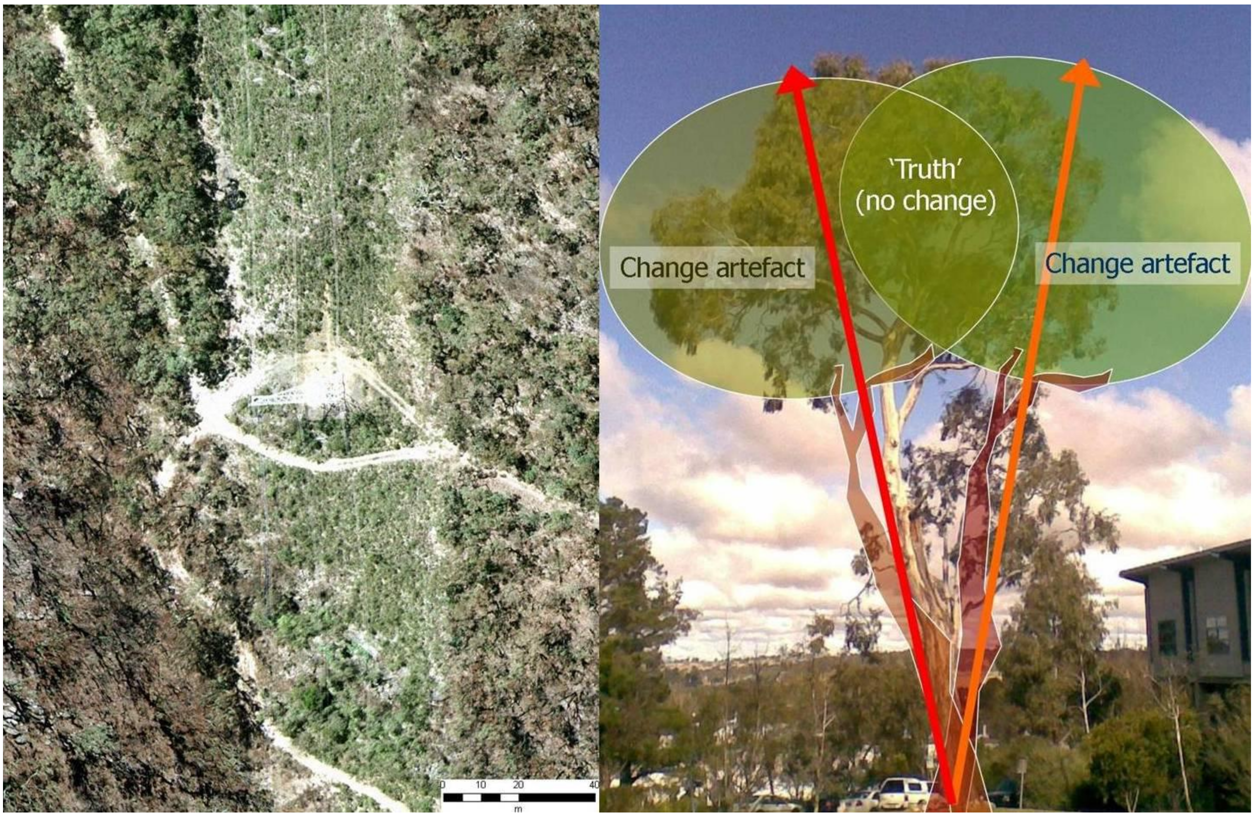

Figure 1 Horizontal layover

The effects of horizontal layover, due to off-nadir imaging, are seen in the apparent tilt of the pylon (left) and diagrammatically illustrated (right) showing the apparent position of a tree at two opposing look angles of c. 10°. Traditional change detection by image comparison would result in loss-gain artefacts where apparent position of the tree crown does not overlap. Imagery from Woronora Plateau study area (cf. Chapter 2).

High spatial resolution remote sensing has a diverse range of vegetation science applications, and a number of recent studies are summarised in Table 2. A variety of methods are used, most notably statistical comparison (correlation-regression) of field and remotely-sensed data, the use of image segmentation to isolate spatial features of interest, and the incorporation of image texture into classification routines in order to account for high spectral variance within features of interest.

Table 2 Recent studies using high spatial resolution imagery

Author	Title	Methods	Pro	Con
(Aguilar et al. 2007b)	Geometric accuracy assessment of QuickBird Basic imagery using different operational approaches	Tested various 2D and 3D ortho-correction techniques	Tests against large number (79) of check points	Could not adequately test 3D, DEM-based corrections with abundant ground control points
(Coops et al. 2006)	Assessment of QuickBird high spatial resolution imagery to detect red attack damage due to mountain pine beetle infestation	ANOVA for spectral bands, NDVI and RGI (red-green index) compared with affected areas	RGI best, R^2= 0.48, compare with Landsat red attack R^2 0.61	Method may have a high degree of specificity
(Dillabaugh & King 2008)	Riparian marshland composition and biomass mapping using Ikonos imagery	Maximum Likelihood and Neural Network classifiers. Biomass by regression	Classification 61-88% accuracy. Biomass R^2 0.61	Required very dense field sampling
(Gilmore et al. 2008)	Integrating multi-temporal spectral and structural information to map wetland vegetation in a lower Connecticut River tidal marsh	Data fusion ALS and QuickBird imagery. Field spectra. Image segmentation	Class accuracy 76-97%. NIR separates simple species clumps in marsh vegetation	Seasonal factors critical to classification
(Ivits et al. 2005)	Landscape structure assessment with image grey-values and object-based classification at three spatial resolutions	Image segmentation and PCA	Image grey values better explained variance between sampling plots better than segmented patch indices.	Relatively coarse comparison of old growth, forest-woodland and agricultural fields
(Johansen et al. 2007)	Application of high spatial resolution satellite imagery for riparian and forest ecosystem classification	Semi-variograms used to determine spatial scale for calculation of grey-level texture. Image segmentation	Combined spectral and textural bands gave vegetation structural class accuracy 79%	Applies to relatively simple-structured coniferous forest
(Laba et al. 2007)	Influence of wavelet type on the classification of marsh vegetation from satellite imagery using a combination of wavelet texture and statistical component analyses	Research note. Discrete wavelet transform and principal component analysis	Wavelets effectively distinguish shrub from other marsh plant communities	Distinguishing non-marsh communities highly dependent on wavelet type
(Lackner & Conway 2008)	Determining land-use information from land cover through an object-oriented classification of IKONOS imagery	Image segmentation. Classify land cover then derive land use	6-class land use 90%; 10-class land use 86%	Urban application
(Laliberte et al. 2004)	Object-oriented image analysis for mapping shrub encroachment from 1937 to 2003 in southern New Mexico	Image segmentation. Aerial photos	87% shrubs > $2m^2$	Problems with varying moisture and different photo image characteristics
(Leboeuf et al. 2007)	A shadow fraction method for mapping biomass of northern boreal black spruce forests using QuickBird imagery	Segment image shadow, adjust length factor for look angle - solar azimuth, regression to field biomass	Shadow to biomass R^2 = 0.84	Requires open canopy to adequately estimate shadow length

Author	Title	Methods	Pro	Con
(Malhi & Román-Cuesta 2008)	Analysis of lacunarity and scales of spatial homogeneity in IKONOS images of Amazonian tropical forest canopies	Scale-dependent heterogeneity (lacunarity)	Assess self-similarity and crown-shadow scales	Results strongly dependent on solar elevation (shadow length) hence most suited to tropical locations
(Maxa & Bolstad 2009)	Mapping northern wetlands with high resolution satellite images and Lidar	Update mapping to standard inventory classes	Improved mapping accuracy over field and c. 1980 aerial photography	Manual interpretation and mapping
(Mitri & Gitas 2006)	Fire type mapping using object-based classification of Ikonos imagery	Multi-resolution segmentation	Distinguish surface burn and canopy burn in open Mediterranean forests	Problems detecting sub-canopy burn (lack of optical penetration)
(Mutlu et al. 2008)	Mapping surface fuel models using lidar and multispectral data fusion for fire behavior	Data fusion ALS and QuickBird imagery. ALS height bins. Supervised classification	Classification accuracy higher (90%) with fused data than QuickBird alone (77%)	Small number of accuracy assessment sites
(Nichol & Hang 2008)	The influence of DEM accuracy on topographic correction of Ikonos satellite images	Use different interpolation methods on 1:5000 scale contouring to produce DEMs and test subsequent 3D orthorectification	Natural neighbour or Sibson interpolation methods most appropriate	Initial contour accuracy not rigorously tested.
(Peuhkurinen et al. 2008)	Estimation of forest stand characteristics using spectral histograms derived from an Ikonos satellite image	Examine frequency distributions of radiometric values	Total stem volume, basal area and mean height comparable accuracy to aerial photo interpretation	RMSE c. 20-30%
(Radoux & Defourny 2007)	A quantitative assessment of boundaries in automated forest stand delineation using very high resolution imagery	Image segmentation to delineate clear-cut boundaries. Compare offsets	Residual parallax (horizontal layover) and shade is main source of boundary position error	Applies to even-height (production forestry) stands with well-defined clear cut boundaries
(Tian & Chen 2007)	Optimization in multi-scale segmentation of high-resolution satellite images for artificial feature recognition	Compare segmentation results with 'meaningful objects', simple geometrical shapes defining known features	Segmentation scale, shape and compactness parameters must differ according to type of feature targeted	Focus on sports fields, roads and residential buildings
(Wulder et al. 2008)	Multi-temporal analysis of high spatial resolution imagery for disturbance monitoring	Red-Green Index to develop time series of tree crown insect attack. Segmentation to accommodate viewing angle and solar azimuth artefacts	89-93% positive accuracy for attacked crown	Narrow observation windows required. Forest structural condition and sun-sensor viewing angle still play critical role in longitudinal assessment
(Yang et al. 2006)	Comparison of QuickBird satellite imagery and airborne imagery for mapping grain sorghum yield patterns	Correlation of yield with spectral band rations and vegetation indices	r = 0.5 - 0.6 for field 1, r = 0.7 - 0.9 for field 2. Unsupervised classification outlines differing yield areas	
(Yarbrough et al. 2005)	QuickBird 2 Tasseled Cap transformation coefficients: a comparison of derivation methods	Gram-Schmidt orthogonalization, Principle Component Transformation and statistical approaches compared	Gram-Schmidt most useful for QuickBird sensor	

1.1.4 Laser scanning

A potential solution to both the vegetation structure and horizontal layover problems is found with the advent of airborne laser scanning (ALS, also known as LiDAR – light detection and ranging) (Lefsky et al. 2002). ALS operates through the principle of laser ranging, where a laser signal is emitted from an opto-mechanical instrument on an airborne platform, and the reflected signal, returning by the same optical path, is timed so that the distance between the sensor and the illuminated spot on the target is measured (Wehr & Lohr 1999). The high intensity, high collimation and short wavelength of lasers allows a dense pattern of return signals from the target accomplished by the side-to-side sweep (scanning) of the instrument, and the forward motion of the aircraft. Precise positional control by onboard navigation systems locates the instrument, and hence the position of the target, in space. Since both scan angle and the target distance are known, the illuminated feature can be located in three dimensions (xyz coordinate space) (Wehr & Lohr 1999). The resolvability of the system depends on factors such as the sensitivity of the sensor, the accuracy of the timing and navigation systems, and the reflectivity of the target (Baltsavias 1999). Laser scanning systems can be constructed as either continuous waveform (CW) or discrete pulse instruments, with CW systems having relatively greater vertical discrimination but wider footprint (Wehr & Lohr 1999). While CW systems were mainly used for research purposes, current application is dominated by commercial, discrete return, small footprint systems with typical horizontal point spacing, target footprint, horizontal and vertical accuracy of c. 1 m, 0.2 m, 1 m and 0.2 m, respectively (Hyyppã et al. 2008; Lefsky et al. 2002). (Figure 2) ALS point data can be used to develop gridded (rasterized) surfaces such as high-resolution digital elevation models (DEM) for accurate terrain-based analysis (Figure 3), as well as vegetation canopy height models (CHM), which are surfaces based on the local, vertical elevation of the vegetation (Figure 4). Further, with the high density (c. $1 \cdot m^{-2}$) of ALS returns, each tree crown can be sampled by many points, so a statistical analysis of the vertical distribution of foliage (*s.l.* the leaves, twigs and branches) can be determined for individual trees or over the same area as field-based sample plots, allowing development of simple regression models to predict vegetation structural attributes over the entire scanned landscape (Næsset 2002).

ALS offers greater precision for forest metrics compared to other remote sensing methods such as stereo photogrammetry or multispectral image analysis (St-Onge et al. 2008). Much of the research to date involves northern hemisphere, cool temperate or boreal coniferous forest, where methods are becoming well-established (Hyyppã et al. 2008). Applications in tropical areas are comparatively rare (Clark et al. 2004). Because ALS responds to the arrangement of canopy foliage, different forest types are expected to elicit different responses (Næsset 2005). In Australia, Eucalyptus species predominate (Groves 1994) and their canopy architecture typically presents irregular, open crowns with pendant leaves (Ashton & Attiwill 1994; Darwin 1836: XIX - Australia) hence their ALS responses may differ from cool climate coniferous or deciduous trees. Previous Australian ALS studies include inland woodland canopy density (Lee &

Lucas 2007), biomass (Lucas et al. 2008) and structure (Tickle et al. 2006). Vegetation canopy structure has also been assessed for sub-tropical tall coastal forest (Goodwin et al. 2006; Goodwin et al. 2007; Lee & Lucas 2007), and sub-alpine forest (Lovell et al. 2003).

A diverse range of studies have been undertaken in northern hemisphere forests. Because of the relatively high data cost, a large number of studies focus on timber production, and where allometric equations are used to relate canopy height to basal area for estimation of gross mercantile timber (Hudak et al. 2006; Hudak et al. 2008). Efforts are also made to map individual tree crowns (Holmgren & Persson 2004; Popescu et al. 2003; Popescu & Zhao 2008). Basal area estimation and crown mapping are enabled by the regular growth form and conical shape of conifers, especially in production forests, but these methods are unlikely to translate to Australian forest due to the irregular and open architecture of eucalypt canopies. While support for forest inventory and resource estimation are common objectives, the potential for monitoring and short term change detection has also been demonstrated (Vepakomma et al. 2008; Yu et al. 2008), although multi-temporal applications have been limited by the relative newness of the technology. ALS has also been used to map canopy gaps for bird breeding behaviour (Hinsley et al. 2008), low-lying vegetation and possible sediment dynamics in tidal salt marshes (Rosso et al. 2006) and terrestrial wetlands (Maxa & Bolstad 2009), and fuel estimation for fire ecology studies (Mutlu et al. 2008)

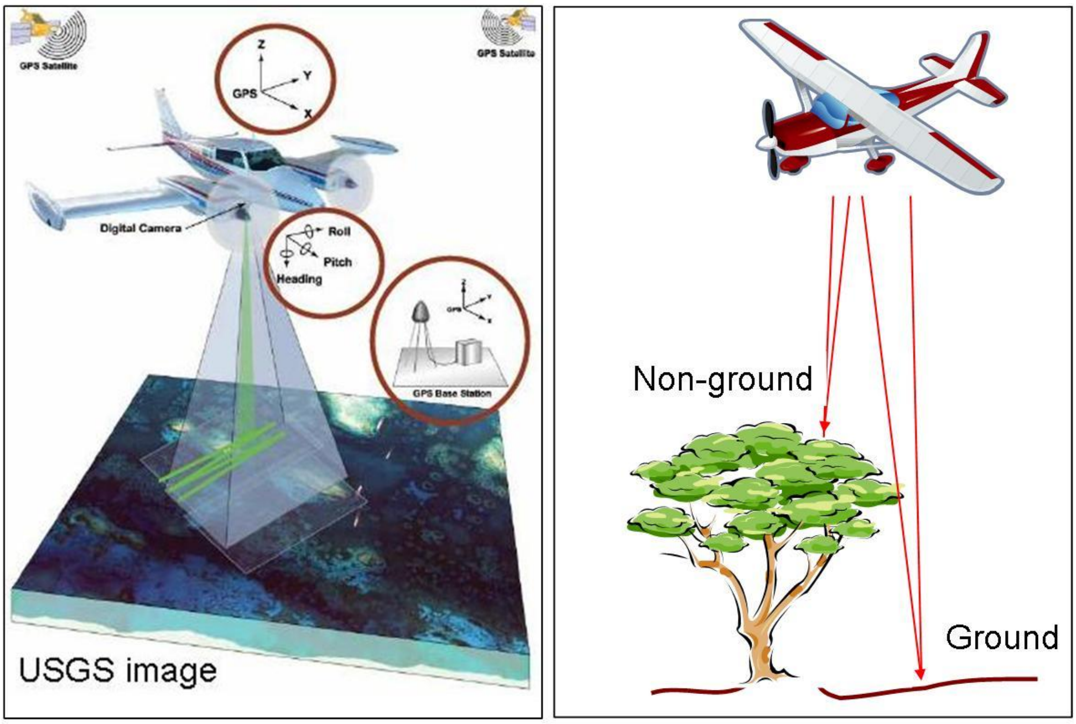

Figure 2 ALS scanning principles

The sweep of a laser scanner (left) covers a swath due to the forward motion of the aircraft, and point correct positioning is attained by a combination of inertial measurements from the aircraft as well as precision GPS. Discrimination of ground and non-ground reflections (right) is typically provided by the vendor using proprietary algorithms.

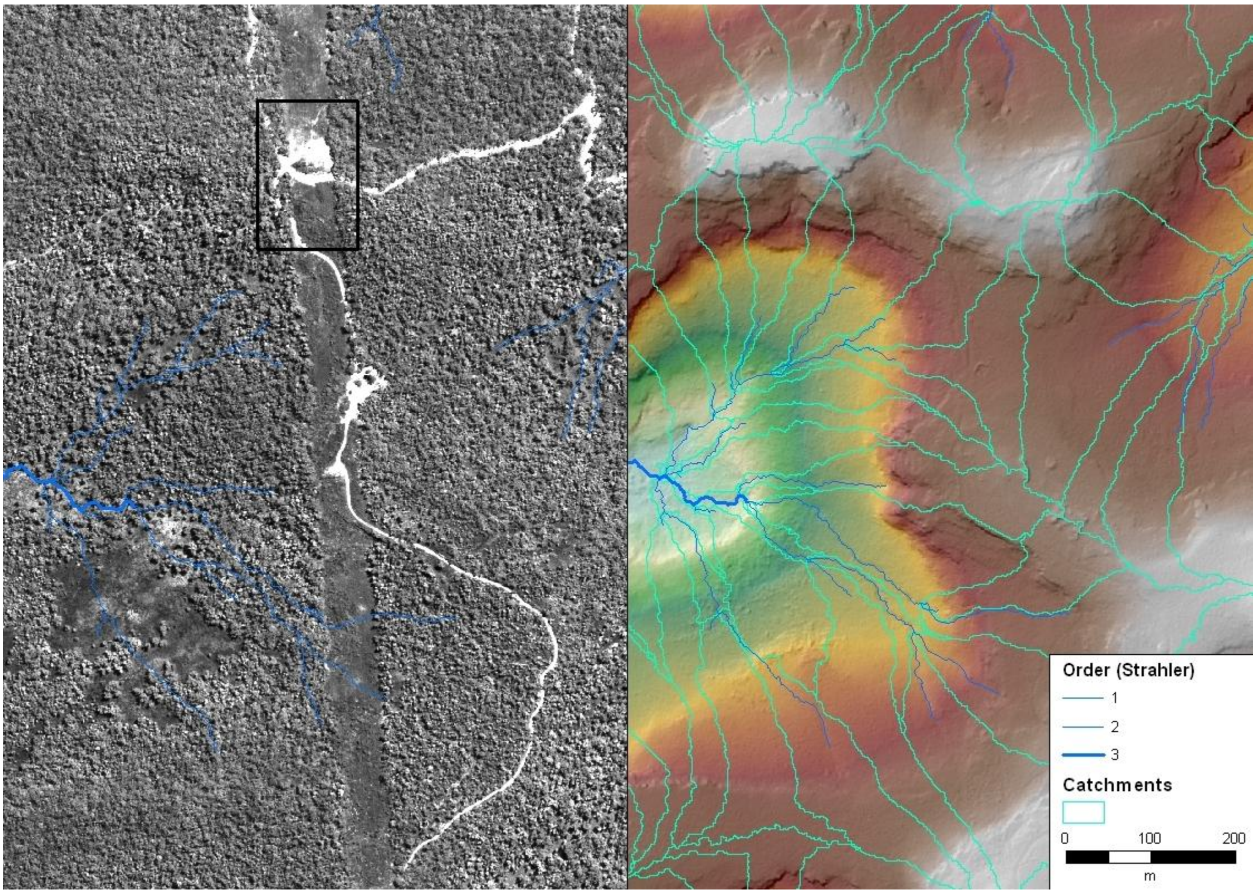

Figure 3 ALS-derived topographic information

ALS DEM-based topographic derivatives such as elevation, hillshade, drainage and catchments (right) derived with GIS software. A QuickBird panchromatic image of the same area is shown for comparison (left). Box shows location of

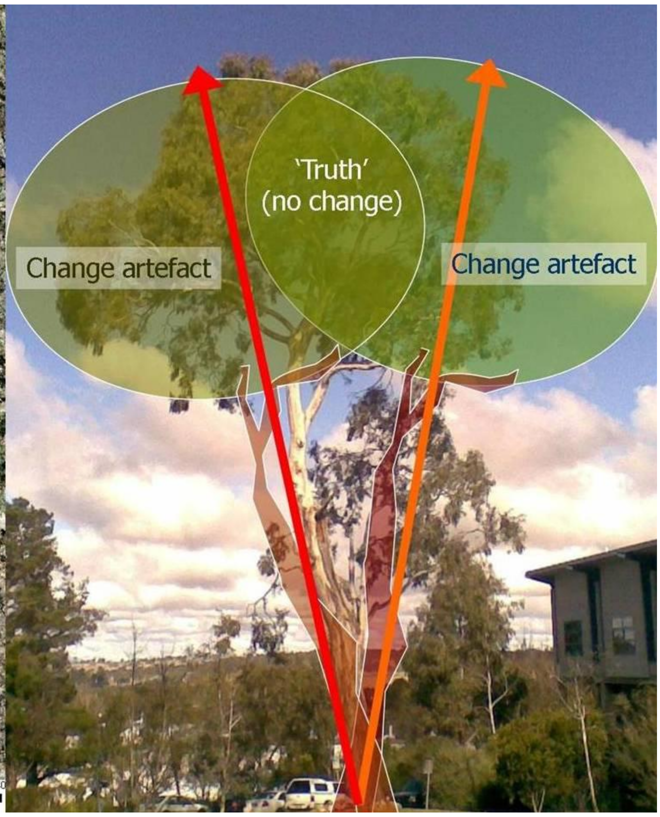

Figure 1 1. Imagery and ALS data from Woronora Plateau study area.

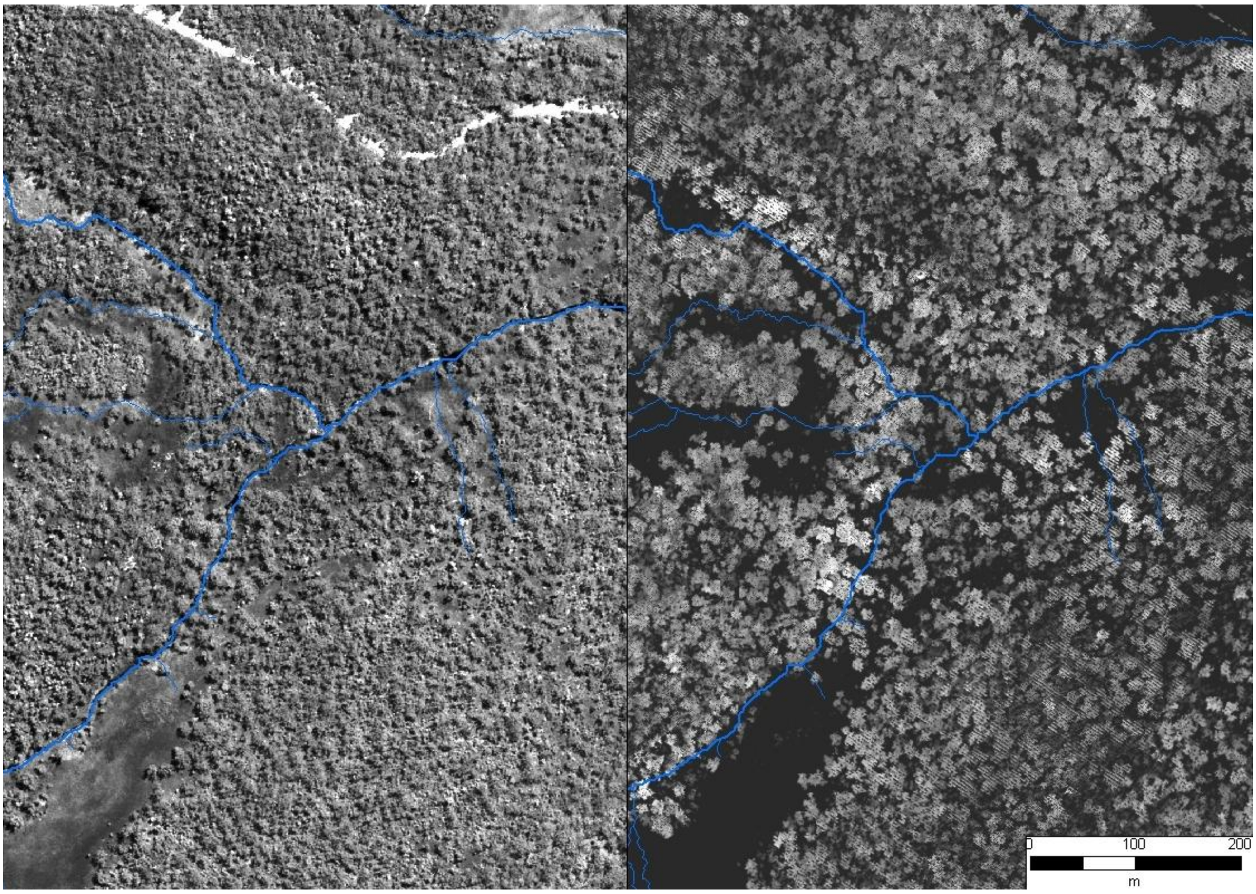

Figure 4 Canopy height model

A QuickBird panchromatic image (left) shown in comparison with a canopy height model (CHM, right). Imagery and ALS data from Woronora Plateau study area.

1.2 The impact assessment framework

Assessment and monitoring require an analytical framework, such as remote sensing change detection (Coppin et al. 2004), ecological (Attiwill 1994) or modelling (Bugmann 2001) approaches. Here, a vegetation condition and impact assessment approach (Conacher & Conacher 2002) is undertaken, for which the framework is a set of criteria and indicators that identify the goals or core values (criteria) and the objectives or means to measure the realisation of the goals (indicators). Formalisation of the use of criteria and indicators for impact assessment was through the development of tripartite environmental-social-political frameworks such as the Pressure-State-Response model (PSR) (OECD 1993), or refined versions such as the DPSIR (Driving forces, Pressure, State, Impact, Response) (Smeets & Weterings 1999). Criteria and indicator frameworks can be developed at different scale and approaches. Policy focussed, or 'top-down', frameworks are primarily geared towards identifying suitable, national/international protocols, such as for sustainable forest management (Hall 2001). Sustainable forest management, while embodying policy protocols, can also report on indicator status, thus embodying a 'bottom up' approach (Howell et al. 2008). At this level, indicators tend to report losses and gains, rather than condition of extant vegetation. Criteria and indicators can be also targeted more specifically to ecological systems models, allowing an ecosystem function-based approach, where individual components and their interrelationships comprise the indicator set (Niemeijer & de Groot 2008). Indicator choice of ecological condition should take account of structure, composition and function components, and meet criteria of their own: to be sensitive, measurable, and responsive, while still being simple enough to be easily monitored and understood (Dale & Beyeler 2001). This approach is similar to the familiar SMART (specific, measurable, attainable, realistic and timely) business and corporate goal setting paradigm. Vegetation condition assessment frameworks are currently being implemented in eastern Australia (Eyre et al. 2008; Gibbons et al. 2008a; Parkes et al. 2003), where different criteria (e.g. natural, anthropogenic) and indicators (e.g. canopy cover, firewood collection) are assessed at site level (c. 50 m · 20 m). Condition reports, protections strategies, and clearing actions can then be compiled to assess the impacts of land clearing on biodiversity at a state or federal level (Gibbons et al. 2009), thus adding finer-grained detail to Australia's sustainable forest management policy reporting (Howell et al. 2008). While this approach covers the main requirements set out by Dale and Beyeler (2001), some critical problems remain, as outlined previously: 1) the assessments are site-based and only qualitatively (subjectively) represent the broader landscape; 2) site access is not always practicable; and 3) the substantive problem of operator error or bias is encountered when implementing current site-based condition assessment methodologies (Gorrod & Keith 2009). The pressing need, therefore, is landscape-based and quantifiable methods of condition assessment that are operationally practicable, which complement or overcome the deficiencies of site-based assessment and monitoring.

2 AIMS AND OBJECTIVES

The aim of this thesis is to develop tools for high resolution remote sensing-based impact assessment and monitoring. The approach is through a specific impacting process – longwall mine subsidence (LWMS) due to underground coal mining (DPI 2006). LWMS is listed as a key threatening processes for alteration of habitat (NSW Scientific Committee 2005), and provides a landscape-based context for condition assessment. The objectives are to 1) establish the LWMS impact framework, and 2) establish and apply methods for vegetation condition assessment and monitoring under the LWMS impact framework. The methods developed include fine-grained data assessment (orthorectification accuracy and ALS-based forest metrics), which then allows development of protocols for mapping and monitoring key vegetation communities as well as landscape-based assessment of forest variation. The rationale for these approaches is established in the following sections.

2.1 Longwall mine subsidence: components, criteria and indicators

To refine the condition assessment and monitoring criteria and identify suitable indicators, a causal system model is developed. The approach is based on description of the impacting process, selection of the relevant system components from LWMS, vegetation and groundwater fields, organising them according to hierarchy theory to accommodate different spatial and temporal scales (Turner et al. 2001), identifying their interactions, and evaluating them to prioritise an indicator set. The procedural steps are outlined as follows:

- Describe and tabulate the system components
    - Identify known impacts
    - Identify potential indicators
- Relate the components via a spatio-temporal contingency matrix
    - Identifies causal system structure
- Prioritise indicators and identify information requirements
    - Identifies needs and approaches
- Develop methodology and justify approach
    - Confirm analytical soundness and relevance

The system components are described below and summarised in Table 3 and Table 4, where additional examples are provided as appropriate for illustration and clarification. Some of the examples refer to conditions within the study areas (Chapter 2), particularly upland swamps, identified as a specific threatened habitat (NSW Department of Planning 2008; NSW Scientific Committee 2005).

2.1.1 Coal mining

Coal is Australia's leading export resource commodity, with a 2008-9 value of c. AUD50 billion (DRET 2009), and coal-based generation dominates the domestic energy market (c. 40%) (ABARE 2009a). Approximately 25% of black coal production is from underground mining (ABARE 2009b). Underground coal mining is mainly undertaken by the longwall method (DPI 2006).

2.1.2 Longwall mine subsidence

In longwall mining, coal is extracted from a series of tabular panels, typically 150 m – 300 m wide, 1 km – 3 km long and with seams 2 m – 5 m thick. The panels are separated by permanent headings (roadways) for access, ventilation, utility supply and conveyance. Coal is extracted by a mechanical shearer that passes back and forth across the mining face with the coal discharged from the mine by a belt conveyor along the permanent headings (Guo et al. 2009). The strata above the working space are temporarily supported by hydraulic jacks, which advance with the shearer as it progressively cuts through the coal face (Figure 5). Mining rates are typically in the order of 10 m – 50 m per week (MSEC 2007a). As the face retreats, the roof collapses into the mined void, resulting in progressive subsidence of the overlying strata, which propagates to the surface to form a shallow, plate-like or U-shaped subsidence trough (Kratzsch 1986). Roof collapse commences immediately after support is withdrawn, and the bulk of subsidence occurs within days or weeks at any particular locality, although final consolidation and surface settling may proceed for some months afterwards (Luo & Peng 2000). As mining progresses, a series of subsidence troughs form as individual panels are extracted (Figure 6).

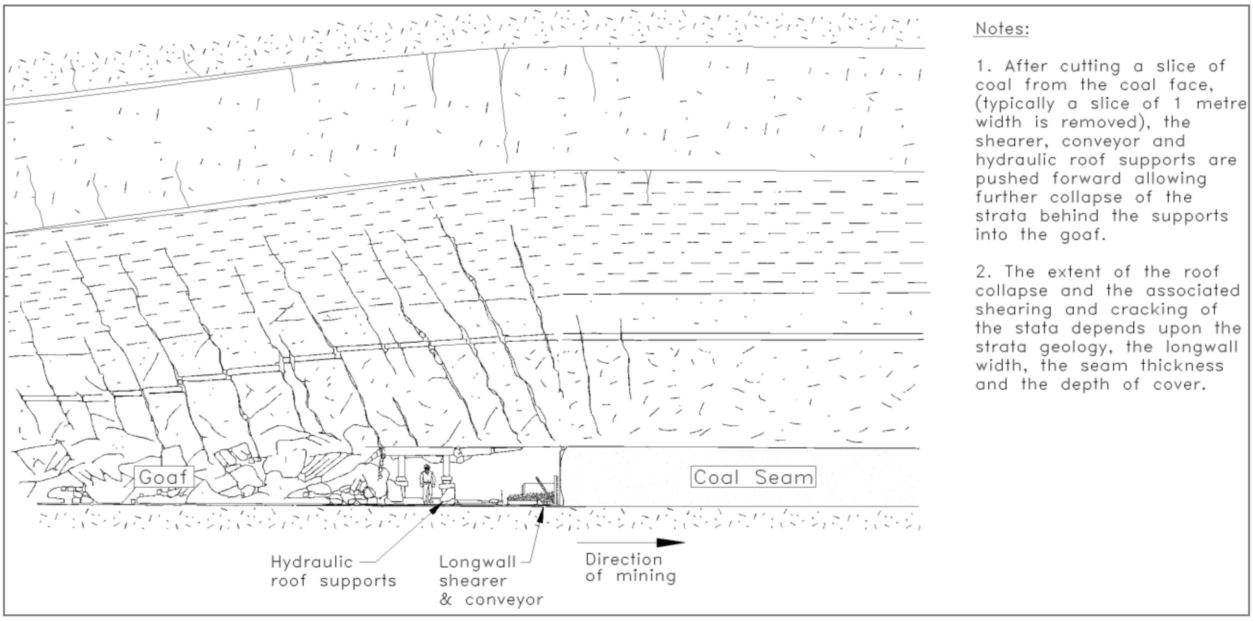

Figure 5 Longwall mining cross-section

Diagrammatic cross-section of longwall mining (courtesy of Waddington Kay & Associates).

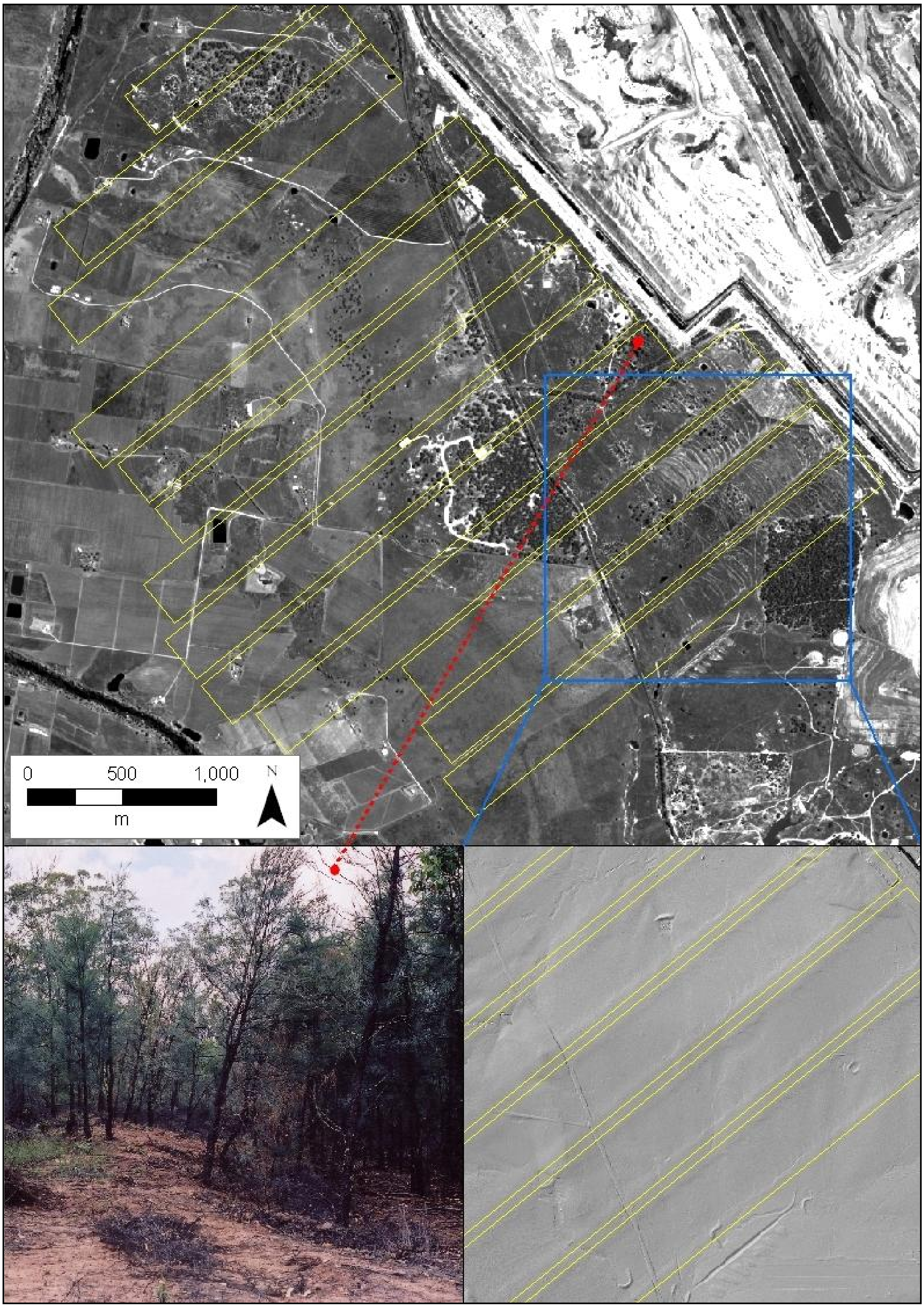

Figure 6 Longwall mining, Beltana area

Longwall panels (yellow outline) at the Beltana study area, Lower Hunter Valley (see Chapter 2). Panel extraction results in surface subsidence (hillshade; lower right) and ground tilt (lower left). Surface cracks associated with tilt have been mechanically ripped to reduce erosion risk, and the ripped/tilled area is visible as a series of light curves near the open pit on the QuickBird satellite image (top).

2.1.3 Subsidence mechanism

The LWMS mechanism is generally well-understood, and modelling is used to predict the amount and extent of subsidence based on local area conditions such as mine design, seam thickness, depth of cover, geological properties, and topography. The gravitational collapse of strata imposes a stress field in the adjacent rock mass, causing deformation as a strain response (e.g. Hobbs et al. 1976). Strain, measured in mm · m^{-1}, is heterogeneously distributed around the panel with (horizontal) tensile strain highest above the panel margins, and compressive strain highest over the panel centre (Holla 1997). LWMS can be expressed as horizontal and vertical movements, with vertical movement greatest over the panel centre, and horizontal movement greatest towards the margins, at areas of highest tensile strain (Figure 7). The subsidence trough depth can be up to 70-90% seam thickness, and trough depth decreasing as the height of overburden increases due to formation of void space in the overlying strata (Bell & Genske 2001). The relative vertical movement between the trough margin and centre adds a shear strain component, and associated surface slope change, with greatest slope change at half maximum vertical subsidence (Holla 1997). Typical horizontal strain and slope are in the order of 10 mm · ·m^{-1} and 30 mm · m^{-1}, respectively (Bell & Genske 2001). While the strata involved in subsidence have highly variable internal stress state and deformation moduli (bulk and Young's), the displacement response is essentially decoupled from the rock properties, so LWMS can be modelled effectively, particularly in areas of relatively gentle topography (Liu et al. 1997). Steep topography, such as deeply-incised valleys above the panel, allow greater horizontal movement towards the panel axis, which with the high horizontal compressive strain over the panel centre, results in localised reduced subsidence producing a valley-floor bulge or 'upsidence' component (Holla 1997). Subsidence prediction is continuously refined by site-specific engineering studies and overestimated prediction errors < 20% occur locally, and often within survey tolerance elsewhere (Figure 8).

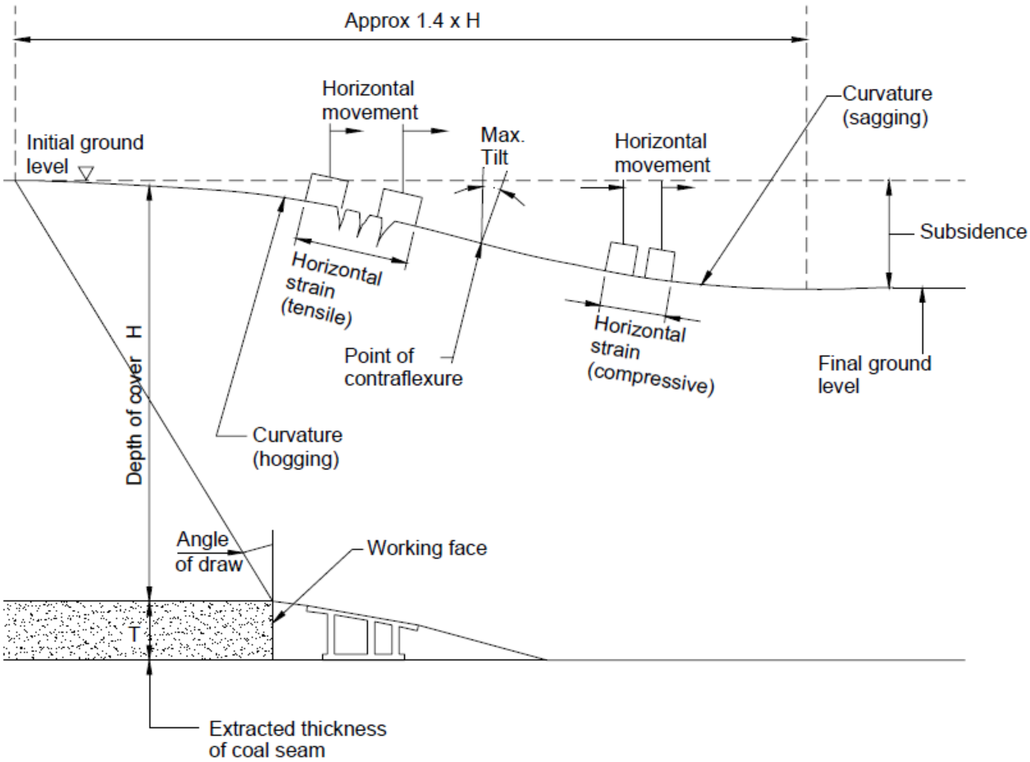

Figure 7 Subsidence profile

Subsidence and strain distribution, in particular transient strain encountered as the mining face retreats. Compare with permanent strain profiles (Figure 10) (MSEC 2007a).

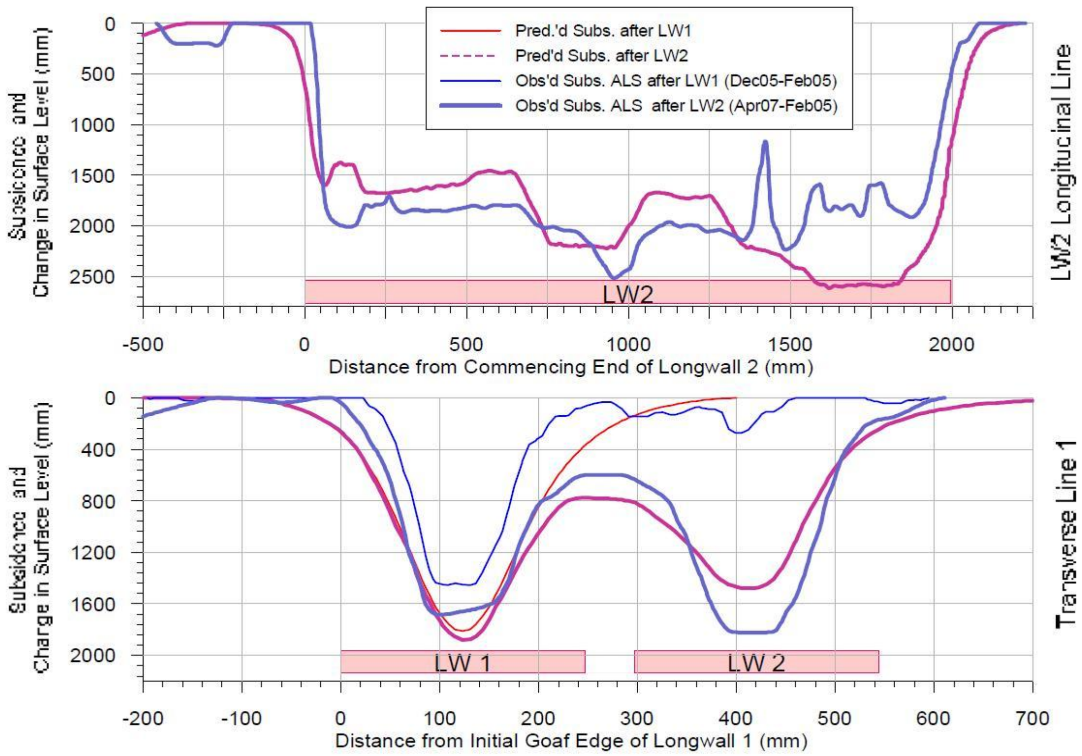

Figure 8 Subsidence modelling and subsidence profiles

Modelled subsidence and actual profiles generally show good agreement (MSEC 2007b).

2.1.4 Subsidence fracture and hydraulics

Surface subsidence consists of both transient phenomena occurring as the trough front migrates as mining progresses, as well as the permanent trough and fracture systems following extraction (Figure 7; Figure 8). Near-surface deformation can cause tensile and shear fracture of the regolith, typically adjacent to panel margins and within zones of maximum curvature, situated farther towards the panel centre (Holla 1997; MSEC 2007a)(Figure 9). Cracking of the bedrock also occurs, with crack width generally decreasing as depth of cover increases, typically c. 200 mm (50 m cover) to 20 mm (200 m cover) (MSEC 2007a).

Subsurface fracture of the strata results in a “strongly heterogeneous [spatially variable] and anisotropic [directionally variable] hydraulic conductivity field” (Liu & Elsworth 1997), and three characteristic zones of enhanced conductivity are identified, due to caving within and above the panel, shear failure above the un-subsided, permanent structures (roadways or chain pillars), and extensional fracturing ahead of the advancing mining face (Figure 10) (Liu & Elsworth 1997). Note that the latter component may largely be a transitory effect as the strain differential is resolved as the mining front progresses.

Figure 9 Soil cracks and subsidence trough

Soil cracks on edge of Beltana area subsidence trough (upper left) may have a shear component (upper right). Subsidence results in a shallow, U-shaped trough, clearly visible along a company monitoring line at Beltana (lower image).

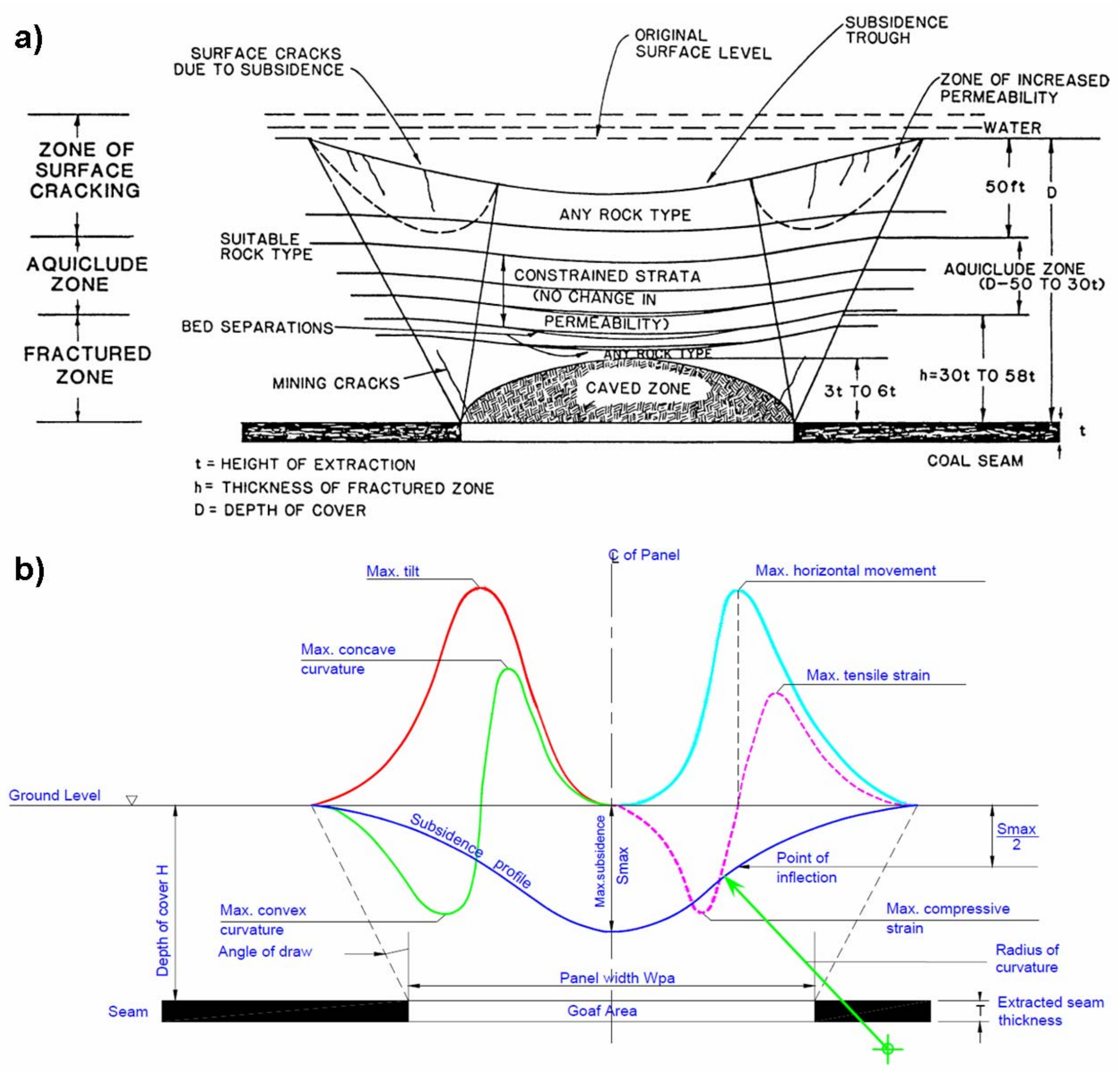

Figure 10 Subsidence fracture zones and strain parameters

Diagram of fracture style relative to mined area **a)** (Booth 2006) and strain distribution **b)** (MSEC 2007a).

2.1.5 Reported impacts

There are relatively few published studies of LWMS impact on native vegetation, and those that occur typically refer to quite specific, local issues. Of importance are instances of gully erosion in upland swamps in the Southern Coalfield, NSW associated with mining-related surface mechanical disturbance, wildfire and extreme rainfall events (Tomkins & Humphreys 2006). Pre-European occupation erosion profiles preserved in the swamps' stratigraphy (*ibid.*), suggest that episodic erosion is a natural feature, although potentially accelerated by mining. A recent NSW Governmental inquiry identified subsidence-related impacts on upland swamps as a priority area for industry and Government research (NSW Department of Planning 2008). Gas emissions affecting riparian vegetation have been observed in the

Southern Coalfield where dieback affected young trees and saplings in four sites (c. 0.12 ha total) (Biosis Research 2007). The site was monitored 1997-2000 and by 2006 vegetation had reverted to a condition comparable with unaffected vegetation elsewhere in the same riparian zone (*ibid.*).

In the absence of wide-ranging studies, inferences can be drawn from related contexts such as agricultural land and slope stability studies. The main agricultural production impacts relate to water accumulation (ponding) in subsidence troughs (Bell et al. 2000; Darmody 1998). Subsidence has exacerbated ponding in flood prone areas of the Ruhr district (Germany), where it may be accompanied by reversals in drainage direction (Bell et al. 2000). In flat Illinois (USA) farmland with poorly-drained, low permeability soils, ponding or wet areas occur due interception of the subsided surface and shallow water table, resulting in low seed germination and an average 5% reduction in corn yield (Darmody 1998). Darmody (1998) also noted instances of soil erosion (presumably on subsidence troughs flanks) as well as the potential effects of surface cracking on soil hydrology. Areas of steep topography are also prone to impact, such as landslides (Donnelly et al. 2001) and cliff falls (Zahiri et al. 2006). Subsidence-induced landslides have occurred in the tectonically active, landslide-prone Columbian Central Cordillera, where subsidence has reactivated geological faults and channelled groundwater to slopes covered by deep residual soils, and initiated or re-activated landslides (Donnelly et al. 2001). Zahiri et al. (2006) document nine mining-related rock falls along a 2 km section of cliffs adjacent to the Nepean River (NSW, Australia). Rock falls appear to occur only in the immediate vicinity (i.e. directly above or between adjacent panels); however they do not compare these occurrences with possible background values (i.e. recent falls not associated with mining). These examples suggest that LWMS impacts are most prevalent in areas predisposed to similar impact (flood-prone, poorly-drained soils – steep, unstable landmass). In contrast, some recent Australian subsidence case studies in areas of undulating topography and well drained soils have shown negligible effects on broad-acre cropping, lucerne (alfalfa) and viticulture production (Thompson 2009; Trotter & Frazier 2009).

2.1.6 Groundwater

Hydraulic conductivity impacts are likely to be highly variable, depending on mining conditions, and mines can be affected by water inflow and gas emission (Guo et al. 2009). Shallow mining (c. < 50 m – 100 m) beneath weakly-consolidated aquifers can cause inrush of a sediment slurry, with caving producing sinkholes at the surface (Zhang & Peng 2005), although such mining conditions would not be approved in Australia. Deeper mining or shallow mining with overlying aquitards or aquicludes tends to isolate the caved zone from unconfined, near-surface aquifers (Booth & Bertsch 1999), although high permeability or transmissivity occurs around surface fracture zones (Booth 2006).

Soil fractures can cause significant changes to the hydrological properties of soils (Arnold et al. 2005; Buttle & McDonald 2002), and promote local desiccation that can directly impact on vegetation. Fractures also act as macropores that can increase hydraulic conductivity by several orders of magnitude (Beven & Germann ; Ward & Robinson 2000), and high flow in fractures can lead to erosive piping that in turn can lead to catastrophic erosion, particularly after extreme rainfall events (Dykes & Warburton 2007). Second, capillary flow rates change rapidly in close proximity to the water table (Ward & Robinson 2000), and where water tables are within one metre of the surface, atmospheric conditions control groundwater evaporation, but with increasing depth soil properties become limiting and evaporation rates decrease rapidly (Todd & Mays 2005). In other words, subsidence-related topographic change in the order of one metre over shallow groundwater systems (water table depths c. 2 m) can have a pronounced effect on vegetation-available groundwater. Temporal variations in groundwater can vary from minutes (e.g. infiltration in shallow, porous soils), through days (e.g. diurnal evapotranspiration), seasonal (climate) to secular (multi-year climate irregularities) time scales (Todd & Mays 2005).

2.1.7 Native vegetation

Potential vegetation impact may be predicted as a result of mechanical disturbance due to ground shaking, soil shear-tension fracture and ground tilt, or hydraulic changes associated with soil fracture and vertical subsidence. Shearing and shaking may disrupt the root-ball function of tree and shrubs, as well as providing rain-wash erosion initiation points. Ground tilt may destabilise standing vegetation, particularly if already weakened by soil disturbance.

The study of native vegetation can range by approximate orders of magnitude from individuals (trees, shrubs, forbs, gramminoids etc) at c. 1 m – 10 m extent, through clusters of co-occurrent individuals (communities or associations) at 10 m – 100 m extent, to structural formations (e.g. forests versus grasslands) nominally at kilometre extent. Also important are the boundaries between vegetation communities, which may be disjunctive (ecotonal) or transitional, where species from one co-occurring group intergrade with another (Specht & Specht 2002). The dimensions given above are, of course, both arbitrary and contestable, but they are offered to allow some semantic order. Also, they align with scaled geomorphic concepts as advocated by Speight (2009) who identified ‘landform patterns’ at a characteristic scale of c. 600 m (e.g. floodplains, dune fields, hill), which can decompose to ‘landform elements’ at c. 40 m dimension (e.g. valley bottom, dune, toeslope). Also included for reference in this evaluation is fire, which while not a vegetation component *per se*, is so intrinsically linked to Australian vegetation as to be unavoidably included (Bradstock et al. 2002). Temporal variations in vegetation can vary from c. hours (e.g. mortality due to uprooting or lightning) through days (diurnal evapotranspiration), seasons (phenology), to multi-year seral stage, or successional (Perry & Enright 2006) time scales.

Table 3 Temporal components of the analytical framework

The LWMS impact components and potential ground water and vegetation responses at different orders of magnitude. Note that the scale factor is approximate and indicates a central point e.g. 0.1 years (= month) spans hours or days to c. six months; one year spans six months to five years, etc. Similar scale trends apply to Table 2.

Time (y)	LWMS	Groundwater	Vegetation
0.1	Roof collapse	Rainfall event & season	Sprouting & tree mortality: e.g. forest gap formation (Shugart 1984)
1	Panel extraction	Season cycle: e.g. groundwater-dependent ecosystems (Eamus et al. 2006)	Phenology: e.g. seasonal changes in forest canopy (Gillespie et al. 2004)
10	Panel succession	Secular: e.g. El Nino – La Nina events (Meyers et al. 2007)	Seral stage: e.g. fire-seral succession in heathlands (Keith et al. 2007)
100	Mine completion	Climate change: e.g. pan evaporation trends (Rotstayn et al. 2005)	Primary-secondary succession: e.g. multi-decade boundary change in upland swamps (Keith et al. 2006)

Table 4 Spatial components of the analytical framework

Space (m)	LWMS	Groundwater	Vegetation
1	Soil and rock fracture, subsidence	Vertical soil profile, capillary fringe gradient: e.g. edaphic variables in wetlands (Peters et al. 2008)	Shrubs and groundcover: e.g. obligate phreatophytes (Froend & Drake 2006)
10	Ground flexure	Depth to groundwater: e.g. abstraction and water sources in shallow aquifer (Zencich et al. 2002)	Trees and ecotones: e.g. boundaries and alterative stable states in wet tropics (Warman & Moles 2009)
100	Trough width	Hillslope: e.g. drainage and vegetation (Bedford & Small 2008; Wilkinson & Humphreys 2006b)	Patches and ecoclines: e.g. biogeography and transitional areas (Kent et al. 1997)
1000	Trough length, mine width	Catchment hydrology: e.g. DEM resolution and modelling (Hancock 2005)	Associations and fire: e.g. salinization (Lyons et al. 2007)

2.2 Assessment framework: contingency and causality

The temporal and spatial components of the analytical framework identified in Table 3 and Table 4 elicit a broad range of geographical or ecological phenomena related in scale to the impacting process. Not all these components are of direct relevance to the current study, and the contingency matrix (Figure 11) condenses the relevant components to known features within the study areas, which can then be regarded as indicators for the initial criteria – vegetation condition – arrayed with respect to their spatial and temporal domains. This shows the intrinsic link between different temporal and spatial scales (Wu & David 2002), highlighting the need for assessment to cover an appropriate scale range.

The contingency matrix identifies individual indicators such as erosion nick-points (c. < one month, 1 metre) as well as indicator trajectories such as tree falls (10 m) accumulating from months (0.1 year) to decades. The particular emphasis on (upland) swamps follows their prior identification as key threatened features of the Southern Coalfield, due to their high species diversity, groundwater dependence and susceptibility to mechanical disturbance (NSW Department of Planning 2008; NSW Scientific Committee 2005; Tomkins & Humphreys 2006). A general trend with time is for broadening spatial scale, with different indicators following separate trajectories.

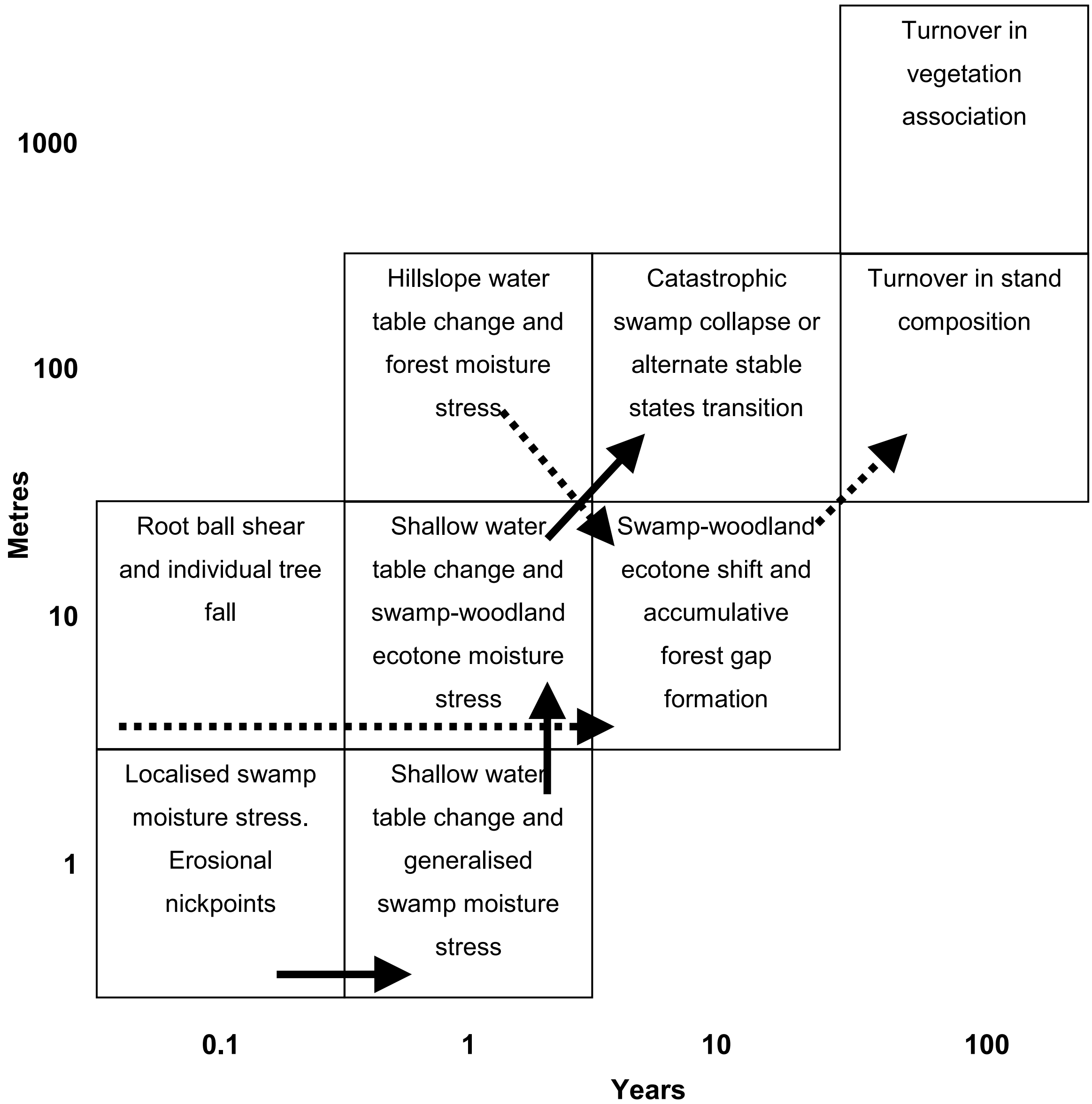

Figure 11 Impact framework contingency matrix

Indicators for vegetation condition criteria are shown for a range of spatial and temporal scales representative of potential LWMS impacts. Indicator trends are shown for upland swamps (solid arrows) and forest tree mortality (dotted arrows).

2.3 Assessment framework: indicators and methodology

The preceding sections have identified three main vegetation features as indicators for potential LWMS impact. These are upland swamps, individual forest trees, and the forested landscape in general. These indicators can also be re-evaluated as criteria, decomposable into fined-grained indicators, to identify the data and procedures necessary for appropriate assessment and monitoring.

Upland swamps are threatened by a range of processes including soil/bedrock rupture and tilt initiating drainage and erosion nick-points, as well as moisture stress due to watertable change. Groundwater-based impacts for upland swamps are likely to be highly variable and locally unpredictable, since both water table elevation (subsidence) and lowering (crack drainage) could occur in close proximity which, coupled with local gradient change due to surface tilt, will result in complex patterns of optimum plant moisture, waterlogging and desiccation. The integrity of swamps is based on the organic binding of a peaty surface mat (Keith et al. 2006; Tomkins & Humphreys 2006), which if disrupted by plant mortality or mechanical disturbance will be highly prone to erosion, making swamps a priority target for assessment and monitoring. Indicators for upland swamp criteria are then short-term loss of vigour due to over-dry and over-wet soils, and increase in bare ground due to erosion.

For forest individuals (trees and shrubs) disturbance of the root ball by soil rupture, mechanical shaking during active subsidence, or ground tilt could all result in rapid in-situ tree mortality or tree fall, detectable over relatively short timeframes. Vegetation stress due either to mechanical disturbance or water table elevation could result in foliar discolouration, partial defoliation or increased pathogenic attack (Barry et al. 2008; Coops et al. 2006; Coops et al. 2004a; Desprez-Loustau et al. 2006). The effect of environmental perturbations are not always immediate (Ives 1995), and given the general resilience of eucalypts to extreme environmental conditions (fire, drought, intense rainfall), impacts may not become apparent for several years, but may be more likely in areas where moisture conditions are more critical, e.g. in riparian corridors or around the margins of upland swamps. Indicators for forest criteria are then short-term loss of individual trees, or longer-term reduction in foliar condition.

2.3.1 Indicator sensitivity

While indicators for swamp and forest condition criteria can be discussed in general terms of vegetation vigour, appraisal of indicator variability or environmental specificity is required to refine the indicator definition and suggest appropriate analytical approaches. Ecological indicators should, for example, be measurable, sensitive to the implied stress, predictable in response, and, preferably, be anticipatory of impending change (Dale & Beyeler 2001). The indicator sensitivity for this study is based on landscape-functional approaches, using 1) the concept of groundwater dependent ecosystems (Eamus et al. 2006) for upland swamps, and 2) landform-based vegetation variation in response to energy and water availability (Stephenson 1998).

Groundwater dependent ecosystems (GDE) can be split into obligate (necessarily dependent) and facultative (assisted by) types, a situation somewhat analogous to the wet heath/dry heath distinction made on seasonal waterlogging and seasonal drought, respectively (Groves & Specht 1965). For Woronora Plateau upland swamps, Keith and Myerscough (1993) identified two communities – Tea-Tree Thicket and Cyperiod Heath – present on permanently waterlogged soils, which are interpreted as obligate GDE, with Sedgeland, Restiod Heath and Banksia Thicket on progressively drier soils with the latter having many species in common with the understorey of adjacent woodland/forest (NPWS 2003b), and interpreted as a facultative GDE. Tea-Tree Thicket and Cyperoid Heath are expected to remain green year-round, whereas the other communities are expected to senesce on a seasonal basis, so the two groups should be distinguishable by the relative abundance of green and dry plant matter, using high resolution remote sensing (Dillabaugh & King 2008). Given the swamps' abundance of short lived and water-dependent species such as ferns, sedges and forbs (Keith & Myerscough 1993), changing GDE status should have discernable effects within seasonal to annual timeframes. Changing abundance and spatial location of the 'wet' and 'dry' communities can then be used for monitoring. Given the expected high level of natural variability in swamp vegetation, monitoring should examine a large number of individual swamps so that potentially anomalous values can be assessed against seasonal trends.

Swamp boundaries form an important indicator as a mapped baseline for longitudinal assessment. Boundary expansion and contraction occurs over decadal timeframes due to climate cycles (Keith et al. 2006), suggesting that a hydrological impact may cause local perturbations in the vicinity of the boundary. This may be reflected either in change in swamp vegetation community or in fringing forest, as discussed above. Current swamp boundary mapping, based on air-photo interpretation, lacks the accuracy necessary for the boundary to be used as an indicator (Figure 12).

Eucalyptus open-forest structure has shown sensitivity to topographic aspect and moisture availability in southeast Australia (Gill 1994), and landscape-based variation in growth form has been noted for forest-woodland on the Woronora Plateau (NPWS 2003b). Topographic variables such as insolation and wetness indices can be derived from digital elevation models (Burrough & McDonald 1998; Kumar et al. 1997), hence forest growth quantification through metrics such as tree height, crown cover, foliage cover and spectral response can be compared to the energy- and water-related landscape variables. The metrics can then be assessed for sensitivity with the assumption those metrics that are most sensitive to landscape position are also those that are most sensitive to LWMS impact. As with swamp assessment and monitoring, a large number of sample sites are required for trend detection and statistical quantification of the high range of natural variability.

The requirement for abundant assessment and monitoring sites effectively precludes field-based sampling as the main analytical approach, on logistical grounds. Even if logistically possible, field trials in the Sydney region have shown that operator error or bias is too prevalent for valid monitoring from different operators over extended time periods (Gorrod & Keith 2009). Remote sensing is thus the preferred approach, provided the data and techniques used can be shown to have both the required sensitivity and reliability.

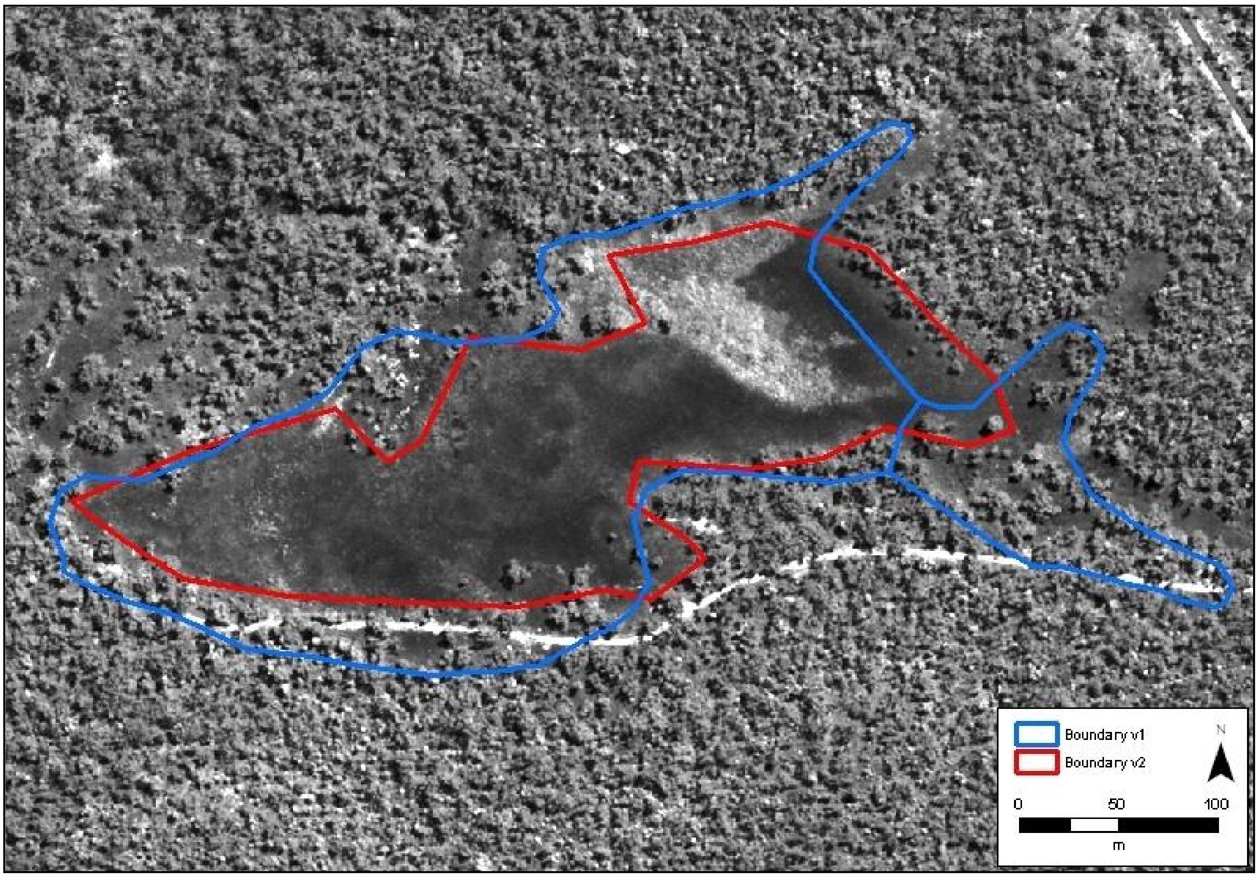

Figure 12 Swamp boundary mapping.

Published (NPWS 2003b: blue line) and unpublished (Horsley 2003: red line) upland swamp boundary mapping varies by c. 50 m, and is unsuitable for boundary-related monitoring. Imagery from Woronora Plateau study area.

2.3.2 Data and techniques

The indicators' spatial and temporal scale and sensitivity requirements allow choice of data and analytical technique, summarised in Table 5. Swamp vegetation is the most sensitive indicator and is accorded a higher priority. Since swamp vegetation individuals are small (< 1 m) and form dense, low-lying ground cover the effect of horizontal layover is negligible and the different communities are ideally sensed and classified by current high-resolution satellite imagery using traditional, per-pixel techniques. Post-classification change detection (Coppin et al. 2004) can then be applied to establish areas of difference. Validation of the initial indicator assessment (i.e. the classified image) can come from ground truth (field site data) as well as other imagery sources, including the higher-resolution panchromatic band captured with the multi-spectral bands, high-resolution orthophotography, and intensity ‘images’ interpolated from ALS data. ALS data are ideally suited to indicators that have a vertical component, such as tree height, crown cover and foliage cover. While the vertical accuracy of ALS is typically high (c. 0.2 m), the finite width of a laser pulse (c. 10 ns) (Baltsavias 1999) means that quantitative discrimination between ground surface and low-lying object reflections (c. 1 m – 2 m) are problematic, so ALS is better applied to canopy, rather than understorey, indicators. Canopy height models are essentially images of crown foliage cover, so image differencing techniques (Coppin et al. 2004) can effectively assess tree mortality. Multi-spectral data can complement the ALS forest analysis, although image classification in forested areas is not recommended due to limitations of pixel versus feature size and horizontal layover. Instead, use of a vegetation index such as normalised difference vegetation index (NDVI) (Jensen 2005) is appropriate, with average index values for a site used for comparison.

Table 5 Indicator analysis parameters

Indicator	Time (y)	Resolution (m)	Data	Priority	Technique
Swamp vegetation	1	10	QuickBird MS	1	Per-pixel classification
Swamp boundary	< 10	< 10	ALS	2	Tree-swamp height differentiation
Forest gap	< 10	< 10	ALS	2	Canopy height model difference
Forest condition	< 10	< 10	ALS + QuickBird MS	2	ALS structural indices, vegetation index (e.g. NDVI)

2.3.3 Statistical validation

A critical requirement for monitoring is indicator reliability (Dale & Beyeler 2001). In other words, are the indicator measurements repeatable and consistent in both space and time? This is essentially the problem of experimental replication, conducted at a regional scale, as in the classic BACI (before-after-control-impact) approach (Smith 2002). Replication occurs in two ways: by multi-temporal epochs of both satellite imagery and ALS data, captured relative to the impacting event (BA) and by selection of study areas both within and away from the expected LWMS impact area (CI). As mentioned above, both upland swamps and forest locations need to be well replicated. Upland swamps are abundant and well-distributed throughout the main study area (Chapters 2 & 5), so can be assessed in the classic sense of a population to which a treatment (impact) is applied. Forest areas can be replicated by random spatial sampling, and the sample sites stratified by landscape position.

The accuracy of baseline spatial data can be assessed by comparative means. Off-nadir imagery, in particular, is subject to local distortions due to look angle and differences in terrain elevation. The distortions are geometrically predictable (Toutin 2004) and image rectification attempts to remove the distortions. Where multi-temporal images of the same area are available, the effectiveness of different rectification methods can be quantified by image matching, where the point-by-point matching errors can be assessed by statistical regression and ANOVA. The reproducibility of ALS-derived forest metrics can be validated by multi-temporal survey and statistical comparison, and their utility established by regression with comparable field data (Hyyppã et al. 2008; Næsset 2002) While field data may be subject to error, if a range of sample sites are chosen and field techniques are consistent then operator bias or random error effects are minimised.

3 THESIS STRUCTURE

Three critical issues and analytical tool requirements emerge from the foregoing discussion: 1) how to assess and monitor upland swamps; 2) how to assess and monitor the forest landscape; and 3) what data-specific techniques are required to satisfy questions 1 and 2? The current analytical gaps for upland swamps are boundary mapping suitable for monitoring, and a means to assess and monitor their vegetation vigour throughout. The current gaps for the forested landscape are a means to detect tree falls as well as robust indicators of tree health, such as foliage cover, canopy cover and height, as well as an evaluation of which indicators are likely to be impact-sensitive. The suggested solution to these gaps relies on developing high resolution remote sensing tools, with appropriate data validation. Validation in this case is both by comparison with field data, and, critically, by cross-validation through use of multi-temporal satellite image and ALS data.

As stated earlier, the objectives of this thesis were to establish the LWMS impact framework, and to develop and apply methods for vegetation condition assessment and monitoring under the LWMS impact framework. This chapter has described the LWMS process, and explained the potential impacts that may arise. From this, both key vegetation targets were identified, as well as the methods for their assessment and monitoring. In other words, a set of analytical tools has been proposed, in accord with the aims of the thesis. This approach provides a novel application using multi-temporal ALS and high-resolution imagery in an environmentally sensitive Australian location, through an uncommon, though environmentally significant framework.

The results from the research methods described above are presented as a series of papers, most of which have been submitted for publication. Of necessity, this entails some repetition, particularly in regard to study area and data description, and methodological justification. The thesis layout is as follows:

- Chapter 1: Introduction
    - Overview and methodological development
- Chapter 2: Study areas
    - Beltana and Dendrobium Mine Areas
- Chapter 3: Orthorectification

  - Accuracy assessment using different DEM and ground control data
    - Paper submitted to *Internal Journal of Remote Sensing*
- Chapter 4: ALS validation
  - Assessment of ALS metrics using field data and replication, and evaluation of CHM image differencing
    - Paper in preparation for submission to *Austral Ecology*
- Chapter 5: Upland swamp assessment and monitoring
  - Post-classification change assessment and boundary mapping
    - Paper submitted to *Wetlands*
- Chapter 6: Landscape-based variation in forest metrics
  - ALS metrics, NDVI and texture (semivariance) assessment relative to insolation and topographic wetness
    - Paper submitted to *Landscape Ecology*
- Chapter 7: Discussion

Chapter 2

Study areas

1 LOCATIONS

The study sites are situated in the geological Sydney Basin (Figure 13), consisting predominately of Permian and Triassic sedimentary sequences (Herbert & Helby 1980). Coalfields occur in Permian strata in both the Sydney and adjacent Gunnedah Basins (DPI 2005; Standing Committee on Coalfield Geology 1986). The two study areas are located in the Dendrobium Mine Area (Illawarra Coal Holdings Pty Ltd 2007) in the Southern Coalfield and Beltana Underground Mine Area (Bulga Coal 2009) in the Hunter Coalfield.

1.1 Dendrobium study area

1.1.1 Location and landuse

The study area is located in elevated coastal hinterland, c. 70 km southwest of Sydney at the southern end of the c. 1000 km^2 Woronora Plateau (Figure 14). The area falls within the Sydney water-supply catchment (SCA 2007). The major part of the area is drained by Wongawilli Creek, between the water supply reservoirs Lake Cordeaux and Lake Avon (Chapter 4: Figure 14)

1.1.2 Landform, geology and hydrology

The Dendrobium Colliery extracts coal from the Wongawilli Seam, c. 3.5 m thick at depth from 150 m in the east to 400 m in the west near Wongawilli Creek (Illawarra Coal Holdings Pty Ltd 2007). The seam is part of the Late Permian Illawarra Coal Measures, overlain by the Late Permian – Middle Triassic Narrabeen Group and the Middle Triassic Hawkesbury Sandstone (Illawarra Coal Holdings Pty Ltd 2007; Moffit 2000). The terrain is typically rugged, and consists of sandstone plateaux, with an elevated easterly escarpment draining towards the west (Young & Young 1988). The underlying lithology is dominated by relatively impervious quartzose sandstone, producing shallow watertables with subsurface drainage controlled by joints and seepage planes (Hazleton & Tille 1990). The lithology is dominated by resistant, gently west-dipping Triassic Hawkesbury Sandstone, with scarp retreat controlled by undercutting of the underlying, less-competent Narrabeen Group (Moffit 2000; Sherwin & Holmes 1986). Hydrological investigations suggest that groundwater supplying stream baseflow comes mainly from hillslope aquifers contained in weathered sandstone slopes, soil catenas and swamps (Ecoengineers 2007).

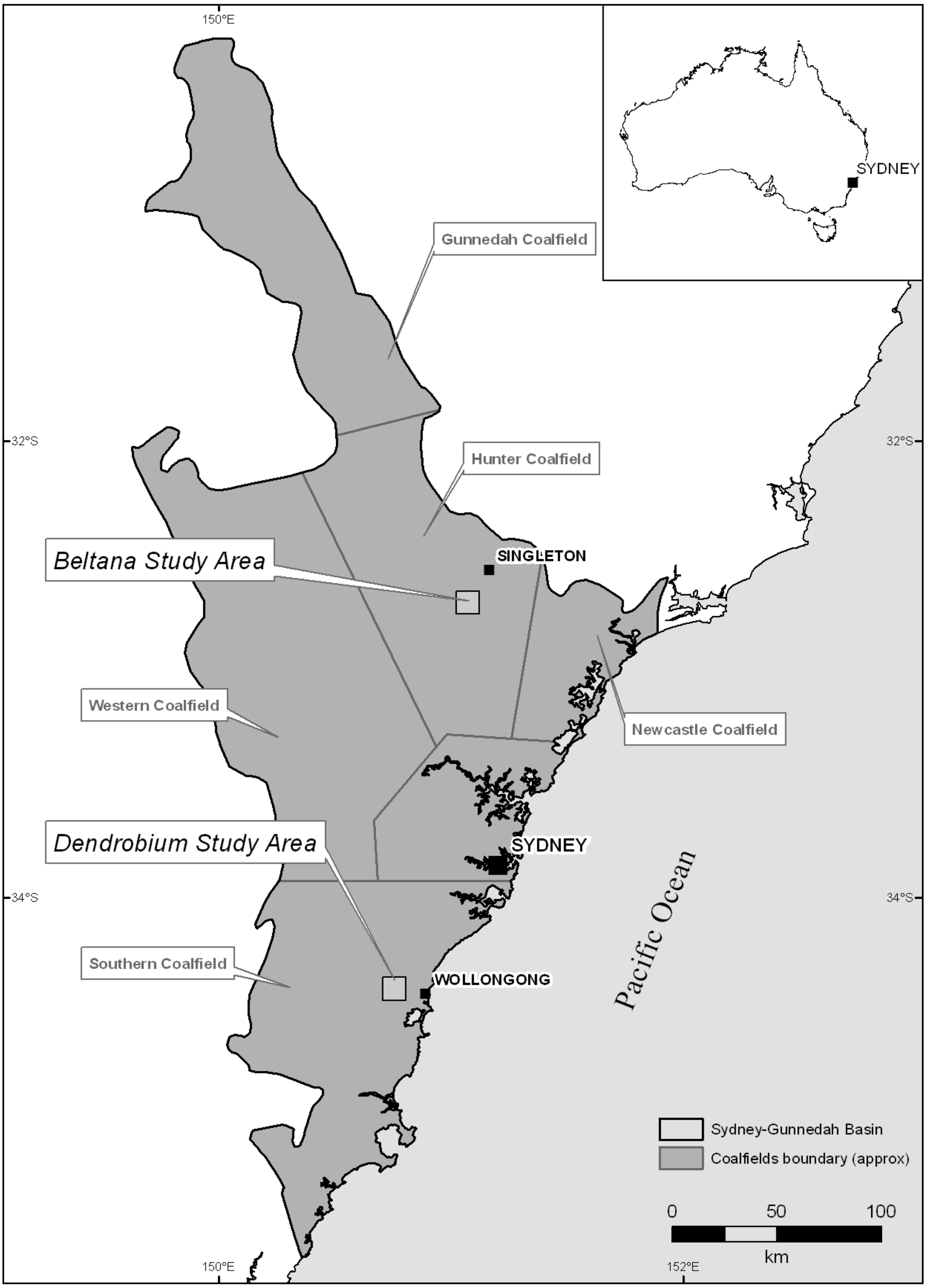

Figure 13 Study areas

1.1.3 Climate

The climate is temperate, with mean maximum temperature at Wollongong varying from 26°C in January to 17°C in July, and rainfall varies across the region from c. 1550 mm in the east, adjacent to the coastal escarpment, to c. 850 mm in the west (BoM 2008). Evaporation generally exceeds precipitation in the area with similar topography and vegetation to the north, except at the seaward edge of the range, where orographic rainfall effects are most pronounced (Keith et al. 2006).

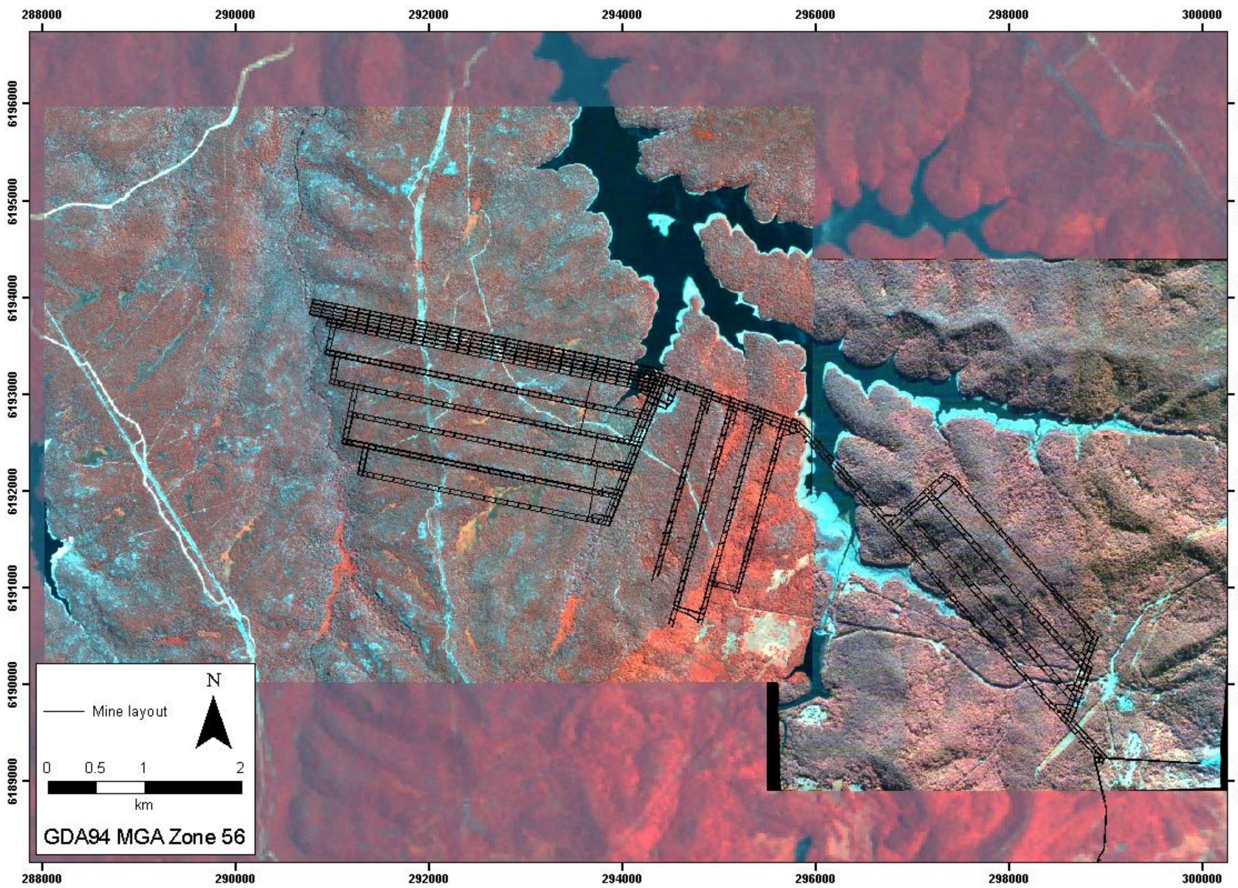

Figure 14 Dendrobium study area

1.1.4 Vegetation

The dominant vegetation of the Sydney Basin consists of open forest, with similar vegetation in the eastern Victorian highlands, and south-western Western Australia (Gill 1994). Vegetation growth is primarily limited by Phosphorous (P) availability. The very low P Hawkesbury Sandstone is dominated by ‘xeromorphic woodland’, with open forest in low P in parts of the Narrabeen Group and overlying lateritic Wianamatta Shale, and rainforest gullies in higher P Narrabeen Shale (*ibid.*). Additional growth control occurs through local-regional rainfall patterns as well as swamp formation in areas of impeded drainage, and seepages with sedges and ferns within open forest (*ibid.*).

The Woronora Plateau vegetation is dominated by mixed eucalyptus woodland with upland swamps, tall open forest and rainforest occupying moister sheltered areas and gullies and becoming increasingly common in higher rainfall areas towards the coastal-side plateau escarpment (NPWS 2003). Common forest trees include Sydney peppermint (*Eucalyptus piperita subsp. piperita* Smith, Silvertop ash (*Eucalyptus sieberi* L.A.S. Johnson), Scribbly gum (*Eucalyptus sclerophylla, E. racemosa, E. haemastoma)*, and Red bloodwood (*Corymbia gummifera* (Gaertn.) K.D. Hill & L.A.S. Johnson) with common understorey shrubs such as *Banksia*, *Leptospermum*, *Hakea*, *Acacia*, *Pultanaea*, and *Dillwynia*. Detailed floristics for the Woronora Plateau is available via published mapping and accompanying report (NPWS 2003). Local, edaphic controls on plant species distribution in wet heathland (upland swamps) are well-established (Keith & Myerscough 1993). Moisture-related variations seem to be more significant for heath-woodland transitions in the Blue Mountains, which is in a similar physiographic setting but west of the current study area, where control by shallow soils, related to slope length and inclination, rather than aspect, is dominant (Wilkinson & Humphreys 2006b).

1.1.5 Fire

Fire is common, with several major fires since 1960 affecting heathland floristic succession (Keith et al. 2007) with the latest major wildfire occurring December 2001 – January 2002 (Chafer et al. 2004).

1.1.6 Disturbance

The rugged topography and low nutrient status of soils that typify the Triassic lithologies (Hazleton & Tille 1990) mean that much of the area is uncleared. Localised disturbance includes powerlines corridors, water supply reservoirs and fire trails. Recent disturbance includes fire trail upgrading, infrastructure emplacement for air shafts, and temporary track construction for seismic survey access (Illawarra Coal Holdings Pty Ltd 2007).

1.2 Beltana study area

1.2.1 Location, landuse and climate

The study area is located c. 16 km south-west of Singleton in the Hunter Valley, NSW (Figure 15). Landuse consists of open-cut and underground coal mining (Bulga Coal 2009), cattle grazing, viticulture, olive farming, and rural residential holdings. Landform is gentle to undulating, with vineyards and other cropping located mainly on alluvium and toeslopes west and south of the underground coal operations areas. The climate is warm-temperate with hot wet summers and cool mild winters. For Singleton, the mean maximum temperature is 30°C December-January and 18°C June-July, and mean annual rainfall 722 mm (1969-1990 figures) (BoM 2008).

1.2.2 Geology

Beltana Underground Mine extracts coal from the Upper Permian Singleton Super Group Wittingham Coal Measures. Extractable resources come from four coal seams within the Jerrys Plains Subgroup: the Lower Whybrow, Blakefield, Glen Munro and Woodlands Hill seams. The uppermost Whybrow seam is currently mined, and seam thicknesses range from c. 1.8 m – 4 m, and seam depth varies from c. 35 m in the north east adjacent to the Whybrow pit, to c. 400 m to the south west (Umwelt (Australia) Pty Ltd 2003, 2009). Soils consist mainly of yellow, red and grey duplex/podsol (Umwelt (Australia) Pty Ltd 2003)

1.2.3 Vegetation

The area is mostly cleared for grazing or planted to vines and olives. Intact native vegetation is limited to the Wollemi National Park, beyond the study area to the south west. The native vegetation is described as Hunter Macleay dry sclerophyll (Keith 2004), which locally consists of mixed eucalyptus woodland containing Narrow-leaved Ironbark (*Eucalyptus crebra*), Grey Box (*Eucalyptus moluccana*), Spotted Gum (*Corymbia maculata*), Broad-leaved Ironbark (*Eucalyptus fibrosa*) Grey Box (*Eucalyptus moluccana*), Forest Red Gum (*Eucalyptus tereticornis*) and Grey Gum (*Eucalyptus punctata*). A grazing-reduced grassy understorey consists of Bull Oak (*Allocasuarina luehmannii*), Black Cypress Pine (*Callitris endlicheri*) and White Feather Honeymyrtle (*Melaleuca decora*) (Umwelt (Australia) Pty Ltd 2003).

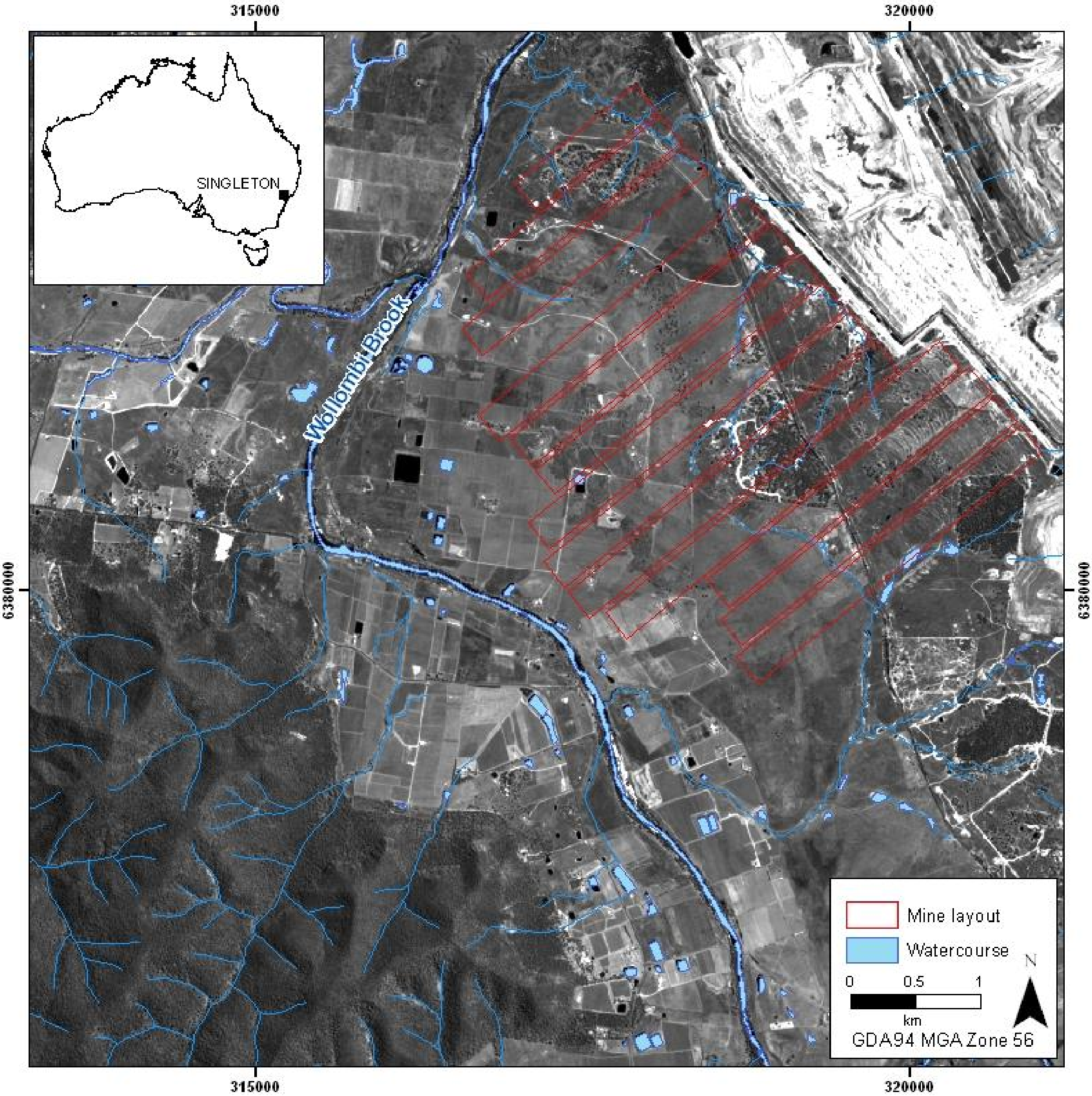

Figure 15 Beltana study area

The study area is situated between Wollombi Brook in the west and the Bulga Open Pit to the north east.