Chapter1
Introduction

This research was based on the premise that a ratio or regression method using empirical equations and allometric models is the most reliable and appropriate non-destructive, field-based method for quantification of biomass and carbon stored in trees, and that the diameter at breast height (DBH) is closely related to tree biomass and carbon stocks. As field based methods are laborious, expensive and time consuming, and often constrained to human-accessible terrain, the aim of this research was to consider alternative methods to field based measurements of DBH which would help in minimizing time and cost involved in undertaking such measurements over large scales. The study focused on remnant vegetation on farming land, in particular scattered Eucalyptus trees owing to their importance in the Australian landscape. The research focused on using remote sensing data as a plausible alternative to field based measurements for DBH and other tree parameter estimations at the whole-farm level.

This introductory chapter begins by articulating the context of this research, introducing relevant tree characteristics and providing a review of remote sensing technologies and potential benefits in large scale mapping. This chapter concludes with the specific aims of the research and an outline of the structure of the thesis.

1.1 Context and defining the research challenge

Carbon dioxide (CO_2) is one of the most important components in greenhouse gases as it traps heat within the atmosphere and causes a global warming effect. Photosynthesis binds CO_2 and stores it as carbon in plants. Plant communities thus act as carbon 'storehouses' and through their impact on CO_2 flux processes, ultimately play an important role in influencing our climate. With the clearing of vegetation on agricultural lands, the carbon is released and the land effectively acts as a greenhouse gas (GHG). When vegetation is restored, carbon is sequestered and the land can be considered a sink of carbon.

Biomass is an important component of the global carbon cycle (Scurlock et al., 2002): forest and woodlands contain carbon in the form of biomass (trunks, branches, foliage, roots, etc.) and organic carbon in the soils, accumulated through growth of trees over the years and increase in soil organic carbon. In addition to forests, grasslands can also act as a carbon sink due to their ability to store large amounts of carbon.

Agriculture is a major feature of Australian life and farms dominate the Australian landscape. More than two-thirds of the Australian landmass is devoted to agricultural production (Wells, 2013) with approximately 90 per cent of farm land used for grazing on native pastures, occurring mostly in the arid and semi-arid zones (Wells, 2013).

The Northern Tablelands region of northern New South Wales (NSW), Australia, is typical of Australian farming land dedicated to the production of livestock and wool (Cottle et al., 2013). Such farming landscapes, or ‘farmscapes’, consist of a range of landscape features such as forests and open woodlands, pockets of remnant vegetation of varying density, sparsely scattered trees, natural and improved grasslands and cultivated pastures and forage crops.

Native eucalyptus trees, both individual and in clusters are an important feature of Australian farmscapes (including the New England Region) and they contribute significantly to above and below-ground carbon stocks in these landscapes (Baffetta et al., 2011; Soto-Pinto et al., 2010). The assessment of biomass in eucalypt systems has, to date, been largely restricted to plantation forestry systems. However there is also a growing need to assess carbon and biomass stocks across our farmscapes in order to fully quantify carbon storage change in response to management and provide evidence-based support for carbon inventory and ultimately carbon trading. Such assessments must also include scattered native trees.

This thesis is ultimately focused on scattered tree communities that exist on these farmscapes as a necessary adjunct to the considerable volume of scientific knowledge surrounding the measurement of biomass in forests and established tree communities. Unlike forestry, where often the spatial extent and composition of constituent trees is well known, farmscapes are as diverse in size as they are in tree composition and density. Certainly, like in forestry, measurement of tree-related biomass and carbon in farmscapes through manual techniques is time consuming and impractical, especially given the potential scale over which measurements must be taken. Furthermore, the spatial heterogeneity of farmscapes renders them unsuited to extrapolation of small-scale measurements too.

1.2 Literature Review

According to the IPCC (Intergovernmental panel for Climate Change) Good Practice Guidance for LULUCF (Landuse, Landuse Change and Forestry (2003), the carbon pools of terrestrial ecosystems involving plant biomass are conceptually divided into above-ground and below-ground biomass, dead mass and litter. Above-ground biomass is measurable with some accuracy at the broad scale. While below-ground biomass stores a large part of total carbon stocks, it is still poorly known because it can only be assessed through *in situ* measurements that tend to be labour- and time-intensive (particularly for forest ecosystems): currently in most of cases the below-ground component is derived from above-ground biomass.

There are a number of ways to measure biomass which can be used either alone or in combination.

Conventional physical methods of biomass estimation

Two methods are traditionally available for the determination of tree biomass (Murli et al., 2005). The destructive sampling which involves physically harvesting the plant material and subsequent extrapolation to a mass value per hectare (Klinge and Herrera, 1983). The second method involves allometry to extrapolate sampled data to a larger area based on easily-measured parameters such as diameter at breast height (DBH), tree height etc. For example, Malimbwi *et al.*, (1994) estimated forest biomass and volume through direct harvesting in the Miombo woodlands in Tanzania. Stromgaard (1985) estimated the above-ground tree biomass in the same woodland using multiple regression analyses of parameters such as measured trunk diameter (at breast height), tree height, and frequency of trees in a specified area.. Both methods proved comparative but similarly proved time consuming, costly and generally limited to small areas and small tree sample sizes (Ketterings et al., 2001; Hyde et al., 2006; 2007). Ultimately they are both labour intensive. In addition, extending this method to map biomass across a large area is extremely challenging because of ecological differences and scattered sources of biomass data. Also, the allometric coefficients developed are often site and species specific, and hence cannot be standardized for all areas (Chave et al., 2005). Nonetheless, efforts have been made to develop generalized regional and national tree biomass equations (Lambert et al., 2005; Case and Hall., 2008) with mixed degrees of success.

Non-destructive biomass measurement

One of the recent advances in biomass estimation approaches is the incorporation of parameters derived from remote sensing. The synoptic view afforded by remotely sensed data offers the capability of capturing the spatial variability in above-ground vegetation parameters such as tree height, crown closure etc. Remote sensing data available at different scales (local to global), from various sources (optical or microwave) and platforms (airborne to space borne), are expected to provide information which can be related directly, and in different ways, to biomass information (Rosenqvist et al., 2003; Foody et al., 2003). Numerous studies have been carried out to estimate tree/forest biomass from remote sensing data (Nelson et al, 1988; Franklin and Hiernaux, 1991; Ranson and Sun, 1994; Steininger, 2000; Foody et al., 2003; Zheng et al., 2004; Zachary and Rundolph, 2005; Sun and Ranson, 2009). ().

Among the different remote sensing data types, optical image data have been widely used for forest biomass estimation with varying degrees of success. These are: Landsat TM (Steininger, 2000; Foody et al., 2003; Calvao and Palmeirim, 2004; Lu 2005), Landsat ETM+ (Zeng et al., 2004; Rahman et al., 2005), IKONOS (Thenkabail et al., 2004; Asner et al., 2002; Greenberg et al., 2005; Song et al., 2010), Quickbird (Hyde et al., 2006; Song et al., 2010); Spot-5 (Li et al., 2006; Soenen et al., 2010), NOAA AVHRR (Barbosa et al. 1999; Dong et al, 2003), MODIS (Baccini et al., 2004), and ASTER (Muukkonen and Heiskanen, 2005). The commonly used biomass estimation approaches are multiple regression analysis, *k*-nearest neighbor, and neural network (Roy and Ravan, 1996; Nelson et al., 2000; Steininger, 2000; Foody et al., 2003; Zeng et al., 2004). Optical image data allows spatial stratification of vegetation for possible direct estimates of biomass, generally through empirical relationships. Different vegetation indices and band ratios from optical image data have been used to extract biomass by correlating vegetation index values or band ratio values with field estimations (Dong et al., 2003). Alternatively image data may be used indirectly, for example by determining tree canopy parameters such as crown diameter using multiple regression analysis or canopy reflectance models (Phua and Saito 2003, Popescu et al., 2003).

Microwave remote sensing data such as Synthetic aperture radar (SAR) data have been found useful for forest ecosystem analyses, particularly in areas of frequent overcast conditions. Radar systems have capability of collecting data in all weather (and light) conditions. The SAR sensor can detect the H (horizontal) or the V (vertical) component of the backscattered radiation. Significant correlations have been found between radar backscatter (P and L bands) and someforest parameters, such as tree age, tree height, DBH, basal area, and total above ground dry biomass (Imhoff et al., 2000; Sun et al., 2002; Santos et al., 2003). A detailed review on use of radar data for biomass estimation can be found in Kasischke et al. (1997; 2004). Previous studies showed SAR L-band data to be more useful for forest biomass estimation (e.g.,Sun et al. 2002) as compared to SAR C-band (Le Toan et al. 1992). Most of the previous studies were based on radar system of single polarization and incident angle and of low resolution, however, with the establishment of Phased Array L-band SAR (PALSAR) and RADARSAT-2 (C-band), the data are now available in different polarizations and resolutions, and varying incident angles and hence can provide more opportunity to assess the potential of SAR data in forest biomass estimation.

The two dimensional nature of optical and SAR data limit their ability of quantifying some vegetation characteristics like tree height, canopy height, volume directly. Light detection and ranging (LiDAR) is a relatively new and sophisticated technology which helps overcome this limitation due to its ability to extend the spatial analysis to a third dimension. A detailed review of LiDAR data application in forestry can be found in Lim et al., (2003). The three dimensional LiDAR points represent latitude, longitude and ellipsoidal height based on the WGS84 reference ellipsoid. There are currently two types of LiDAR in operation today. 1) Discrete return LiDAR (small footprint), and 2) full waveform LiDAR (large footprint) (Todd et al., 2003). Both are generally calibrated to operate in the 900-1064nm wavelengths, where vegetation reflectance is highest (Lefsky et al., 2002). The structural forest canopy measurements permit the accurate estimation of leaf area index (LAI), net primary productivity (NPP), and above ground biomass (Lefsky et al., 2002). For tropical and deciduous forest biomass estimation, large footprint waveform systems have shown to provide accurate estimates (e.g., Drake et al., 2002). The DEM's generated from airborne LiDAR data can be very accurate and are often used in forest mapping and tree parameters estimations. It captures elevation information from the forest canopy as well as the ground beneath and can be used to assess the complex 3D patterns of canopy and forest stand structure such as tree density, stand height, basal area, leaf area index (LAI) and forest biomass and volume (e.g., Lefsky et al., 2002; Næsset and Økland, 2002). The estimation of biomass is generally based on regression equations relating vegetation biomass to LiDAR derived variables. Though LiDAR data was found very useful in forest biomass estimation, particularly in areas of frequent cloud conditions; expensive data acquisition process, complexity in data analysis, software requirement, are few issues that restrict its use for limited applications.

Tree-based biomass studies carried out in Australia

Forests (plantations, commercial forests and conservation forests) cover about 21 per cent of Australia and store an estimated 10.5 billion tonnes of carbon (Forest and Wood products Research and Development Corporation). The Australian Greenhouse is one of the leading organizations working in the field of carbon sequestration and carbon monitoring. In a collaborative effort through National carbon accounting System, the Australian greenhouse Office has developed a national wood products carbon accounting model that tracks the flow of carbon and contributes to the Australian National Greenhouse Gas Inventory. Numerous Researchers have contributed towards the study of biomass and carbon in Australian Forestry system by developing allometric equations for different regions for the predominant species found in the region. A detailed report on Review of Allometric equations for woody regions across Australia ha been prepared by Australian Green house Office (Keith et al., 2000; Eamus et al., 2000). Harrington (1979) carried out a study in Cobar, New South Wales for estimation of above-ground Bbiomass of trees and shrubs. Burrows et al. (2000; 2001) studied allometric relationships to community biomass stocks of Eucalypts and pine. Chen et al. (2003) reported on carbon balance in tropical savanna in northern Australia.

The use of advanced technologies like LiDAR and SAR in forest biomass studies has also been numerous. Though the use of SAR images in Australia dates back to 1992-93, fewer studies have been carried out especially for Eucalyptus forests. Lucas et al. (1990) conducted a Biomass study in Queensland Australia in which they examined correlations between the biomass of mixed species of Eucalyptus woodland with SAR backscatter from both airborne and satellite images. Austin et al. (2002) undertook a study on estimating forest biomass using satellite radar. The results suggested that biomass for Eucalypts can be estimated using satellite radar, taking into account landscape characteristics like topography, surface water and forest structure. Turner (2007) presented an overview of Airborne LiDAR applications in New South Wales forests. Lovell et al. (2014) used Airborne and ground-based LiDARs to probe the structure of forest canopies. Such information is not readily available from other remote sensing methods but is essential for modern forest inventory in which growth models and ecological assessment are becoming increasingly important. They concluded that current laser ranging systems can be used to derive canopy structural parameters such as height, cover, and foliage profile provided information based on multiple returns or the intensity of returns is used to minimize the bias induced by the size of the footprint and the detection threshold. The other LiDAR system which has gained much attention is the near infra red light detection and ranging system, the Echidna Validation Instrument (EVI) developed by CSIRO Australia. A study conducted by Strahler et al.(2008), showed that the forest structural parameters like mean diameter at breast height, stand height, distance to tree, stem count density, Leaf area index and stand foliage profile could be retrieved quickly with good accuracy. Similar study was also carried out by Jupp et al. (2008) for Estimating forest LAI profiles and structural parameters using a ground-based laser called 'Echidna'. Lovell et al. (2004) carried out a simulation study for cost effective measurement of forest inventory parameters. Arroyo et al. (2008) have worked on LiDAR and multispectral data integration for mapping of riparian environments.

1.3 Research objectives

Given the potential of optical remote sensing techniques to provide a synoptic view of landscapes at a range of scales and spatial resolutions, this thesis seeks to investigate the use of remote sensing to infer an important parameter for estimating tree biomass- the trunk diameter at breast height (DBH), for scattered Eucalyptus trees in a New England (Australia) farmscape. It is acknowledged that much research has already been done in the field of tree biomass and carbon estimation using both using image-based remote sensing systems and more recently light detection and ranging (LiDAR) systems. However much of this work is confined to forestry. LiDAR, in particular is widely applauded for its applicability to directly measuring tree structural parameters, from which biomass would be estimated. Yet the technology, especially when deployed in aerial platforms, remains expensive, sophisticated and the generated data requires specialist software and skilled technicians to process it. Despite the promise of LiDAR, large scale, regular, operational use of airborne LiDAR for tree biomass estimations on scattered trees outside the forest (STOF) remains 'scattered'.

Notwithstanding the historical focus on forestry and on LiDAR, image-based remote sensing systems are evolving rapidly with metre resolution satellite systems such as WorldView2, and sub-metre airborne systems now widely available.

The main objective of this thesis was therefore to investigate the potential of very high resolution, image-based remote sensing data for estimating DBH of our scattered trees, while also examining the use of LiDAR as an adjunct to image-based systems rather than an alternative. The work has been divided into the following specific aims:

a) Establish allometric equations for estimating the DBH of scattered Eucalyptus trees (including continuous tree clusters) using regression equations involving physical characteristics such as tree height and crown dimensions,

b) Examine various image processing methods of delineating tree crowns from very high spatial resolution satellite and airborne imagery of farmscapes, and quantify the accuracies of these methods,

c) Evaluate the accuracies of relevant tree crown and tree height parameters as extracted from the remotely-sensed imagery, and

d) Evaluate the performance of entirely image-based methods of inferring DBH of scattered Eucalypus trees in our candidate farmscape.

1.4 Study area description

The research area selected for this study was located within the University of New England's 'Newholme–Kirby SMART farm', Armidale, New South Wales, Australia (longitude 151°360′8.0144″ E to 151°39′34.1217″ E and latitude 30°26′31.9827″ S to 30°24′57.0713″ S) which is extensively used for field based research and livestock studies. The farmscape encapsulates an area of approximately 1500 ha. The study site comprises large tracts of natural eucalypt woodland and pasture cover. Approximately one third of the area is dense eucalypt woodland, one third open woodland, and the remainder native pasture. Most of the study site is unimproved pasture grazed by sheep. The soils within the study site are brown and yellow chromosols, and the mean annual rainfall is 780 mm. The climate is cool temperate with 60 % of the rain falling in the summer months (National Parks and Wildlife Service, 2003; BoM, 2014). Figure 1.1 shows the location map of the study area. The area is dominated by *Eucalyptus* species with other species present. The dominant species are *E. bridgesiana, E.caliginosa, E. blakelyi, E.viminalis, and E. melliodora*

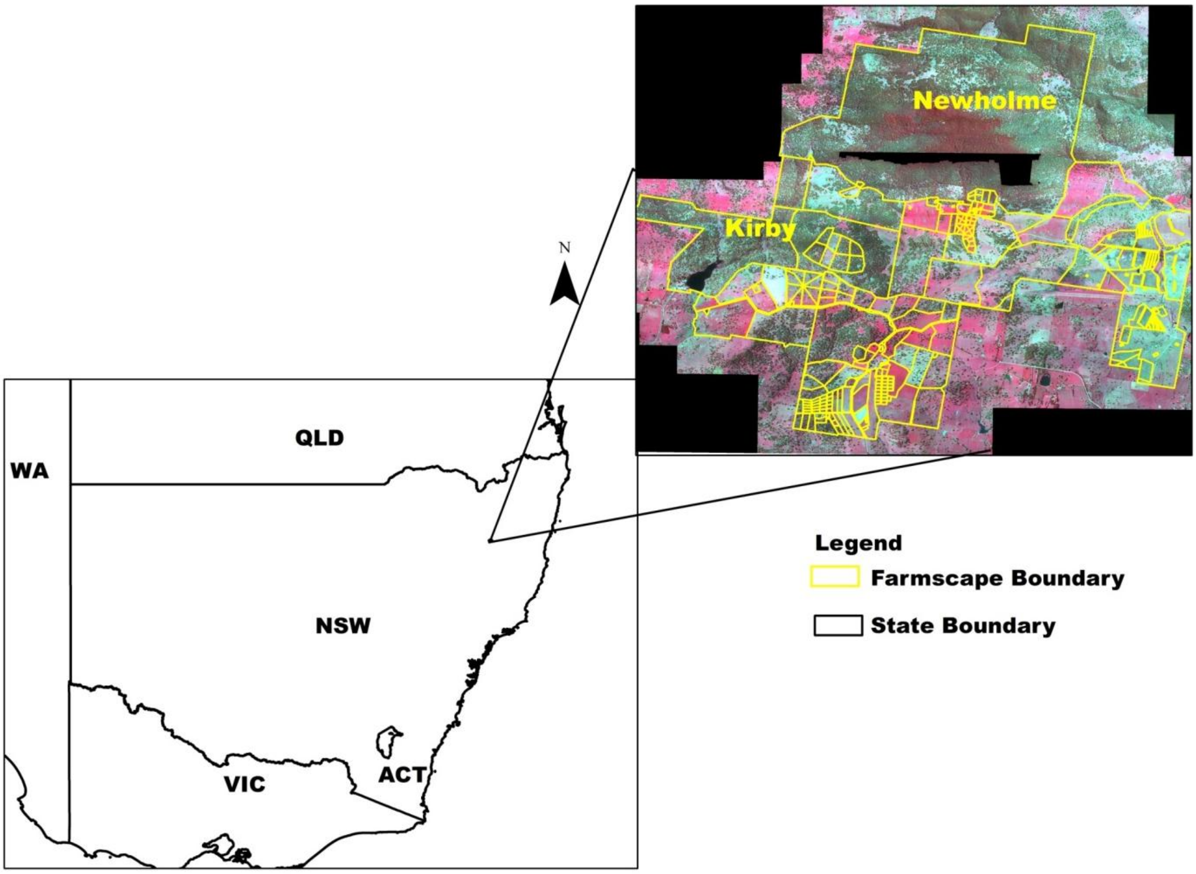

Figure 1.1 Location map of the study area

1.5 Format of this thesis

The thesis comprises ten chapters, three of which have been published as peer-reviewed journal or full conference papers with another one submitted and 'in review'.

The entire thesis has been structured in the following sequence:

Chapter 2 develops allometric equations for estimating DBH of both individual and clusters of Eucalyptus trees based on field measurement of a number of physical tree characteristics. This work was published in the journal *Forest Ecology and Management*;

Chapter 3 investigates image processing techniques to delineate tree crowns in very high spatial resolution (10-50 cm), airborne, multispectral, remotely sensed images. The chapter focusses on comparing feature based tree attribute extraction methods with the conventional pixel based techniques using a number of subjective measures. This work was published in the *Journal of Photogrammetric Engineering and Remote Sensing*;

Chapter 4 examines image processing methods for delineating tree cover from other landscape features in WorldView2 satellite imagery and quantifies the accuracy of the results using a manual vectorization method. This work has been published as a full paper in IEEE Geoscience and Remote Sensing Society's '*International Geoscience and Remote Sensing Symposium*' (*IGARSS 2013);*

Chapter 5 develops a theoretical framework for extracting tree height from shadows in remotely sensed imagery of undulating farmland (i.e. farmscapes) and provides quantitative accuracy data. The chapter has been submitted for publication in the *Remote Sensing of Environment;*

Chapter 6 illustrates and discusses the effect of sensor spatial resolution on tree crown area estimation and identifies an optimum spatial resolution that provides a tree crown area estimation that is comparable to field based measurement methods;

Chapter 7 investigates the use of image-based remote sensing to infer tree canopy volume and determines whether image-based remote is a viable alternative to LiDAR in large scale canopy volume estimations;

Chapter 8 determines whether LiDAR can be deployed, as an adjunct to image-based remote sensing, to estimate the stem density under the closed canopies of tree clusters, and hence provide an average DBH value of each stem under these clusters;

Chapter 9 examines whether LiDAR, and very high spatial resolution airborne multispectral imagery can be used to delineate Eucalyptus species on our farmscape; and finally,

Chapter 10 summarizes the key findings of the thesis, presents a set of general conclusions and highlights future research needs