UNDERSTANDING THE ENVIRONMENTAL FUNCTIONS OF URBAN FORESTS IN SYDNEY, USING REMOTE SENSING TECHNOLOGIES

BY

MINGZHU WANG

DEPARTMENT OF ENVIRONMENTAL SCIENCES
FACULTY OF SCIENCE AND ENGINEERING
MACQUARIE UNIVERSITY
NEW SOUTH WALES, AUSTRALIA

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Declaration

I, Mingzhu Wang, declare that the thesis entitled “Understanding the environmental functions of urban forests in Sydney, using remote sensing technologies” contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Signature: Date:

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Abstract

With global warming and rapid urbanisation, improved urban forest management is essential and, while the importance of green infrastructure is generally acknowledged, surveys of Australian urban forests have identified several major challenges. These include: better protection for existing forest assets and active rehabilitation of degraded areas; increased local government area (LGA) data collection, and vegetation plan development; improved co-ordination between LGAs to resolve forest disputes or priorities; and more comprehensively incorporating ecosystem service benefits into land-use instruments (Chap. 2).

To investigate the general research question of how to integrate remotely sensed data to rapidly assess resources in more detail for better management outcomes, two major transport corridors in the Sydney Metropolitan Area (SMA) were selected for detailed studies. These sites are examples of the linear or dendritic forms of urban forest commonly resulting from urban sprawl. Among residual ecological corridors, roadside forests have become more important due to the high density of road networks. In these SMA studies two remote sensing technologies (LiDAR and aerial hyperspectral imaging) were integrated and results post-analysed using geographic information systems (GIS). The surveys (see Chap.3) demonstrated: unexpected tree diversity on both Parramatta Road and the Pacific Highway; limited and patchy roadside forest distribution, especially along Parramatta Road; the prime role of local government in maintenance and management; how urban vegetation policy had changed and become connected with many other issues; the variability in strategies or management between LGAs and other factors that influence the status and composition of roadside forest.

Urban forests modify microclimates by intercepting radiation and levels of solar radiation are a prime determinant of how much energy urban surfaces absorb and temperature distribution patterns. So understanding shading impacts of trees on buildings is essential to estimating energy use or potential energy conservation. Remotely sensed data sets were used to model direct and diffuse radiation received by building roofs by season, then, radiation profiles were

related to tree features at plot level. Even the limited street trees present reduce radiation received by adjacent building roofs by up to 14% (Chap.4).

To extend understanding of urban trees on received solar radiation in urban environments, further information on individual tree characteristics was needed. Local maxima algorithms identified tree tops, while watershed segmentation was used to delineate individual tree crowns. These attributes were then related to modelled shadows and solar radiation on building roofs. Analyses showed that tree height and canopy area were inversely related to solar radiation, emphasising the importance of keeping taller trees for radiation reductions. Higher ratios between tree and building features (tree height : building height; crown area : building roof area) were significantly related to lower radiation, suggesting that larger trees are more effective in areas with larger commercial or industrial buildings; broad-leaved deciduous species may be more appropriate in these areas, permitting maximal use of lowered radiation in winter. In residential areas with smaller buildings, smaller trees are recommended (Chap.5).

Urban forests create management problems that require active managerial attention. Roadside stands form very extensive networks, comprising a major component of the urban forest complex. The choice of tree species and sizes should be optimised and tailored to different land uses with different building and ground characteristics. The value of existing mature trees should be fully recognised and these larger trees preserved when possible, taking cultural and medical issues into account. To compensate for continuous canopy loss, on-going planting strategies are essential. Aside from monitoring existing forest, integrating remote sensing and GIS can assist decisions for new plantings (Chap.6).

Clearly remote sensing technologies can assess tree characteristics with precision, and model tree environmental impacts and interrelationships. These data can then be used to assist planning for shade provision, improving management and connectivity of all urban forest sub-systems. The basic management framework proposed permits incorporation of diverse data from multiple resources to enhance decision-making.

List of Publications

Book Chapter

Wang, M-Z., Amati, M. and Byrne, J. 2014. Chapter 9 Urban vegetation. pp.104-117. In Byrne, J., Dodson, J. and Sipe, N. (eds.) *Australian Environmental Planning: Challenges and Future Prospects.* Routledge, Oxford, UK. 296 pp. (Chapter 2)

Peer Reviewed Papers

Amati, M., Brack, C., Ghosh, S., Kachenko, A., McManus, P., Shrestha, K., **Wang, M**. and Yung, S-H. 2013. Understanding the carbon and pollution mitigation potential of Sydney's urban forest. pp. 151–158, *Proceedings of the Institute of Foresters of Australia National Conference, April 2013.* Canberra.

Wang, M-Z., Merrick, J. R. and Amati, M. 2012. Urban forests along Sydney transport corridors: the possible role of LiDAR in future planning and management. *Proceedings of the Australia and New Zealand Association of Planning Schools, 2012 Conference 21-23 September, La Trobe University* , Bendigo.

Wang, M-Z. and Merrick, J. R. 2013. Urban forest corridors in Australia: policy, management and technology. *Natural Resources Forum (Special Issue)*, 37(3), 189 - 199. (Chapter 3)

Wang, M., Merrick, J. R., and Chang, H.-C. 2014. Improving urban forest management using remote sensing technologies along transport corridors in Sydney, Australia. *The International*

Forestry Review – Sustaining Forests, Sustaining People: The Role of Research XXIV IUFRO World Congress, 5-11 October 2014. Salt Lake City, USA, Abstracts, 16(5), 31.

Wang, M-Z., Chang, H-C., Merrick, J. R. and Amati, M. Using LiDAR to assess solar radiation reduction from urban forests on buildings along highway corridors in Sydney. *Urban Forestry & Urban Greening*, (submitted in Jul. 2015). (Chapter 4)

Wang, M-Z., Chang, H-C. and Merrick, J. R. Identifying tree characteristics and their contribution to shading impacts along highway corridors using remote sensing. *Urban Forestry & Urban Greening*, (in preparation). (Chapter 5)

Wang, M-Z., Merrick, J. R., and Chang, H-C. Improving urban forest management – A remote sensing approach. *Australasian Journal of Environmental Management*, (in preparation). (Chapter 6)

Reports

Amati, M., Ghosh, S., Shrestha, K., McManus, P., Brack, C., Kachecnko, A., **Wang, M.**, Yung, C-H., Saldarriaga, N. and Gomez, A. M. 2013. *Understanding the carbon and pollution mitigation potential of Australia's urban forest: final report*. Sydney: Horticulture Australia Ltd.

General Article

Wang, M-Z. 2015. Assessing roadside forest resources by remote sensing technologies. *NSW Roadside Environment Committee Newsletter*, February (21), 6-7

Conferences and Workshops

2014 National Green Infrastructure Research Network Forum, Macquarie University, Sydney, NSW, 27 November 2014

Oral Presentation (as sole author)

Title: *Shading roles of urban forest along transport corridors in Sydney*

2014 XXIV IUFRO World Congress 2014, Salt Lake City, UT, United States, 5-11 October 2014

Oral Presentation (as senior author)

Title: *Improving urban forest management using remote sensing technologies along major transport corridors in Sydney, Australia*

2013 NGIA-HAL Research Group, Final Project Meeting, UNSW, 9 August 2013

Oral Presentation (as sole author)

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Title: *Urban forests along Sydney transport corridors: the possible role of LiDAR in future planning and management*

2012 Australia and New Zealand Association of Planning Schools (ANZAPS) Conference, La Trobe University, Bendigo, VIC, 21-23 September 2012

Oral Presentation (as senior author)

Title: *Urban forests along Sydney transport corridors: the possible role of LiDAR in future planning and management*

2012 Climate Futures Workshop, Macquarie University, Sydney, NSW, 4 December 2012

Oral Presentation (as senior author)

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Chapter 1 Introduction and Background

1.1 Impacts of Urbanisation on Vegetation

Australia is one of the most urbanised nations in the world with around 40 percent of the national population living in just two cities, Sydney and Melbourne (Major Cities Unit, 2013). As urbanisation accelerates, expanding urban environments have been highly transformed by human activities and have specific climatic conditions due to high levels of fossil fuel combustion and larger areas of impervious surfaces (Hamada et al., 2013, Vailshery et al., 2013, Middel et al., 2014). Most governments in Australia have attempted to reduce the energy consumption of low-density urban areas by consolidating urban growth and increasing density (Bunker et al., 2002). However, authors have claimed that certain types of medium or high density urban development may pose a threat to existing green suburbs (Troy, 1996, Low et al., 2005). High density housing is always related to the permanent removal of habitats and substantial losses of trees on private property (Lindenmayer and Burgman, 2005, Moore, 2009). Even the lower density suburbs are not as green as they traditionally have been. As the 2010 exhibition 'Boomburbs' by the photographer Andrew Merry at the Museum of Sydney reminds us, the gardens of Australian houses are getting smaller as houses get larger and the size of lots are reduced (Lang and LeFurgy, 2007, Hall, 2010). To enable effective environmental planning all of these forms require careful planning and management of urban trees.

1.2 Urban Forest and Remote Sensing Technologies

The remaining and new vegetation within urban areas play significant roles in mitigating the increasing environmental problems and challenges (Yang et al., 2014). In the broad context, urban forest can be defined as the sum of trees and vegetation on public and private land within cities, including the large remnant vegetation patches, forested water catchments, street trees and trees in parks and private yards (Roy et al., 2012). Major concepts and management strategies that have developed in recent years include ecological permeability, green corridors, catchment management and urban management plans (Thomson, 2006, Carreiro et al., 2007, Grimm et al., 2008, Boon and Raven, 2012, Standish et al., 2013).

The benefits delivered by urban forest are reflected at all scales, from regional carbon sequestration and storage, to energy conservation, reduction in storm water run-off and removal of air pollutants, to local noise reduction, increased property values, and enhanced visual amenity (McPherson, 2000, Nowak and Crane, 2002, Nowak et al., 2006, Nagendra and Gopal, 2010, Sander et al., 2010). The roles of urban forest are changing and their functions now extend beyond traditional urban forest management and link closely to various aspects of environmental planning at the whole city scale. However, due to their size and longevity, urban forests also cause a range of management problems and risks, such as bushfire potential, physical damage caused by trees to buildings or infrastructure, potential damage to overhead and underground services, and medical problems such as allergies or irritations (McPherson, 2000, Brack, 2002). Effective urban forest management should balance both benefits and costs of urban trees (Hitchmough, 1994).

Recently, a variety of models have been developed to estimate different environmental functions of urban forest. Some freely accessible packages such as i-Tree that provides urban forestry benefits assessment have wide international applications (City of Toronto, 2005, Rogers et al., 2011). However, these tools are mainly based on field survey methods which are relatively time-consuming and labour-intensive. The rapid and ongoing development in remote sensing technologies presents great potential for the improvement of urban forest management. Remotely sensed data have been widely used for tree assessment in large natural forests as well as urban areas.

Light detection and ranging (LiDAR) is an active remote sensing technology that emits its own energy and measures radiation reflected or backscattered from the target (Lefsky et al., 1999, Lim et al., 2003). It utilises laser technology to create a three-dimensional point cloud data set that provides accurate elevation information (Lim et al., 2003). LiDAR sensors can be embedded in three types of platforms, which are ground, airborne, and spaceborne (Popescu et al., 2011); but all discussion here is based on airborne LiDAR systems. Although LiDAR has often been used in assessment of large forest areas it can also be used to assess small vegetation patches, including individual trees in very small areas, which is the priority in many urban situations. It generates multiple returns that can penetrate through tree canopies to reach the ground and result in accurate measurement of canopy height (Lefsky et al., 2002) (Figure 1-1). Hyperspectral imagery is a passive remote sensing which only detects natural radiation emitted or reflected by the target (Turner et al., 2003). It provides spectrum information that can be used to identify types of vegetation and potentially to identify tree species (Clark et al., 2005, Dalponte et al., 2008). These two technologies can be integrated to measure a number of tree parameters such as tree height, tree crown width as well as species.

As reduced natural shading is one of the major factors contributing to changed urban environmental conditions, and problematic extremes, the studies in this thesis concentrate on relating tree attributes to environmental functions of urban forest and their shading impacts. Urban forest ameliorates microclimates by shading, evapotranspiration, and wind speed reduction (Akbari, 2002, Simpson, 2002, Tooke et al., 2011, Block et al., 2012). Through these processes, trees planted near buildings can affect household energy usage. Trees can directly reduce the solar heat gain on buildings, as well as surrounding surfaces that radiate heat towards buildings, by shading; and, indirectly, modify energy use by lowering ambient temperature through evapotranspiration and reducing outside air infiltration rate (Akbari, 2002, Loughner, 2012). Since LiDAR data are advanced in providing morphological information of urban objects, LiDAR derived digital surface models (DSMs) are well suited to model shadows and solar radiation.

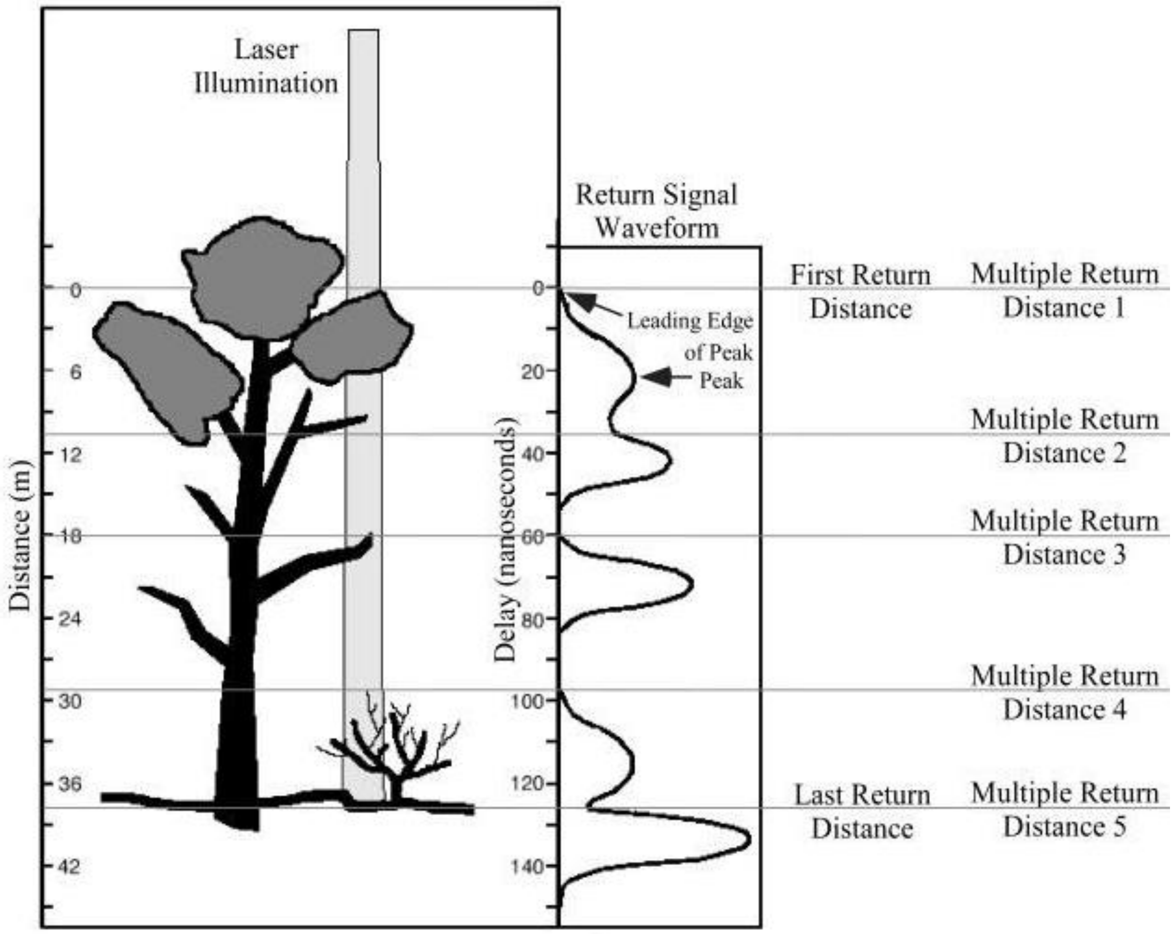


Figure 1-1 Multiple returns from LiDAR waveform. *Source*: *Lefsky et al. (2002)*

The significance of investigating urban forests in the Sydney Metropolitan Area (SMA) is that this is the largest, most densely populated metropolitan area in Australia, with clearly identified population/development pressures. There are unusual conservation challenges because although the SMA is clearly limited by major geographic barriers, it also contains variable topography and high habitat heterogeneity with significant biodiversity (Williams, 2012). Further details of the physical and environmental features of the SMA are provided in successive chapters.

1.3 Research Questions and Objectives

This research initially commenced as part of a broader project to gain understanding of the carbon and pollution mitigation potential of Australia's urban forest which was funded by the nursery industry levy with support from the Australian Government through Horticulture Australia Limited (HAL). The project employed both i-Tree and remote sensing methods, combined with social analysis, to develop a comprehensive evaluation of the environmental contributions that the urban forest can make through carbon sequestration, shading and air pollution (Amati et al., 2013b). As a case study and major facet of the project, this thesis focuses on urban forest along transport corridors, and the primary objectives are:

(a) to demonstrate the significance of existing urban forest corridors or networks and associated public land, as an emerging policy and management issue;

(b) to assess urban forest features and their shading impacts based on airborne LiDAR and Hyperspectral data, using two transport corridor segments as case studies;

(c) to relate shading to broader implications, optimal tree plantings and other factors, and to improve ecological management of roadside and adjacent forest as a basic structural web for all residual urban forest;

(d) to develop a more integrated model for urban forest management using remote sensing technologies

1.4 Structure of Thesis

The thesis consists of seven chapters, of which five are in journal article format: Chapters 2 and 3 have been published and Chapters 4, 5, and 6 have been submitted for review. It is acknowledged that preparing sections of the thesis for publication requires some duplication of basic background and illustrations; however, even when similar tables or figures are included, they have usually been modified or are being utilised in different ways to demonstrate the main focuses of the papers.

Chapter 1 explains the original rationale, outlines the main research objectives, and summarises structure of the thesis and sequence as well as broad connections.

Chapter 2 is based on a chapter contributed to a planning text that has been published (Wang et al., 2014a). The chapter reviews the importance of urban forestry for environmental planners. It provides the broad definition of urban forests and emphasises their ecosystem services. Although increasing urban growth and development have a great influence on urban forest, this chapter demonstrates the often fragmented policy response towards urban forest and highlights potential ways to improve monitoring and urban tree management strategies by employing new technologies. It sets the context of the whole thesis in terms of planning and management of urban forest, the usage of new tools and techniques, and challenges and possible future directions.

Chapter 3 then extends the discussion in more detail on management tools, comparative strategies in Sydney, specific results of surveys and lessons learned. This chapter addresses the increasing need for integrating existing urban forest strategies with other urban issues and illustrates the benefits of using remote sensing technologies such as LiDAR by providing accurate morphological characteristics of urban trees. Using two major roads as a case study, different patterns of the roadside forest resources are found, resulting in high variability in species composition, canopy cover and shading. The discussion demonstrates a number of issues and lessons from conservation, pollution and socio-economic perspectives, which have broader applications and can be related back to policies and planning at regional and local government area (LGA) level. This chapter is based on a paper that has been published in the journal *Natural Resources Forum* (Wang and Merrick, 2013).

Having explained the roles of remotely sensed data in urban forest policy and management, it was logical to undertake specific data analyses to gain understanding of the impacts of urban tree shading. Chapter 4 investigates ways of assessing shading as well as potential energy conservation from street and backyard trees forming a linear urban forest along two major infrastructure routes in Sydney. Two remote sensing technologies, LiDAR and hyperspectral imagery, are integrated to quantify the influence of tree shade on solar radiation received by building roofs – relating radiation to tree attributes and energy demand profiles. After calculating global solar radiation trends for both corridors, LiDAR derived digital surface models (DSMs) are used to contribute to a model of direct and diffuse radiation received by building roofs, at hourly intervals on spring/autumn equinox and summer/winter solstice dates. Correlating solar radiation with different tree and building dimensions, shows that canopy height is the most important factor influencing a reduction in solar radiation across the whole study area. For landscape planners, this shows the importance of preserving taller trees for solar radiation reduction. More broadly the methodology provides a means to optimally use deciduous species and position solar panels. This chapter is based on a paper that has been submitted to *Urban Forestry & Urban Greening* (Wang et al., 2015b).

Since tree features studied in Chapter 4 are measured at plot-level, Chapter 5 refines the measurement to individual tree level by using the same remote sensing data sets. LiDAR provides height models of surface objects and hyperspectral images provide spectral data to extract vegetation. Individual tree crowns are delineated by applying local maxima algorithms and watershed segmentation on these data. Tree attributes are then calculated for each tree segments. These attributes are related to modelled shadows and solar radiation on building roofs. Larger trees are shown to be more efficient at casting shadows. The correlation analyses also show that tree height, crown area, and tree volume are inversely related to roof received solar radiation, again indicating greater effects of large trees in reducing radiation. However, the impacts of these tree attributes substantially decrease within the areas with limited trees. Higher ratios between tree and building attributes are significantly related to lower radiation, suggesting that larger trees are more effective and preferable in areas with larger commercial or industrial buildings and that broad-leaved deciduous species may be able to be utilised more effectively. In residential areas with smaller buildings, smaller species may be considered, balancing tree benefits with various management issues such as damage by larger trees to public services and infrastructure. This chapter is based on a paper that is being prepared for submission to *Urban Forestry & Urban Greening* (Wang et al., 2015a).

Based on previous chapters of data analyses, Chapter 6 connects the overall shading patterns and findings, and urban forest features with practical management as well as conservation. This chapter analyses the key components of urban forest management and develops a more integrated model by using remote sensing technologies. The discussion is around the ecological management of roadside and adjacent forest as a basic structural web for all residual urban forest. The roadside forest along the two corridors is assessed through shading impacts and allergenic species mapping and is linked to broader management issues. Some of these findings were presented at the 2014 IUFRO Congress (abstract only), but this chapter is based on a detailed paper that is being prepared for submission to *Australasian Journal of Environmental Management* (Wang et al., 2015c).

Finally, Chapter 7 draws together all strands of the study. Parts of this chapter are based on the 2014 IUFRO abstract and presentation, but discussion is extended to conclusions and future directions.

Appendix A is the Statement of Authorship which specifies the contribution of authors for each paper.

Appendix B is a peer-reviewed paper for the *Australia and New Zealand Association of Planning Schools, 2012 Conference* (Wang et al., 2012). This mainly focuses on the planning and management of green infrastructure – from an educational perspective.

Appendix C is a paper for the *Institute of Foresters of Australia National Conference, 2013* that I contributed to (Amati et al., 2013a). This paper summarises the initial results of the combined research project, including both i-Tree and LiDAR analyses.

Appendix D is the abstract for the paper 'Urban forest corridors in Australia: policy, management and technology' that is published in *Natural Resources Forum*.

Appendix E is the abstract for the *XXIV IUFRO World Congress 'Sustaining Forests, Sustaining People: The Role of Research'. Salt Lake City, Utah, USA*. 5-11 October (Wang et al., 2014b). This published abstract (*International Forestry Review*) outlines the overall structure of the whole research study.

Chapter 2 Urban Vegetation

2.1 Introduction

Most Australians would be familiar with land that was once covered in trees being cleared for wall-to-wall housing, schools, factories, and roads. When people think about the impact of urban development, vegetation clearing is one of the first things to come to mind. Indeed, land clearing for agriculture and urban development is an important cause of vegetation loss and associated environmental harm (e.g. soil erosion, habitat loss, rising temperatures and sedimentation in waterways) (Lindenmayer and Burgman, 2005). Vegetation loss in many Australian cities is accelerating; as urban development increases, so does land clearing – with significant impacts on biodiversity at local, regional and global scales (Bryant, 2006, Cook-Patton and Bauerle, 2012). If left unchecked, vegetation loss will have profound consequences for humans and non-humans in Australia's cities (Lindenmayer and Burgman, 2005). Environmental planners have an important role to play in better managing vegetation in urban areas.

Urban vegetation plays a vital role in alleviating a range of urban problems such as heat island effects, air pollution, stormwater run-off and noise (Nowak, 2006, Roy et al., 2012). However, urban vegetation can also cause problems, with associated social and financial costs, such as tree maintenance, infrastructure damage, storm-throw, bushfires and even respiratory illnesses like asthma (Roy et al., 2012). In Australia, urban vegetation planning and management revolves around a range of issues, including: fire management, biodiversity conservation, turf and oval management, weed control, and street tree and park management. In this chapter, we focus on urban forests, and we consider the role of environmental planners in their planning and management.

The primary objective of this chapter is to review the importance of urban forestry for environmental planners. The chapter has four aims: (1) showing the importance of urban forests in providing ecological services; (2) demonstrating the fragmented policy response towards urban forest issues; (3) highlighting exemplary responses to the management of urban forests; and (4) explaining how knowledge from new technologies can contribute to improved management strategies. We begin by considering what is meant by the term 'urban forest', and discuss why environmental planners need to know more about urban forests.

2.2 What are Urban Forests?

Urban forests are one of the most visible aspects of the structure of built environments (Pickett and Cadenasso, 2008). Urban forests are not just the large remnant vegetation patches found on the outskirts of cities, nor are they confined to the forested water catchments. Urban forests include these spaces as well as the vegetation in parks. But they also include street trees and trees in private yards. Urban forests can thus be defined as the sum of trees and vegetation on public and private land within cities (Roy et al., 2012). Together with other urban green-spaces, they are often referred to as components of 'green infrastructure' (Gill et al., 2007). An increasingly important aspect of urban forests is their ecosystem services.

2.2.1 Ecosystem services

Environmental planners are gradually recognising that green infrastructure like urban forests can ameliorate a wide range of negative environmental impacts associated with urbanisation (Yang et al., 2009). Urban forests perform ecological and environmental functions that are directly beneficial to humans, but also benefit other species (Cook-Patton and Bauerle, 2012) (see Table 2-1). Ecosystem services provided by urban forests include: noise abatement, light diffusion, wind protection, soil stabilisation, carbon sequestration, and pollutant interception. Urban forests also reduce storm-water runoff and increase infiltration and evapo-transpiration, thus reducing peak-flows and flooding (Roy et al., 2012). Urban forests can regulate urban temperatures too, by shading roads and buildings, thereby reducing cooling costs. On a larger scale, the urban forest reduces urban temperatures by lessening heat island effects (De Groot et al., 2010).

Table 2-1 Summary of ecological and socio-economic functions of urban forest trees- some of these overlap between role categories. *(Wang et al., 2012)*

Role	Function (Source)
Ecological	Refuges and additional habitat, enhancing usage of remaining fragmented habitat (Bennett et al., 1999, Bennett and Mulongoy, 2006)
	Corridors and reserve network for enhancing biodiversity in landscape (Bennett et al., 1999)
	Lower or moderate ambient temperatures through evapotranspiration & shade
	Carbon storage and sequestration mitigate local and global climate change (Nowak and Crane, 2002)
	Mitigate air pollution - remove gaseous pollutants, intercept airborne particles (Nowak et al., 1998, Beckett et al., 2000a, Beckett et al., 2000b, McPherson, 2000, Nowak et al., 2006)
	Intercept rainfall, increasing soil absorption and reducing surface runoff and erosion (Brack, 2002) – in turn, reducing sedimentation in waterways
Economic	Shading decreases incident solar radiation - reduces local air temperature lowering need for air conditioning in summer (McPherson, 2000)
	Reduced wind speed reduces building heating demand in winter (McPherson, 2000)
	Combined effects of shading and evapotranspiration directly modify building energy use (Simpson, 2002)
	Combined effects of shading and evapotranspiration indirectly reduces carbon emissions and air pollutants from lowered power plant emissions (Simpson, 2002).
	Reduce stormwater management costs (Brack, 2002)
Social	Street trees protect pedestrians from wind, rain or sunlight (Nagendra and Gopal, 2010)
	Stress reducing effect of natural scenery (Tyrväinen et al., 2005)
	Increased aesthetic qualities and health benefits (Powe and Willis, 2004)
	Improved property values in immediate area (Anderson and Cordell, 1988, Laverne and Winson-Geideman, 2003, Sander et al., 2010)

Although these 'ecosystem services' are well known by environmental scientists and ecological economists, and forest managers, they are seldom factored into urban development decision-making or enshrined in urban policy or land use planning instruments (Tyrväinen et al., 2005). This is partly because environmental planners are not sufficiently aware of forest planning and management. This situation must change, because many cities incur unnecessary costs by not accounting for the myriad free services that urban forests provide (Young, 2010).

2.3 The Impact of Development on Urban Forests

Unfortunately land use planning and development policies in Australia have contributed to a reduction in the amount of urban green-space. This has occurred though broad-scale land clearing on the urban fringe, but also vegetation clearing in middle and inner suburbs, through the loss of backyards and even some parks due to urban densification (Byrne et al., 2010). Because low-density urban sprawl has many negative impacts, including longer commuting times, declining levels of physical activity, and higher levels of energy use, most Australian state and local governments have attempted to reduce the environmental, social and economic costs of sprawl by consolidating urban growth and increasing urban densities (Bunker et al., 2002, Byrne et al., 2010). However, some commentators now argue that medium and high density urban development poses different environmental problems – especially the loss of green-infrastructure and the ecosystem service benefits it provides (Byrne et al., 2010). Higher density development is often accompanied by habitat-loss, particularly substantial losses of trees from private property (Lindenmayer and Burgman, 2005). Even the lower density fringe suburbs are not as green as they used to be. Australian backyard gardens are getting smaller as houses sizes get larger and lot-sizes decrease (Hall, 2010). To ensure the longer-term functioning of the urban forest (much of which is located on private land), we need more effective planning and management of public and private green-space.

In most urban areas of Australia, local government (city, town or shire councils) is largely responsible for the day-to-day regulation or management of urban forests. Presently the planning and management of urban forests across local government areas (LGAs) in Australia is somewhat haphazard (Wang et al., 2012). As noted above, incorporating ecosystem services into urban decision-making processes is still performed in a rudimentary fashion. In a few of the major metropolitan areas, regional forest management strategies have been adopted by some groups of LGAs (e.g Melbourne, Canberra), but they are rare. While some local governments have dedicated street tree teams and tree management plans in place, others pay scant attention to this task.

Some councils regard green infrastructure as a maintenance burden, or as a minor concern, subordinated to engineering services. This means that non-traditional green-spaces are becoming more important in urban management, including transport corridors, rail reserves, brown-field sites, and other ‘left-over’ spaces. But a lack of data about trees within such spaces, combined with poor tree management strategies, has slowed our progress towards better managing urban forests in Australia. So what steps can environmental planners take to improve urban forest planning and management, especially the recognition of ecosystem service benefits?

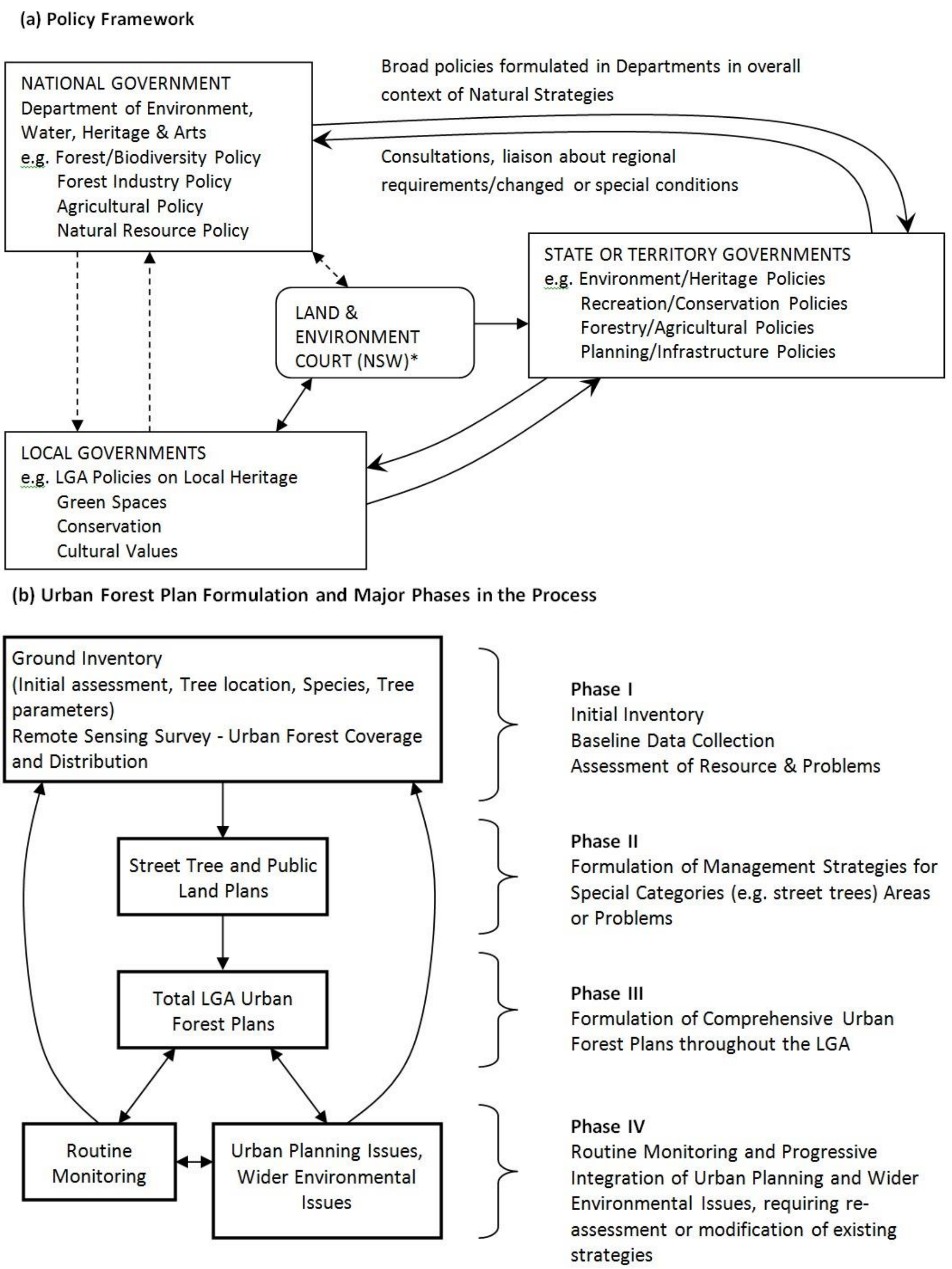


Figure 2-1 General summary of: (a) broad Forest Policy framework and interactions; (b) Urban Forest Plan formulation and modification, in the Sydney Metropolitan Area; and major phases in the process. *Adapted from Wang et al. (2012)*

* In NSW this separate court is charged with conflict resolution (policy interpretation) of environmental issues at all organisational and individual levels.

Note: Dashed lines in (a) represent less frequent, intermittent or indirect interactions (usually of limited importance).

2.4 Planning and Management of Urban Forests

Vegetation within cities requires special consideration for two reasons. First, remnant vegetation in 'urban environments are often linear or dendritic (branch-like) in shape. They are thus relatively susceptible to edge effects' which can harm their ability to maintain biodiversity and ecological function (Lindenmayer and Burgman, 2005 p. 244). Edge effects occur at the edges of vegetated areas, and include: increased evaporation, greater penetration of sunlight, higher temperature, greater risk of fire, and increased competition from predators and weeds. Second, although the number of plant species especially vascular plants is very high in urban areas, the number of threatened and rare species is also high. This is because plant species distribution and composition have been continuously affected by human activities (Bryant, 2006). Since many exotic species are pioneer type species they are more tolerant of paved areas and more commonplace in urban areas, making the conservation of native species a challenge.

The factors affecting urban forest management can be divided into four categories: biophysical, socio-cultural, economic and political/legislative. These factors all influence the health and longevity of urban forests. They are discussed in turn below.

2.4.1 Biophysical factors

Environmental characteristics such as soil type, soil condition, landform, latitude, altitude, rainfall, and local climate all influence the type of trees found in urban forests. Other biophysical factors include whether a tree species is native – which affects disease resistance; and road reserve width – which affects the room available for tree growth (Roy et al., 2012). Although many common native species in Australia like *Eucalyptus* are well adapted to soils with low nutrient levels and rapid drainage, the growing conditions in urbanised areas can be radically different from natural environments.

Urban soils are often highly compacted; soil pH may vary widely, as will soil moisture, the presence of organic material, soil micro-organisms, pollutant levels and temperatures – all critical for tree survival. Endemic (local) species may therefore perform poorly in urban areas. Conversely, many exotic species will often perform better because they are more tolerant of urban conditions. An example is the London Plane Tree (genus *Platanus*) which evolved to withstand regular oxygen starvation of its roots on Northern Hemisphere flood plains, but now thrives in oxygen deficient soils of urban areas around the globe (including Australia). Some deciduous exotic trees have the added advantage of permitting energy savings – through providing summer shade but access to winter sunlight. Considerations in the selection of species for new (or replacement) plantings in urban forests are summarised in Table 2-2.

2.4.2 Socio-cultural factors

Cultural factors also impact urban forest planning and management. People's preferences for particular growth-forms (e.g. open, spreading branches), as well as their aesthetic values (such as overall canopy shape and tree spacing), strongly influence which trees are selected for urban forests. For example, psychological studies on the positive effects of vegetation on human well-being, have demonstrated strongly positive innate reactions to colour (e.g. flowers), and preferences for open, savannah-type woodland (Lohr, 2013). Other considerations include community attitudes to the wildlife that uses the forest, safety concerns about trees or wildlife (e.g. falling branches or animal attack), land-owners' knowledge about tree suitability and maintenance, as well as the values of tree management agencies or local officials (e.g. local councillors) (Kirkpatrick et al., 2013).

2.4.3 Economic factors

Economic considerations include direct maintenance costs of conserving urban forests, as well as the costs associated with tree interaction with adjacent infrastructure (e.g. powerlines, water mains, fibre-optic cables). They also include the savings afforded by tree ecosystem services (discussed earlier in 2.2.1), as well as other revenue-generating activities such as tourism, commercial retail zones and property values. Planners need to account for all of these factors. Indeed Ely (2009 p. 17) has argued that 'streets, and other urban spaces, should be designed or reconstructed to provide greater opportunities for tree planting, and to provide more space and better growing conditions for each tree'. Many local authorities undertake routine tree inspections and maintain a database which catalogues characteristics such as tree species, age, condition, maintenance schedules and replacement dates. As we explain later, newer integrative urban forest management tools (e.g. i-Tree or UFORE) now enable the calculation of comprehensive dollar values for individual tree species, in terms of their ecosystem service benefits, allowing environmental planners and managers to more effectively value the net worth of urban forests, thus facilitating the protection and management of urban vegetation (Roy et al., 2012).

2.4.4 Political/legislative factors

Planning legislation and policies at all levels of government also impact urban forest management. These include international frameworks such as Local Agenda 21 and Habitat for Humanity, the Kyoto Protocol and Convention on Biological Diversity. At the national level, tree governance is shaped by Commonwealth Government policies on climate change, carbon pollution reduction, health, and biodiversity. Many State governments now have legislation or policies that seek to minimise broad-scale tree clearing and some local authorities have written these into town planning scheme provisions or have translated them into local laws. Local authorities also must regulate the impacts of urban forests on public health and safety, need to assess the risk of property damage, and must have liability assessments in place as part of urban tree policy formulation. Many of these concerns are now addressed by comprehensive urban forest plans (see Figure 2-1).

2.5 Tools and Techniques

It is important that environmental planners are able to assess the extent and coverage of urban forests, as well as the type of tree species they contain, and the health of individual trees in forest patches. This can be achieved in a variety of different ways, including by aerial photography and remote sensing (e.g. satellite images), as well as through field surveys and spatial analysis using geographic information systems (Roy et al., 2012). The development of new technologies has meant that tasks related to monitoring urban forests have become much easier (Wang et al., 2012). However, their uptake in Australia has been slow.

New remote sensing technologies such as LiDAR are increasingly being used to collect baseline data for urban forest management. Light detection and ranging (LiDAR) has been extensively used by the forestry industry in the United States for decades, and its use has been well documented by researchers. Although it is only recently that some Australian local governments have begun to use LiDAR, it has many benefits, including: surveying large areas in a short time; producing a very comprehensive database for subsequent analysis; yielding accurate assessments of areas, tree distributions and tree condition; is non-invasive, thus minimising problems of access or privacy; and permits identification of changes or problems that, if necessary, can be investigated by on-ground staff (Jung et al., 2011).

Environmental planners need a variety of data to be able to build a comprehensive inventory of forest assets within municipal jurisdictions, and to estimate their environmental benefits. Newer remote sensing technologies enable forest managers to gather very detailed digital data over wide geographic areas in comparatively short timeframes. Such data permit the identification of vegetation types, even in inaccessible areas, and allow the production detailed models that demonstrate interrelationships between green and 'grey' infrastructure. Detailed modelling using these data can expand environmental planners' capacity to direct urban growth into appropriate areas and facilitate better designs that maximise the multiple benefits of urban forests. As mentioned above, one priority of local government has been to better value their urban forest assets. The quantification of tree values can ensure the appropriate recognition of trees in land use decision-making processes.

2.6 A Case Study: Urban Forests within Sydney Metropolitan Area and Transport Corridors

To better understand how environmental planners and managers can use data from urban forest assessment, it is useful to consider a case study. The Sydney metropolitan region is the largest most densely populated urban area in Australia, with many of the same problems and issues facing cities world-wide. Figure 2-2 below shows the extent of the core metropolitan area as well as the broad distribution of remaining urban forests and corridors. Two major green areas are located to the south and north of Sydney. The Royal National Park comprises most of the southern zone, while Ku-ring-gai National Park and associated smaller National Parks make up the northern zone. Other green areas within the core of the metropolitan area are comparatively very small. Although the Sydney metropolitan region exhibits extensive topographic and local climate variability, habitat fragmentation is threatening biodiversity. Much of this fragmentation is due to transport infrastructure.

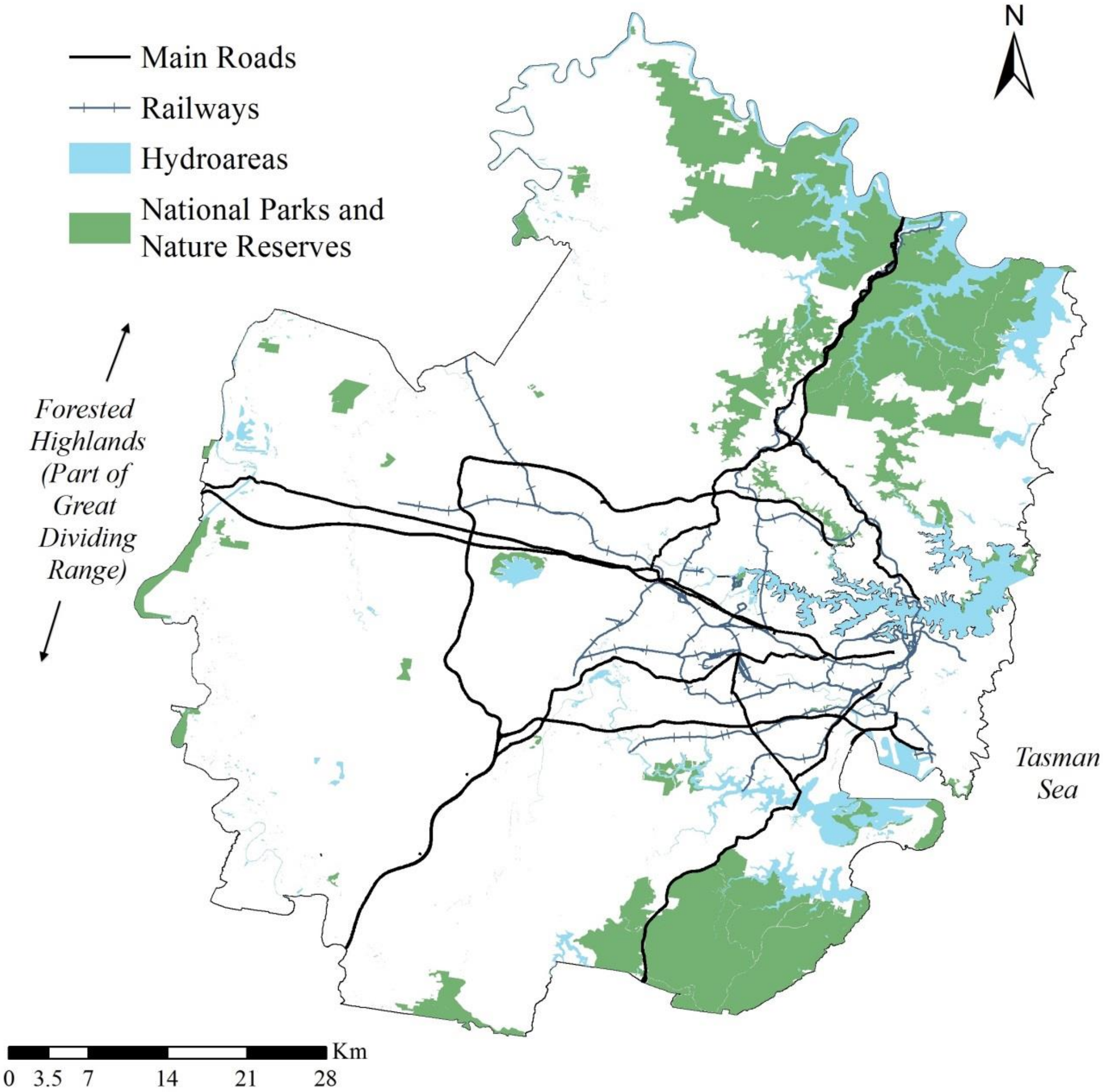


Figure 2-2 Sydney Metropolitan Area showing Urban Corridors (major roads, railways) and Green Areas (National Parks, Reserves). *Data Source: ABS and NSW Lands*

Transportation infrastructure – main roads, highways and railway lines – is concentrated in the urban core of Sydney. While transportation infrastructure offers many socio-economic benefits, it causes extensive habitat fragmentation. Roads and railways can be impassable barriers for animals, restricting gene flow. Vehicle collisions also bring injury and death for individual animals (Bennett et al., 1999, Keller and Largiadé, 2003, O'Brien, 2006). Disturbance to habitats during transport infrastructure construction and ongoing maintenance may also encourage invasion by exotic plant species and feral animals, and can impact adjacent habitats through edge effects (Hansen and Clevenger, 2005). For example, Williams et al. (2005) have found that a primary reason for native grassland degradation in Sydney was their proximity to major roads (Figure 2-3). Transportation construction destroyed native grass patches along and around the route, resulting in the fragmentation of native grasslands.

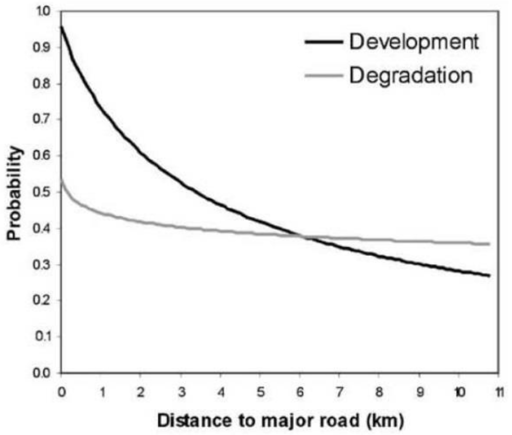


Figure 2-3 Probability of a patch being destroyed by development or substantially degraded with distance to a major road. *Adapted from Williams et al. (2005)*

But transportation corridors can also be beneficial. While the importance of greenways (natural corridors connecting reserves and open spaces) has been widely recognised (Bryant, 2006), the value of roadside vegetation and reserves is often underestimated. Vegetation along these corridors can have particularly important functions in mitigating the impact of vehicle pollution. In Australia, the many roadside areas encompass remnant natural vegetation types such as eucalypt forest or woodland, shrublands and grasslands. These floral complexes include diverse species (Bennett et al., 1999). Road reserves can provide extensive linear habitats for plants and animals too, because of the high density of road systems in cities. But this of course depends on the level and type of management. Roadside vegetation can also play a role as pathways linking urban green areas and facilitating the movement of wildlife between habitats. While many Australian vegetation communities remain intact within urban landscapes, the road verges and railway reserves also provide unique habitats (Lindenmayer and Burgman, 2005).

However we lack baseline data for urban forest condition along the full length of such infrastructure corridors because major transport corridors transect different LGAs. This information is essential to estimate the benefits of these corridors for conservation, as well as their ecosystem services benefits. Moreover, the urban tree data collected by local governments are largely limited to public lands. But trees on privately-owned land are also an important element of urban forests, and need to be accounted for if models are to be accurate (Ghosh and Head, 2009).

2.6.1 Initial surveys – transport corridors

Sections of two long-established major highways in Sydney (the Pacific Highway and Parramatta Road) were surveyed to analyse the vegetation along these transport corridors. Local Government Authority (LGA) plans for the urban forests in these corridors were also assessed. The survey length was around 20 km – along a gradient running from inner central business districts to outer suburbs. One survey extended along the Pacific Highway – from North Sydney to Hornsby. The other extended out along Parramatta Road – from Camperdown to Parramatta (see Figure 2-4). The survey band included the carriageway and road reserve as well as adjacent land up to about 150 metres either side of the road. These particular highways each have five categories of land use (business, residential, industrial recreation, others) along their length.

In addition to the field surveys, existing information was analysed in four ways. First, cadastral data of study areas were combined with land zoning maps from local governments. Then two sets of Geographic Information System (GIS) vegetation data were used to estimate the woody extent and vegetation community distribution along the two corridors. In addition, the GIS layer of native vegetation of Sydney Metropolitan CMA Area in 2009 was obtained from the Sydney Metropolitan Catchment Management Authority (CMA). Finally, immediately after the field surveys, the Tree Management section at each council was contacted to ascertain the status of existing vegetation databases and comment on current problems as well as plans.

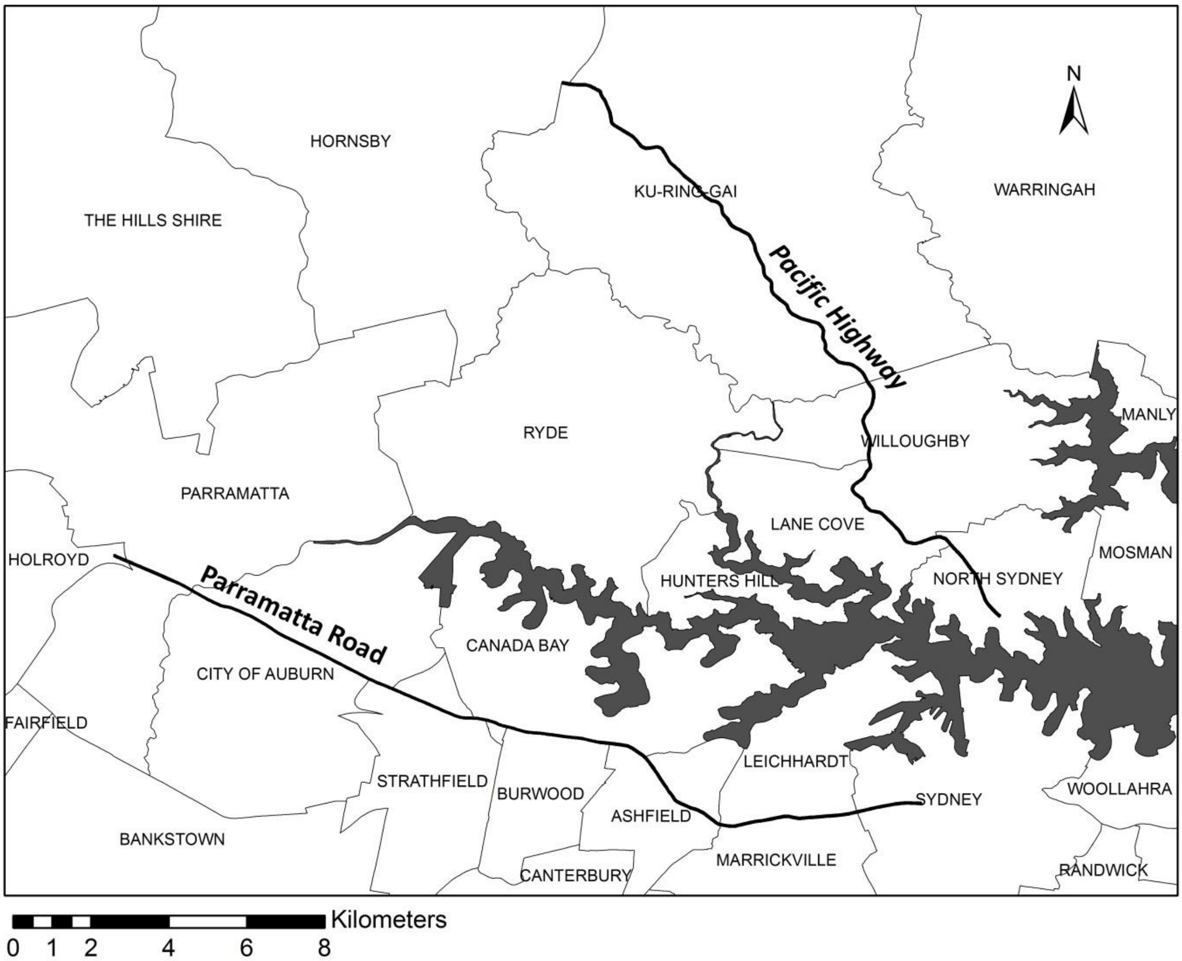


Figure 2-4 Map of inner metropolitan area showing the lengths of Parramatta Road and Pacific Highway surveyed as well as Local Government Area (LGA) boundaries. (Wang et al., 2012) *Data Source: ABS and NSW Lands*

The field surveys demonstrated the following:

- unexpected diversity – beneficial from a conservation point-of-view, but needing more intensive management;
- wide variation in overall species diversity and component species within local areas and between different sections of each corridor;
- very patchy tree distribution in some areas;
- planting and maintenance of some species that did not contribute to conservation, and had limited ecosystem benefits.

The above-described research also found that most councils in the study area had street-tree strategies, at varying levels of development, but they were upgrading their databases and management plans for vegetation in road corridors. Their understanding of the vegetation in the transport corridors, and tree benefits, was therefore limited. Trees in the corridors also presented some costs to local authorities (see Table 2-2). They pose a significant fire risk, and maintenance costs are also high due to leaf and branch litter, and pavement damage (caused by tree roots).

For effective tree management, environmental planners and managers need comprehensive and current tree data. For example, environmental planners can better predict potential problems caused by larger trees if they know the growth rates and maturation height of individual species, and can map the spatial distribution of those species in a municipal area and their proximity to grey infrastructure. As more complete urban forest inventories become available, it is clear that some urban tree stocks are ageing and declining rapidly. For example, in Melbourne, modelling forecasts that 44% of existing urban trees will be lost within the next two decades (Shears and Lynch, 2013). Another management consideration, specifically related to transport corridors, is that although trees planted along these corridors are known to reduce pollution, they have often been undervalued in urban planning. More research is needed to maximise the ability of planners to use urban trees to achieve planning goals – such as adapting to climate change impacts or reducing air pollution. In regard to the latter, we need information about important variables such as distance from the pollution source, density of foliage, and leaf surface texture. (Sæbø et al., 2012) studied leaf characteristics and pollution interception. Unfortunately even when that data is available, we have some way to go before environmental planners can routinely use it in decision-making.

Table 2-2 Summary of factors, limitations or problems that need to be considered in urban tree management. *(Wang et al., 2012)*

Factor, Limitation or Problem	Source
1. Maximum benefits from urban forests are only achieved when density of the tree canopy is appropriate and when each individual tree is properly maintained and replaced when necessary.	(North Sydney Council, 2006)
2. Inappropriate plantings in unsuitable conditions or locations can cause different kinds of problems in local environments or communities. For example: particular tree or grass species can cause allergies or irritations by producing a greater pollen load leaf or fruit droppings can increase litter problems or make ground slippery when fleshy fruits or leaves decompose	(City of Sydney, 2011)
3. Root systems of some vigorous or large growing species can cause damage to underground services, pavements, kerbs and properties	(Pittendrigh Shinkfield Bruce Pty Ltd, 2005, City of Sydney, 2011)
4. Maintenance costs may outweigh benefits when urban trees reach a certain stage or life span (over-maturity) or are in poor condition	(North Sydney Council, 2006)
5. Species selection – especially for new plantings of street trees – should consider: (a) local climate, geology, soil and topography (especially in relation to drainage); (b) growing space – relating to overhead / underground services; (c) height, maturation size, foliage (deciduous / evergreen) and physiology; (d) tolerance to pruning	(Pittendrigh Shinkfield Bruce Pty Ltd, 2005, North Sydney Council, 2006)

2.7 Challenges and Future Directions

This chapter has provided an overview of urban forests, emphasising their ecosystem benefits and identifying planning and management issues. We have illustrated the advantages of new tree management technologies for environmental planners, and have demonstrated their importance in terms of ecological functions – using a case study from metropolitan Sydney.

In the longer term, effective urban forest planning and management requires that local governments not only prevent broad-scale tree-clearing – as is standard practice today, they must also improve their monitoring, maintenance, and replenishment of urban trees assets.

This has important repercussions for environmental planning. For example, green walls and green roofs are currently widely recommended in urban planning policies and guidelines, especially those addressing the impacts of urban consolidation on trees. But these interventions may not always be appropriate, and they should not been seen as a substitute for urban forest conservation. Street tree planting as a climate adaptation strategy is also widely advocated, but it too may have some problems.

For example, the Gold Coast City Council has been planting 15,000 street trees every year for the past several years. While this is an admirable and exemplary practice, we know little about the impact this could have on groundwater. How will it affect property values? How are residents responding to the trees – are some trees being vandalised more than others? If so, is this due to the species planted or where they are planted? Are there any impacts on perceived safety? What are the longer term implications for bat colonies in the city – several of which are already being targeted for removal or eradication? We need answers to these and other important questions if urban forests are to function as effective environmental planning tools (Cook-Patton and Bauerle, 2012).

This chapter has pointed to five major challenges for effective urban forest management. (i) Better management invariably requires better protection of existing forest assets and restoration of highly degraded or cleared areas. (ii) Municipalities need to adequately resource data collection, on-going monitoring, and vegetation plan development. (iii) Councils also need to improve co-ordination between programs in adjacent LGAs to effectively resolve disputes about their forest planning and management priorities. (iv) Ecosystem service benefits must be better integrated within land use planning instruments.
(v) We need to look to novel solutions for improving urban forest cover, including using infrastructure corridors (like roads) as green-links between fragmented habitats – thus turning a problem into a solution.

This chapter provides a broad overview of urban forests including definitions, their benefits and costs, urban tree management and planning, and future challenges and directions. Specific issues associated with urban forest assessment and policy development are further discussed in the next chapter, where the links between new tools such as remote sensing systems and tree management are emphasised as well.

Chapter 3 Urban Forest Corridors in Australia: Policy, Management and Technology

3.1 Introduction

When terms such as forest degradation or management are used, many people think of pristine forests in a remote area being cleared for timber, agricultural development or mining. As urbanisation is expanding globally, native vegetation has been reduced or removed. As a result, many forms of the remaining vegetation are becoming part of a major category of forests. Awareness has increased as to the importance of urban forests for ecosystem function and their economic significance. The benefits and costs of urban forests are demonstrated in Table 3-1. The roles and functions of urban forests have been well documented, but preservation is subject to their status as central components of policy and legislation; maintenance and effective use of these resources also raises new and special monitoring challenges (Wang et al., 2012).

Table 3-1 Summary of benefits and costs of urban forests.

Costs	Benefits	
	Socio-economic	Environmental
• Bushfire potential/flammability risk • Physical damages caused by trees to buildings or infrastructure due to storms • Reduced visibility • Potential damage to overhead and ground service • Increased maintenance/husbandry costs • Allergies or irritations	• Energy saving • Enhanced property values • Increased aesthetic values • Increased social well-being • Health benefits	• Carbon sequestration and storage • Air pollution mitigation • Microclimate mitigation • Reduction in storm water run-off • Remaining wildlife habitat • Biodiversity values

Sources: *McPherson (2000), Brack (2002).*

Australia is one of the most urbanised continents. In the context of global warming, it is appropriate to investigate changing planning situations, as they relate to policy formulation, and discuss the technological potential for improving management. This paper focuses on policy, management and technology associated with urban forest corridors in Australia. The prime objectives of this chapter are: (1) to demonstrate the significance of existing urban forest corridors or networks and associated public land, as an emerging policy and management issue; (2) to summarise the policy framework and interactions with changing planning parameters and management; and (3) to use Sydney as a major metropolitan area in Australia — especially the road corridors — for showcasing the management challenges. To demonstrate the importance of the remaining urban forests, the current situation in the Sydney metropolitan area was briefly reviewed and two long-established main roads in Sydney were selected for detailed studies of the roadside forest resource. The emphasis in the succeeding sections is on publicly owned land for three reasons: (1) the majority of the remaining urban forests are on land managed by a limited number of government or statutory authorities; (2) significant areas can be managed more effectively for specific purposes in the near to medium future; (3) management of all public areas can be coordinated in ways that are not possible with private holdings. The situation discussed and examples used are within a major metropolitan area of a developed nation; however, many of the features, processes, problems and potential solutions are equally relevant elsewhere.

3.2 Urban Forest Assessment, Policy and Management

3.2.1 Available tools for urban forest assessment

Initial forest assessment techniques have developed enormously in the last 20 years. A number of studies have investigated the specific environmental impacts of urban trees and the pollution mitigation capacity of urban forests. Researchers at the United States Department of Agriculture Forest Service have been developing the Urban Forest Effects (UFORE) model since the 1990s, aiming to quantify urban forest structure and functions (Nowak and Crane, 2000). This model utilises four modules to analyse the anatomy of urban forest, biogenic volatile organic compound emission, carbon storage and sequestration and dry deposition of air pollution (Nowak and Crane, 2000). A number of studies have adapted the UFORE model to investigate the environmental functions of urban trees (Nowak and Crane, 2002, Yang et al., 2005, Currie and Bass, 2008, Escobedo and Nowak, 2009).

Based on the UFORE model, a package called i-Tree, which is a comprehensive tool for urban forestry analysis and benefit assessment, is freely accessible to researchers, local government as well as general communities (https://www.itreetools.org/). i-Tree has been widely used internationally (City of Toronto, 2005, Rogers et al., 2011) in recent years. It provides valuable information for decision-makers to enhance urban planning and forest management. The urban forest assessment by i-Tree is based on field collected data. In Australia, North Sydney Council has developed its urban forest strategy based on calculated economic values of existing urban forest using i-Tree (North Sydney Council, 2011).

Researchers in Australia have developed another computer system, the Decision Information System for Managing Urban Trees (DISMUT). This system includes inventory and growth models as well as modelling of urban tree values, considering energy, pollution and hydrology benefits, and greenhouse gas reduction (Brack, 2002, 2006). This system has been used to predict pollution mitigation and carbon sequestration by urban forests in Canberra (Brack, 2006).

3.2.2 Phases in developing plans

The expanded baseline data and increasingly refined outputs from the models have been an essential basis for the formulation of initial policy and management plans. For most urban areas in Australia there are two levels of policy or managerial influence: (a) State or Territory Government (or associated authorities); and (b) local government (or shire councils), which is largely responsible for day-to-day regulation or management. In a few of the major metropolitan areas (e.g., Melbourne, Canberra), there are also regional strategies adopted by groups of local government areas (LGAs).

Figure 3-1 gives a generalised summary of links between policy and management in the Australian context. Figure 3-2 demonstrates the medium to long-term phases of the urban forest plan formulation and management process, which involves increased integration with a range of urban and wider environmental issues. The formulation of urban forest plans and policies is an on-going process. Different aspects, such as public health or safety, property damage and risk management liabilities need to be incorporated in overall policy formulation.

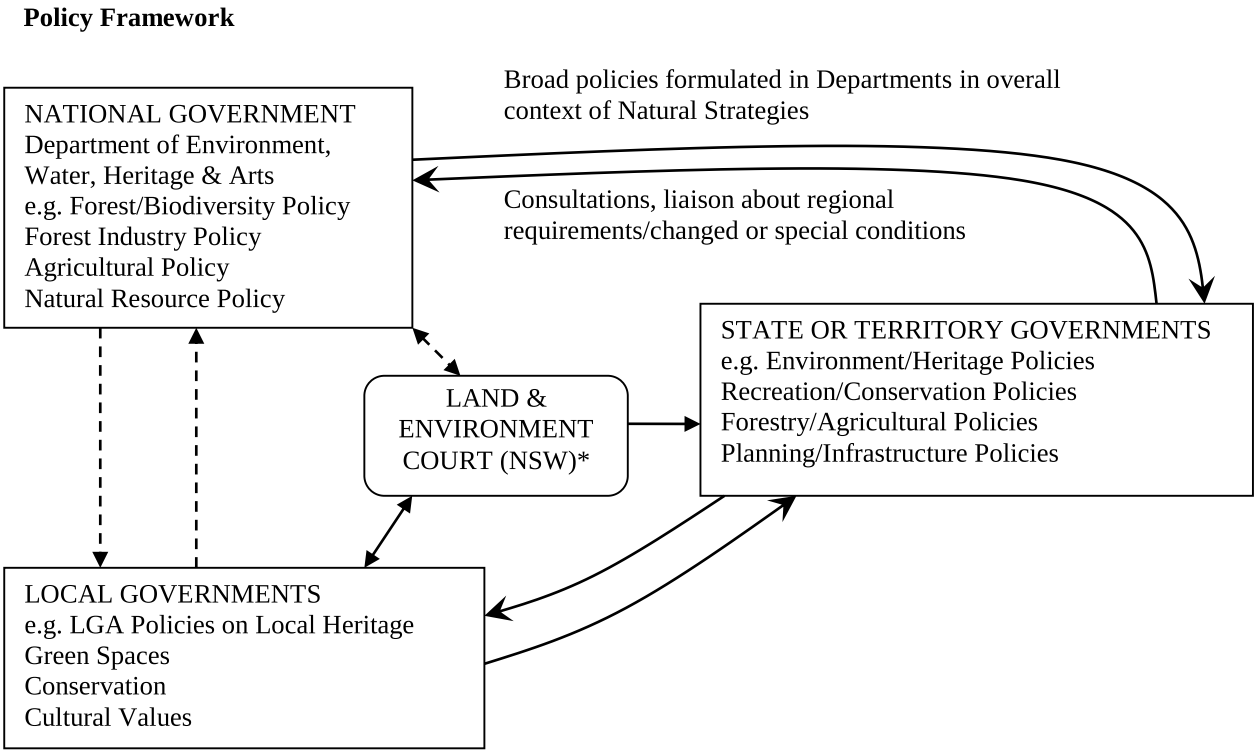


Figure 3-1 General summary of broad forest policy framework and interactions.

* In NSW this separate Court is charged with conflict resolution (policy interpretation) of environmental issues at all organizational and individual levels.

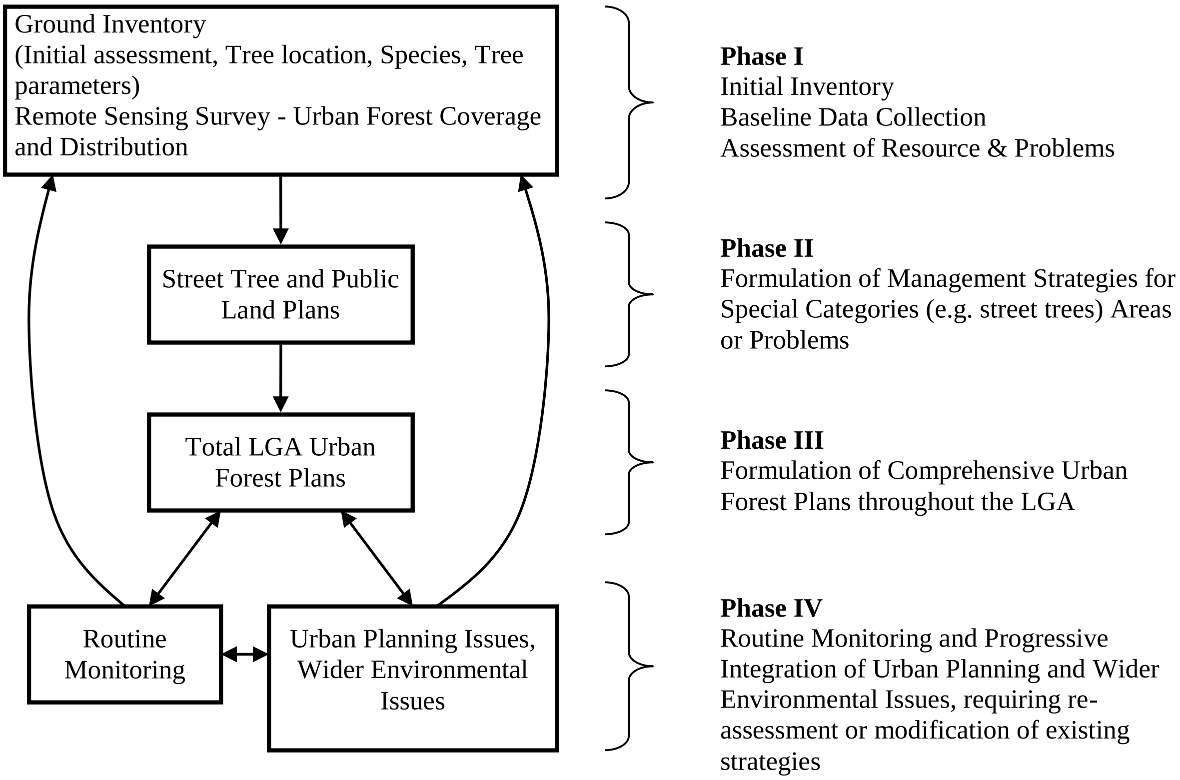


Figure 3-2 Sydney metropolitan area: major phases in the process of urban forest planning.

The broad context in Sydney summarised in Figure 3-2 indicates that prime responsibility for the development of detailed urban forest strategies rests at local government level over the metropolitan area. But among the 38 LGAs in Sydney there are several that recognized the significance of urban trees some years ago and have resourced the development of comprehensive urban forest strategies (City of Sydney, 2011, North Sydney Council, 2011).

3.2.3 Urban forest strategies in Sydney: Comparisons

As indicated above there is no overall urban forest strategy for the whole Sydney Metropolitan Area (SMA). All councils have published documents relating to urban forest management and almost all have tree preservation orders. Under the Environmental Planning and Assessment Act, preservation orders, as part of the urban planning system, are intended to manage and protect trees within LGAs as well as regulate actions that may adversely affect tree resources. These orders apply to both publicly and privately owned land. Effective guidelines for tree management may be included in the orders, but the information provided is usually limited. Some councils (e.g., Ashfield Council, Parramatta City Council) in Sydney only have this document and others have different kinds of documents for their tree management. Since local government responsibilities for trees relate mainly to those on public lands, the council owned and managed trees are commonly divided into street trees and those in parks or reserves. Street trees are a significant and distinctive form of urban forest (Donovan and Butry, 2010, Seamans, 2013).

The City of Sydney and North Sydney Councils have developed the most comprehensive strategies, and major features are briefly compared in Table 3-2. Both councils have extensive databases and well-developed urban forest plans.

Both councils have statements in their Development Control Plans (DCPs) or Local Environmental Plans (LEPs) for tree management. However, the emphases of urban forest strategies differ slightly. North Sydney has developed overall strategies throughout the whole LGA whereas the City of Sydney has focused on more specific policies for different aspects over a larger area. For street trees, the master plan of City of Sydney includes specific precinct plans for 30 villages within the LGA (City of Sydney, 2011) whereas North Sydney has a general strategy based on a comprehensive street tree database (North Sydney Council, 2006). Again, particular plans for trees in parks and significant individual trees have been produced by the City of Sydney (City of Sydney, 2006), but North Sydney has no separate plans for parks. For the whole urban forest complex, North Sydney Council developed a comprehensive urban forest strategy that covers all public and private land (North Sydney Council, 2011). The City of Sydney has a variety of individual plans, and the Urban Tree Management Policy 2005 is more like a link between all relevant Council policies and a guideline for the whole tree management concept, which has been important in the planning system (City of Sydney, 2005b). North Sydney's urban forest strategy contains more updated and comprehensive information. In this instance, a range of specific tree management plans, tied together by a summary document, constitutes the urban forest strategies in the City of Sydney while two major components (street tree strategy and urban forest strategy) form the prime strategies for North Sydney Council.

Table 3-2 Comparative summary of major features of urban forest strategies for two Sydney Councils.

Aspect or feature	City of Sydney	North Sydney	Remarks
Street Trees	Street Tree Master Plan 2011	Street Tree Strategy 2006; Development Control Plan 2002 – Section 22 Street Tree Management; Street Tree Database	Each City village is considered in Sydney's Street Tree Master Plan (City of Sydney, 2011); North Sydney has a comprehensive street tree database for the whole LGA
Trees in Parks	Hyde Park Tree Plan; Redfern Park Tree Management Plan; Observatory Hill Tree Management Plan	N/A	Specific tree management plans have been developed to protect trees in major historic parks in City of Sydney (City of Sydney, 2006); North Sydney has no equivalent park plans – is a much smaller LGA
Significant Trees	Register of Significant Trees	N/A	City of Sydney has a reference to identify and to protect significant trees which have great historical, cultural, aesthetic or botanical values for the LGA (City of Sydney, 2005a)
Urban Forests	Tree Management Policy 2005; Development Control Plan 2012- Tree Management Controls; Local Environment Plan (LEP) 2012 — Tree Management Controls	Urban Forest Strategy 2010 (draft); DCP 2010 — Section 16 Tree & Vegetation Management Tree Canopy Data	North Sydney Urban Forest Strategy covers a wide range of issues related to urban forests (North Sydney Council, 2011); The tree canopy data of North Sydney is derived from aerial photos

3.2.4 Remote sensing in policy and planning

In forested, rural and urban areas, on the ground field methods have been used most widely to measure trees and investigate their environmental functions. For example, i-Tree software has been developed using field-based survey methods. However, such field tree measurements are time-consuming and expensive, as they require labour-intensive fieldwork, complicated sampling designs as well as repeat sampling trips, and hence are only practical in limited geographic areas (Kwak et al., 2007, Popescu, 2007, Forzieri et al., 2009, Jung et al., 2011). In comparison, remote sensing uses a range of relatively new technologies that can be broadly divided into passive and active techniques. These remote sensing techniques are extremely effective in collecting environmental information over large areas, including localities or habitats that are difficult to access from the ground (Kato, 2008, Jung et al., 2011).

Remotely sensed data have already been widely used to support policymaking, urban management and catchment, as well as regional and urban planning. Remote sensing technologies can:(a) monitor rapid urbanisation (urban sprawl) and provide the spatial information essential for infrastructure planning (Gamba et al., 2005, Maktav et al., 2005); (b) contribute to air pollution investigation in cities (Emeis and Schäfer, 2006); (c) effectively assess land degradation (Bai et al., 2008) and impacts on biodiversity of land cover change (Osborne et al., 2001); (d) assist decision-makers by monitoring water resources and the movement of flood waters, carrying out fire front analysis and assessing post-fire effects; and (e) provide information for modelling the effects of climate change (Sawaya et al., 2003, Tralli et al., 2005, Lentile et al., 2006).

Passive remote sensing technologies such as aerial photography or satellite optical images have extensive application in forestry research (Secord and Zakhor, 2007), and a number of local governments in Australia already utilise aerial photos to map the urban forest canopy cover within their LGAs (North Sydney Council, 2011, City of Sydney, 2013). But the quality of the aerial imagery is heavily dependent on weather, season and the time of the data collection (Patenaude et al., 2004, Shan and Sampath, 2005, Jung et al., 2011). Moreover, passive remote sensing is limited in its capacity to provide accurate three-dimensional information for individual trees.

Light detection and ranging (LiDAR), one of the most important active remote sensing technologies, has been successfully utilised in the forest sector to collect tree measurements that can be used to estimate canopy structure, biomass and carbon content (Drake et al., 2002, Patenaude et al., 2004, Koetz et al., 2006, Popescu, 2007). Airborne LiDAR has some distinct advantages for data collecting: it is able to produce high density data containing both vertical and horizontal information for natural and man-made structures as well as underlying topography (Patenaude et al., 2004, Kato, 2008, Jung et al., 2011); it generates more accurate data of tree parameters than traditional field-based methods (Secord and Zakhor, 2007, Jung et al., 2011); and it can provide tree data within both public areas and private land (Kato, 2008).

These features provide great potential for improving urban forest management. For example, LiDAR can provide accurate morphological attributes for individual trees (Popescu et al., 2003). It captures the vertical structure of individual trees and provides data for canopy volume and density, which can be used to investigate the pollution mitigation capacity of urban trees. LiDAR can also map the interrelationship between trees and other urban structures, such as buildings and roads. This provides an effective way to assess the shading impacts of urban forests for energy saving (Levinson et al., 2009, Yimprayoon and Navvab, 2010). LiDAR data is commonly coupled with high resolution photography to identify tree species (Moffiet et al., 2005, Hollaus et al., 2009, Zhang et al., 2011), providing an efficient way for local government to build their tree database.

In summary, the use of these remote sensing technologies has several broad implications for planning and policy:

(a) they provide comprehensive baseline data on which policies can be grounded and on which planning priorities formulated or modified;

(b) they enable the development of detailed visual models for use by professional teams and in community consultations during planning and decision-making processes;

(c) for the first time, they permit necessary micro-management, in terms of the ability to monitor small changes, in small inaccessible areas.

This last feature may be very important in complying with broader policies relating to threatened species that have very restricted distributions.

Land and Property Information (LPI) Division in New South Wales (NSW) provides remote sensing data to NSW state and local government agencies. The data are captured using State-owned sensors and purchased from the private sector. The resulting database is available to provide decision-makers with accurate and updated information within relevant areas. It also offers historical maps that can be used to monitor changes and assess consequences of specific policies.

3.3 Sydney Metropolitan Area

This section examines the Sydney metropolitan area, as the largest and the most densely populated urban area in Australia. Sydney faces many of the same problems and issues as other capital cities worldwide. However, Sydney also has some regional or site-specific characteristics that need to be reflected in local planning and policy. These are summarised in Figure 3-2. For example, Sydney covers a very large area, bounded on the west by forested highlands and to the east by the Tasman Sea. Both of these are significant barriers for the north-south movement of biodiversity. The area itself is deeply intersected by waterways, which further act as local barriers, and the topography varies from low-lying coastal plain to elevated rocky ridges.

3.3.1 Existing urban forest networks

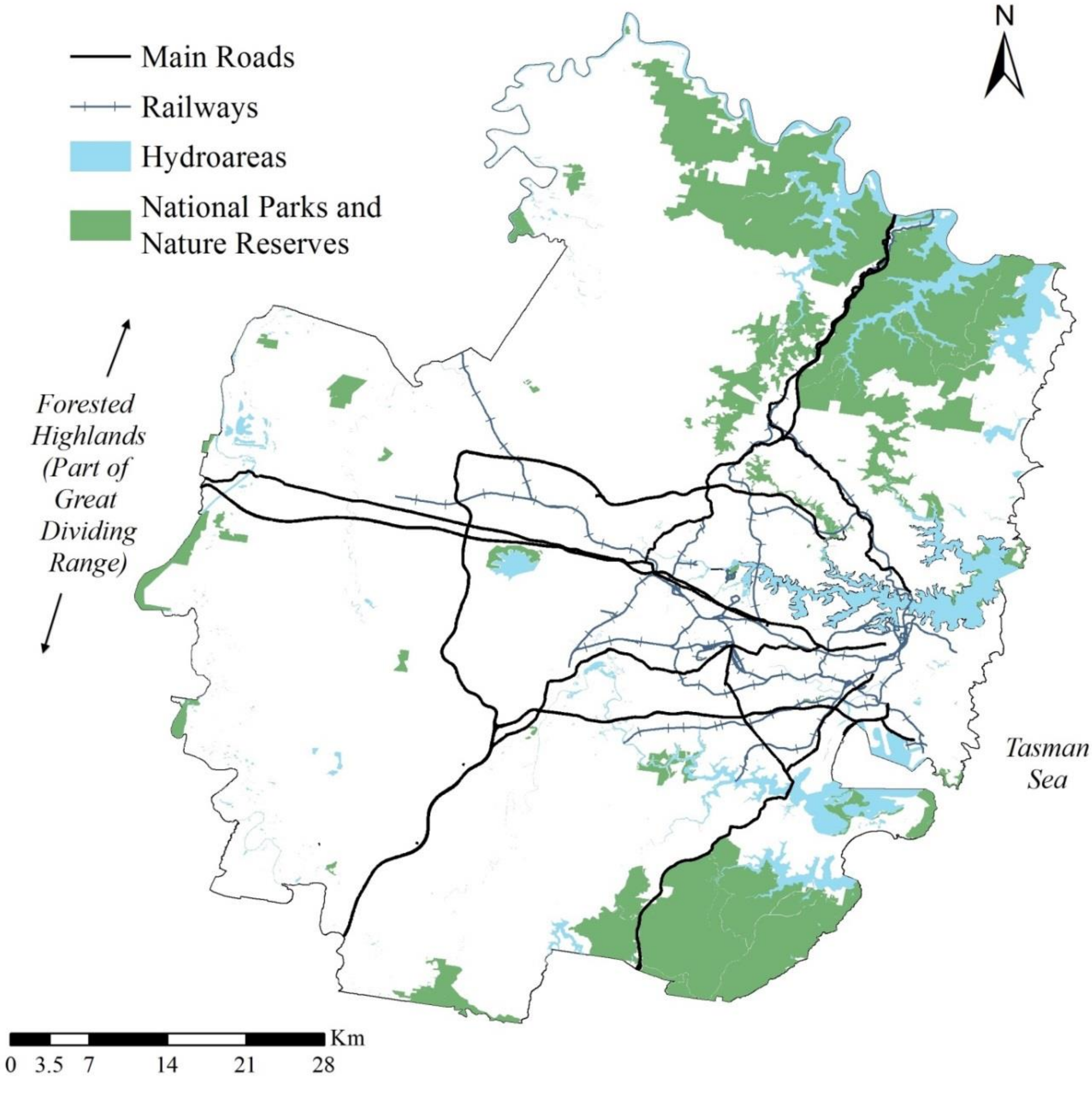


Figure 3-3 The whole Sydney metropolitan area showing urban corridors (major roads, railways) and green areas (national parks, reserves).
Note: The mountain barrier at this point is oriented NNE – SSW.
Data Source: ABS and NSW Lands

Figure 3-3 shows that Sydney retains a limited network of corridors of public land, often associated with transport infrastructure or utility supply lines (e.g., water, power). Other riparian zones are steep and inaccessible. These strips are very small in area and fragmented to varying degrees, but they hold a significant percentage of the remaining urban forest, although the vegetation is generally not well documented and management varies widely. Figure 3-3 illustrates the current distribution and extent of all major transport corridors and vegetation resources throughout the metropolitan area.

Figure 3-3 shows that the two main green areas are located to the south and north of the area, with several pocket reserves scattered on the west and south-west outskirts of Sydney. The main roads and railway lines are more concentrated in the central part of the metropolitan area where green areas are very limited. This developed area has a range of environmental problems, such as an urban heat island, severe air pollution and water contamination. Clearly, urban vegetation along transport corridors is particularly important to ameliorate local environmental conditions and provide linkages to other green spaces in the city.

3.3.2 Road corridors: A case study

Major highway corridors have been considered an essential part of the local economy because they promote strategic economic development (New South Wales Department of Planning, 2008). While transportation infrastructure offers some connectivity, it can also be considered a disturbance to natural habitats. This is because construction modifies the landscape, resulting in the fragmentation of habitat (Rozylowicz et al., 2006, Trocmé, 2006). Roads and railways can be impassable barriers that animals cannot cross or that restrict gene flow, as well as an added source of mortality (Bennett et al., 1999, Keller and Largiadé, 2003, O'Brien, 2006, Trocmé, 2006). They may also encourage invasion by exotic plant species and disturb adjacent habitats (Hansen and Clevenger, 2005, van der Ree et al., 2011).

Despite the acknowledged detrimental effects of transportation (e.g., noise, fumes), the vegetation along these corridors can play particularly important functions in mitigating impacts. Road reserves constitute extensive linear habitats for plants and animals because of the high density of road systems in cities (Bennett et al., 1999, Nagendra and Gopal, 2010).

Roadside vegetation can play a role as pathways linking up the remaining urban green areas and facilitating the movement of wildlife between habitats (Chang et al., 2010, Nagendra and Gopal, 2010). In Australia, the many roadside systems encompass “remnant natural vegetation such as eucalypt forest and woodland, shrubland and grassland”, which suggests a diversity of plant species (Bennett et al., 1999).

In these initial studies, parts of two long-established major highway corridors were surveyed. In each case the survey length was around 20 km, running from inner central business districts to outer suburbs. One survey extended along the Pacific Highway from North Sydney to Hornsby. The other extended out along Parramatta Road from Camperdown to Parramatta (see Figure 3-4). The survey band included the road with an overlap of about 150m either side of it; these particular highways each have five categories of land use (business, residential, industrial recreation, others) along their length.

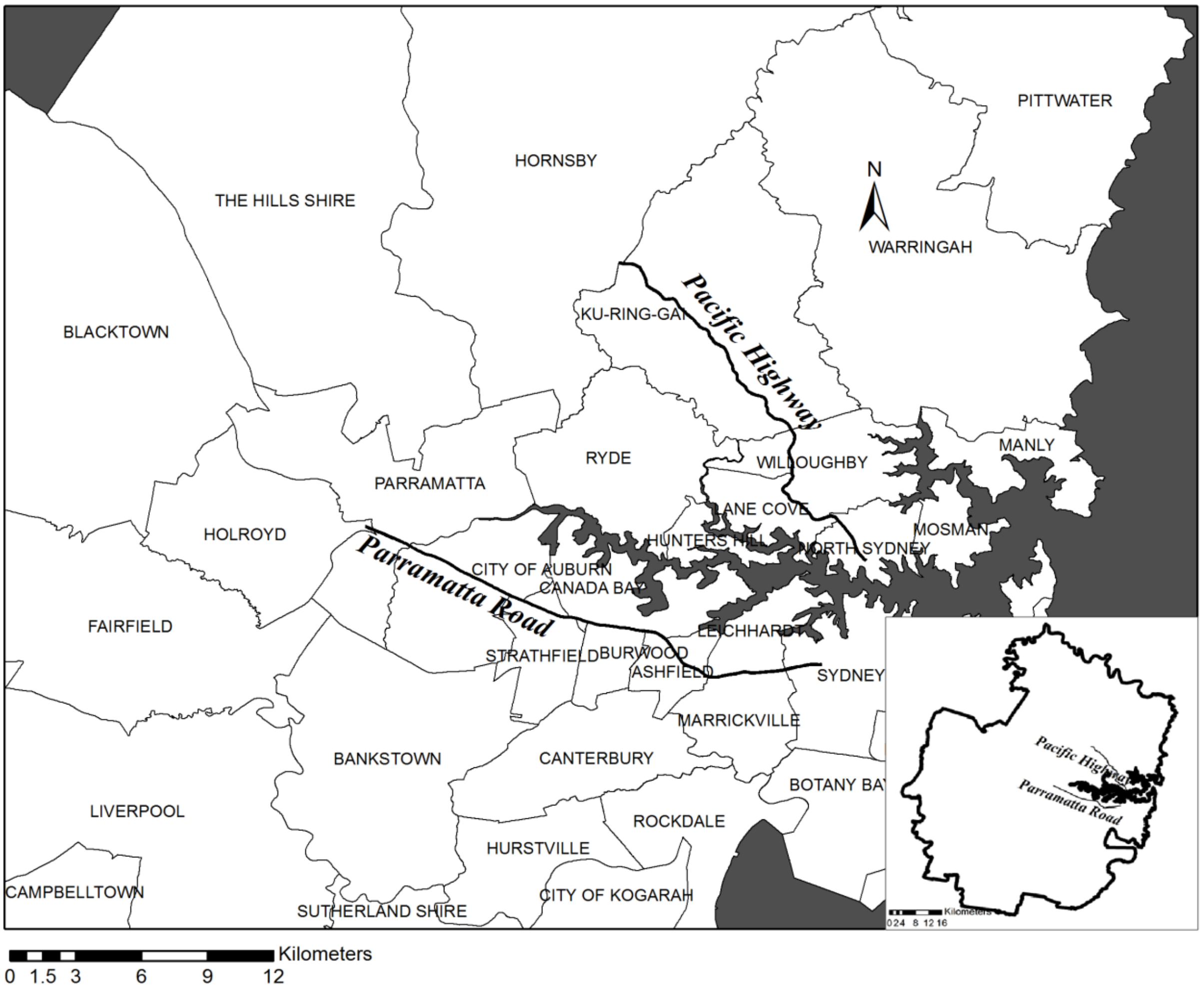


Figure 3-4 Map of inner metropolitan area showing the lengths of Parramatta Road and Pacific Highway surveyed as well as Local Government Area (LGA) boundaries.
Source: *ABS and NSW Lands*

The features of these corridors were investigated in four ways. First, cadastral data of the study areas were combined with land zoning maps from local governments. Then two sets of Geographic Information System (GIS) vegetation data were used to estimate the woody extent and vegetation community distribution along the two corridors. In addition, the GIS layer of native vegetation of the Sydney Metropolitan Catchment Management Authority (CMA) area in 2009 was obtained from the CMA. Finally, a field survey was carried out to investigate the diversity and verify roadside vegetation types along Parramatta Road and the Pacific Highway, as there are no existing data available. This survey was completed during summer (all trees fully foliated) during low-traffic hours (10.00 a.m.– 3.00 p.m.), by driving a car slowly along these two roads. An experienced field botanist sitting in the back of the vehicle identified the tree species on the road verge; where further examination was necessary, car was stopped and samples were collected for subsequent herbarium identification.

Analyses of datasets yield the following findings for the parts of the roads surveyed. First, Parramatta Road is more commercialised and industrialised, whereas the area along the Pacific Highway is more residential. This difference in land use affects environments in the two areas including the vegetation cover. Most areas along Parramatta Road have relatively low percentages of vegetation cover, with a high percentage of non-woody areas. The majority of the 150 m buffer areas have no vegetation. The area along the Pacific Highway, North Sydney as well as the eastern part of Willoughby have less vegetation cover; whereas Lane Cove, Western Willoughby, Ku-ring-gai and Hornsby areas are covered by dense vegetation. Within the 150 m buffer areas, the sections running though North Sydney and Eastern Willoughby have scarce vegetation with a high percentage of non-woody areas, but elsewhere the buffers have good vegetation cover.

Second, unexpected tree diversity is demonstrated along both roads. This is beneficial from a conservation point-of-view, but more intensive management is needed. There are 120 tree species (from 40 families) found along the Pacific Highway; and there are 99 species from 34 families on Parramatta Road. There are 62 common species (from 46 genera in 28 families) along both corridors. A large portion (around 50%) of families is only represented by 1 genus and no more than 3 species as shown in Table 3-2. For both roads, Myrtaceae is the most diverse family with the largest number of genera and species. Most species in this family are native. Within this family, *Eucalyptus* is the biggest genus, which has 13 and 12 species for the Pacific Highway and Parramatta Road, respectively. A few species have been extensively planted on more than 70% of each road verge. 41% of all the species along Pacific Highway are native, which means 59% are exotic; 44% of all the species along Parramatta Road are native, and 56% are exotic.

Third, a wide variation in numbers of species and component species within local areas and between different sections of each corridor was found. For example, along Parramatta Road, there is only scattered urban exotic and native vegetation, and no native vegetation community is present. In contrast, along the Pacific Highway corridor, the density of urban exotic and native vegetation is much higher.

Fourth, the distribution of trees is very patchy in some areas. Most sections along Parramatta Road are heavily industrialised, and roadside trees are relatively sparse and distributed in a patchy way. There is almost no record of trees on Parramatta Road along the borders of Leichhardt, Burwood and Parramatta Council areas. No roadside trees exist within the Marrickville LGA except in front of Fort Street High School, where a line of trees between the road and school buildings shields against noise and traffic pollution. At the beginning of the Pacific Highway, North Sydney LGA has an active program of urban tree plantings for four species along the Highway. These are the London Plane tree, Cocos Palm, Broad Leafed Paperbark and Oriental Plane tree. 86% of the trees planted along the Pacific Highway are Plane Trees, mostly London Plane.

Finally, it was clear that there was planting and maintenance of some species that did not contribute to conservation, shading or pollution mitigation. Cocos Palms are one of most common species along Parramatta Road and this appears related to the dominant commercial activity (car retailing and services). Palms seem to be used as symbols by car dealers, so a few Cocos Palms have been planted in front of many car dealer showrooms or workshops. But they do not provide significant shading or absorb pollutants emitted by heavy traffic.

3.4 Discussion

The importance of the remaining urban forests cannot be overestimated. They play an essential role as the residual ecological skeleton on which basic ecosystem function in highly modified urban areas can be maintained, and they are essential on the neighbourhood to the global scale. They also have influence on local quality of life issues and on regional Climate Change perspectives (refer to Table 3-1). While the benefits are clear, a number of problems or challenges have emerged in recent years.

With increasing acknowledgement, at the highest economic and political levels there is increasing acknowledgement of the urgent need to address urban environmental issues (Asian Development Bank, 2012), it is an appropriate time to emphasise developments in the management of urban forests. As discussed previously, urban forest policies and management cannot be considered independently. They now have to be integrated with strategies for a wide range of other urban issues (e.g., conservation, pollution, socio-economic issues).

3.4.1 Policy, management and technology

The policy framework demonstrated in this paper is diffuse at several legislative scales although planning and management for urban forests has been, and is currently, largely at the LGA level.

Policy will be refined as more detailed geographic data become available and as local or regional conditions change. The major management trend, currently underway, is the increasing use of remote sensing technologies. These have the potential to assist not only with management of urban vegetation, but to contribute to improve monitoring and strategies for other structures and developments. There are some initial access, support and specialist skills costs associated with using remote technologies, such as LiDAR, and the limits of resolution are still being investigated (Wang et al., 2012); however, the many on-going advantages outweigh short-term budgetary constraints. For example, the economic benefits of being able to integrate data collected with many standard databases, and to be able to share relevant data among a number of Departments, for different purposes, are obvious.

3.4.2 General urban forest strategies in Sydney

Earlier sections and analysis have identified a number of urban forest issues that can also be applied in the Sydney metropolitan area. This section addresses these issues and problems, specifically those related to the transport corridors selected in this study.

First, "the enormous benefits that accrue from urban forests are only achieved when the density of the tree canopy is appropriate and when each individual tree is properly maintained" (North Sydney Council, 2006). Second, the inappropriate planting of trees in unsuitable conditions or locations can cause different kinds of problems to the local environment or communities. Particular tree or grass species can cause allergies or irritation concerns by producing a greater load of pollen (City of Sydney, 2011). The leaf or fruit droppings of trees can increase litter problems or make ground slippery when the fleshy fruits or leaves are decomposing (City of Sydney, 2011). Moreover, the root system of some vigorous or large growing species can cause damage to underground services, pavements, kerbs and properties (Pittendrigh Shinkfield Bruce Pty Ltd, 2005, City of Sydney, 2011). For example, *Jacaranda mimosifolia* is a tall-growing and spreading species requiring a wider nature strip and can cause problems of pavement uplift; some she-oak species have large root systems that can cause damage to underground services and structures (Pittendrigh Shinkfield Bruce Pty Ltd, 2005). Additionally, maintenance costs for urban trees may outweigh their benefits when the trees reach a certain stage of their life span (over-maturity), or if they are in poor health (North Sydney Council, 2006). Active planning and management play a key role in maximising the positive contributions of urban trees, while minimising any negative aspects.

Urban forests within LGAs include three general categories: street trees, trees in parks and trees on private land. Table 3-3 summarises the urban forest management issues for trees on both public and private land. The inventory of existing tree assets is essential to achieve effective management. This data can provide an overview of species distribution, mature height, growing stages and health conditions of urban trees. Many councils have street tree databases and street tree plans (Pittendrigh Shinkfield Bruce Pty Ltd, 2005, North Sydney Council, 2006, City of Sydney, 2011), however, most councils do not have a complete inventory of park trees or a specific strategy for this category of urban trees.

Table 3-3 Summary of management issues in relation to trees on public and private land.

	Public land		Private land*
	Street trees	Trees in parks	Trees on private land
Inventory data	Street tree database (tree location, tree species, mature height, current height, crown width, diameter at breast height, tree growth stage and condition) (North Sydney Council, 2006)	Tree inventory (limited) Remote sensing – tree canopy coverage	Remote sensing data (e.g., Aerial photography, satellite imagery)
Species selection	New planting of street trees should consider: local climate, geology, soil and topography; growing space (Pittendrigh Shinkfield Bruce Pty Ltd, 2005); height, maturation size, foliage (deciduous / evergreen) and physiology; tolerance to pruning (North Sydney Council, 2006)	Park provide better growing environment (substantial space, desirable conditions, less pollution) (Marrickville Council, 2010)	Resident request
Tree maintenance	Regular inspection, regular pruning, tree removal and replacement, emergency strategies		Under resident request

* For stated reasons these studies focus on public land, but knowledge of urban forest on private land is essential for effective LGA management of urban forest resources.

Planners choosing appropriate species for new plantings of street trees should consider: local climate, geology, soil and topography, natives vs. exotics, deciduous vs. evergreen, as well as the physiological characteristics of trees. The selected species should be in scale with the width of planting opportunity (City of Sydney, 2011). Broad roads or streets frequently have high traffic loads while narrow roads or streets tend to be located in residential neighbourhoods with less traffic (Nagendra and Gopal, 2010). Large trees grown in narrow streets may result in more damage to overhead powerlines, pedestrians and properties, consequently resulting in higher management costs (City of Sydney, 2011). In contrast, small trees in wide roads cannot make significant contributions to aesthetic views or canopy coverage (City of Sydney, 2011). Moreover, the ability of a tree to absorb air pollutants, alleviate urban heat island effects and slow down water run-off is generally related to the tree's size and canopy area (Nagendra and Gopal, 2010).

In the highly urbanised and modified environment, exotic deciduous trees are more popular since they are more tolerant of constraints and may achieve better performance than some native species. Deciduous trees also have the advantages of energy saving by providing shade in summer and sun access in winter (Wang et al., 2012). In heavily polluted areas such as immediate roadsides, the pollution absorption capacity of evergreen trees decreases with the increments of pollutants on foliage (North Sydney Council, 2006). Native species are predominant in areas where the natural environment is better preserved, such as the northern part of the Pacific Highway Corridor. Many native species are tall-growing, spreading trees which can provide good shade. Eucalypts are present along the majority of the highway; in these areas roadside vegetation communities are connected to wider green reserves and have high ecological values.

Compared to paved streetscape, parks provide better growing environments; consequently trees in parks normally have longer life spans and more stable health conditions (Marrickville Council, 2010). As public parks are now one of the few urban habitats remaining that are suitable for trees, it is logical that they be used more intensively for this purpose (Wang et al., 2012).

It should be noted that local government cannot carry out work on private land except in particular situations. It is difficult for councils to do any surveys for private trees in the field. But the tree information of private land should be considered by councils when they develop their overall canopy cover targets. Remote sensing provides an efficient and accurate way to solve this problem.

3.4.3 Transport corridor surveys: Broader lessons and links

Although limited in extent, the transport corridor surveys and analyses reported here cover some 15 LGAs and raise a number of issues and implications for policy, with relevance over the entire metropolitan area. These are discussed below:

(a) The existing roadside trees (forests) are strongly correlated with marginal land-use. This suggests that a review of urban vegetation policies, in relation to zoning, may be required;

(b) The species diversity is broadly influenced by relict native vegetation and/or deliberate planting for specific purposes. The importance of planned plantings is reflected in the fact that over 50 % of all species on each road were exotic. A few preferred species were dominant (abundant) in some areas. It may be appropriate to amend planning or management guidelines to increase recommended species combinations, where possible;

(c) For the regions which have limited species present locally, it would be beneficial, from a conservation viewpoint, to encourage diverse plantings and perhaps change the pattern of planting of some species for specific purposes (e.g., pollution mitigation). Some review of policy and planning goals in relation to carbon sequestration, pollution mitigation and/or energy savings may be appropriate;

(d) Sparse or patchy distribution of roadside trees in some areas should receive priority attention. This may require checking and clarifying the regulations relating to government responsibilities for trees on public land that is designated for multiple uses. However, these initial surveys do demonstrate that there is considerable potential for expanding or extending roadside forest, with the additional benefit of connecting to vegetation on other public lands (e.g., public parks or railways);

(e) Growing in narrow strips or bands of land, these forest corridors are especially susceptible to natural edge effects, in addition to the inevitable high rates of human impacts. Retaining and improving this resource will necessitate proactive field management, so some of the savings made through use of remote sensing will have to be directed to increasing field staff resources;

(f) Major transport corridors often form LGA boundaries and, given the variation in resourcing and development of urban forest plans between LGAs, it is suggested that increased cooperation between groups of LGAs would be beneficial.

The combination of the increased resolution of LiDAR which enables more precise monitoring and management, and the i-Tree model with accessible value estimates for oxygen production, sequestration and pollution reduction will greatly inform and enhance decision-making. However, these surveys have highlighted some poorly documented aspects, for example, effective control of tree diseases in small areas and optimal planting patterns to alleviate noise levels or reduce fume pollution emissions. Some studies suggest that the effectiveness of fume reduction varies widely with parameters such as distance, foliage density, leaf area and leaf surface texture, but more data are urgently needed for local species.

This chapter provides a resource and comparison for organisations or individuals responsible for urban forests elsewhere.

Chapters 2 and 3 explain initial field surveys, then review current urban tree management and outline the preliminary use of technology in forest management. The following Chapter 4 analyses the airborne LiDAR and hyperspectral data to assess tree shading, by modelling solar radiation on building roofs. The calculated radiation is then related to tree features at plot-level and energy demand profiles.

Chapter 4 Using LiDAR to Assess Solar Radiation Reduction from Urban Forests on Building along Highway Corridors in Sydney

4.1 Introduction

Australia is highly urbanised with three-quarters of its population living in urban areas (Australian Bureau of Statistics, 2013a). Sydney is Australia's largest city (20.6% of the national total population) and has the highest population density in Australia (Australian Bureau of Statistics, 2012, Australian Bureau of Statistics, 2013b). From 2001 to 2012, the population in Sydney increased by 14% and is projected to reach between 6 and 8 million residents by 2056 (Australian Bureau of Statistics, 2012). This increasing population creates higher housing demand and necessitates infrastructure improvement. However, this type of intensive urban development can aggravate heat island effects (Shashua-Bar and Hoffman 2000), because previously vegetated areas are replaced by impervious surfaces with high thermal conductivity, high heat storage capacity and low albedo values (Block et al., 2012, Brunner and Cozens, 2013). Building roofs and pavements absorb high levels of solar radiation and warm the surrounding atmosphere (Akbari and Konopacki, 2005).

Urban vegetation, especially trees, can ameliorate the urban heat island at a microclimate scale by shading, evapotranspiration, and wind speed reduction (Akbari, 2002, Simpson, 2002, Tooke et al., 2011, Block et al., 2012). Through these processes, trees planted near buildings can affect energy usage. Trees can directly reduce the incident solar radiation on buildings, as well as surrounding surfaces that radiate heat towards buildings, by directly shading which reduces solar radiation loads; and by indirectly modifying local ambient temperatures through evapotranspiration and shading of other impervious surfaces (Akbari, 2002, Loughner, 2012). The amount of solar radiation is a significant determinant of how much energy an urban surface absorbs from the sun. Most of incident solar radiation is received on building roofs and walls, and the heat impacts building occupants dramatically influencing energy use and temperature distribution in urban areas (Santamouris et al., 2001).

Many studies have investigated aspects of shading effects of urban forest. Cooling effects of urban trees have been investigated both by measuring air temperatures (Shashua-Bar and Hoffman, 2000, Shashua-Bar et al., 2009, Hamada and Ohta, 2010, Armson et al., 2012, Loughner, 2012, Morakinyo et al., 2013), and monitoring reductions in solar radiation due to shading (Heisler, 1986, Gómez-Muñoz et al., 2010). Although small-scale the temperature data show that tree shade provides regional cooling. Other research utilised computer simulation models to evaluate the potential effects of tree shade on energy use. Investigations in California used prototypical building and tree types to examine building energy performance (McPherson, 1994, Simpson and McPherson, 1996, Simpson and McPherson, 1998, Simpson, 2002). Another study demonstrated energy-saving potentials of urban trees using prototypical building data for five US cities (Akbari and Konopacki, 2005). Currently, the i-Tree model is one of the public and free tools used by researchers, governments and local communities to assess environmental benefits that urban trees provide (City of Toronto, 2005, North Sydney Council, 2011, Rogers et al., 2011). It incorporates functions to estimate building energy savings due to urban forest. However collection of its field based data is time-consuming and labour-intensive.

Recently, optical remote sensing technologies such as aerial or satellite imagery have been utilised to assess green infrastructure as a cost-effective solution. McPherson and Simpson (2003) obtained tree canopy data from aerial photographs to estimate the energy saving potentials of existing trees and proposed new plantings, incorporating the data into previous energy simulation models (McPherson, 1994, Simpson and McPherson, 1996). Hammer et al. (2003) showed that satellite imagery can measure surface solar irradiance, and that aerial photography can provide spatial information of urban features. Aerial imagery has also been used to estimate rooftop photovoltaic potential. Wiginton et al. (2010) digitised available roof areas for solar photovoltaic applications using aerial photos. Whereas Arboit et al. (2008) used both satellite images and aerial photographs to assess the solar potential of low-density urban environments.

In contrast to the passive remote sensing systems mentioned above, light detection and ranging (LiDAR) is an active remote sensing system and operates independently from the solar illumination. LiDAR provides high vertical precision. It has the capacity to measure an expanding suite of features which are important in forest management. These include measuring tree growth, mapping and estimating forest carbon or aboveground biomass, assessment of ecological health indicators and modelling forest soil moisture (Southee et al., 2012, Hampton et al., 2013, Meyer et al., 2013, Li et al., 2014). As LiDAR technology has advanced, allowing denser sampling points, it has become possible to accurately record morphological features of urban structures, including trees and buildings (Popescu et al., 2003, Lafarge et al., 2008). One study used LiDAR measurements to map the shapes of buildings, roofs and tree canopies and then to assess solar access on roofs (Levinson et al., 2009). Nguyen et al. (2012) developed a methodology to extract building geometry from LiDAR points for solar photovoltaic deployment analysis. LiDAR derived models are well suited to assess tree shading by modelling solar radiation or irradiance. Recent studies include: Tooke et al. (2012), who used LiDAR returns to estimate solar irradiance in urban areas, considering transmission through urban vegetation; Lukač and Žalik (2013) simulated shadowing from solid objects and vegetation, and estimated potential solar irradiance using LiDAR data; and Tooke et al. (2011) extracted trees and buildings from LiDAR data, indicating the important effects of tree structures in reducing rooftop received solar radiation.

The above studies use LiDAR to address environmental planning challenges, but do not integrate other potential remotely sensed data sets with LiDAR. Examples of these data types are multispectral or hyperspectral imagery, which provide abundant spectral information that can be combined with LiDAR data for classification of different urban objects and tree species classification (Holmgren et al., 2008, Voss and Sugumaran, 2008). Yu et al. (2009) for example combined LiDAR data with colour infrared aerial photographs to extract buildings and trees. In addition, for shading analyses, seasons need to be considered. Tooke et al. (2009a) differentiated evergreen from deciduous trees using multispectral images and other studies have considered leaf-fall effects of deciduous trees for winter solar radiation analyses. Shading analysis research that includes solar radiation modelling by integrating LiDAR and hyperspectral data is very limited. Moreover, few studies have investigated how building and tree features are correlated with received solar radiation.

Our study focuses on the shading effects of urban forests in highly developed areas bordering parts of two long-established transport corridors. A ‘corridor’ in this case includes the margins (undeveloped buffer zones adjacent to a main road), the paved roadway lanes, as well as middle strips. The inventory for the study site was gathered over a large scale and the modelling is performed on the output. The modelling is not concentrated on prototypical buildings or representative trees, in contrast to prior studies (Simpson, 2002, Akbari and Konopacki, 2005). For our analysis the trees have been divided into evergreens and deciduous as this is essential for understanding seasonal solar radiation. By integrating two remote sensing technologies, LiDAR and hyperspectral imagery, with solar radiation models, our objectives are: (a) to estimate the total radiation received by building roofs along two major urban transport corridors according to the season; (b) to distinguish deciduous trees from evergreen trees to assess their impacts on solar radiation on building roofs in winter; (c) to correlate building and tree features with estimated direct solar radiation; (d) to demonstrate the broader implications of the results, in terms of building energy use and methodology for landscape and urban planners.

4.2 Study Area and Input Data

4.2.1 Study area

The Sydney Metropolitan Area (SMA) is extensive (12,145 km^2) but the main green areas, including both national parks and nature reserves, are located to the south and north (see Figure 4-1). The sections of the transport corridors surveyed were in the central part of the metropolitan area as shown in Figure 4-1, where green areas are very limited. Both Parramatta Road and the Pacific Highway were surveyed for about 20 km, from inner business districts to outer suburbs. One survey extended along the Pacific Highway from North Sydney to Hornsby. The other extended out along Parramatta Road from Camperdown to Parramatta.

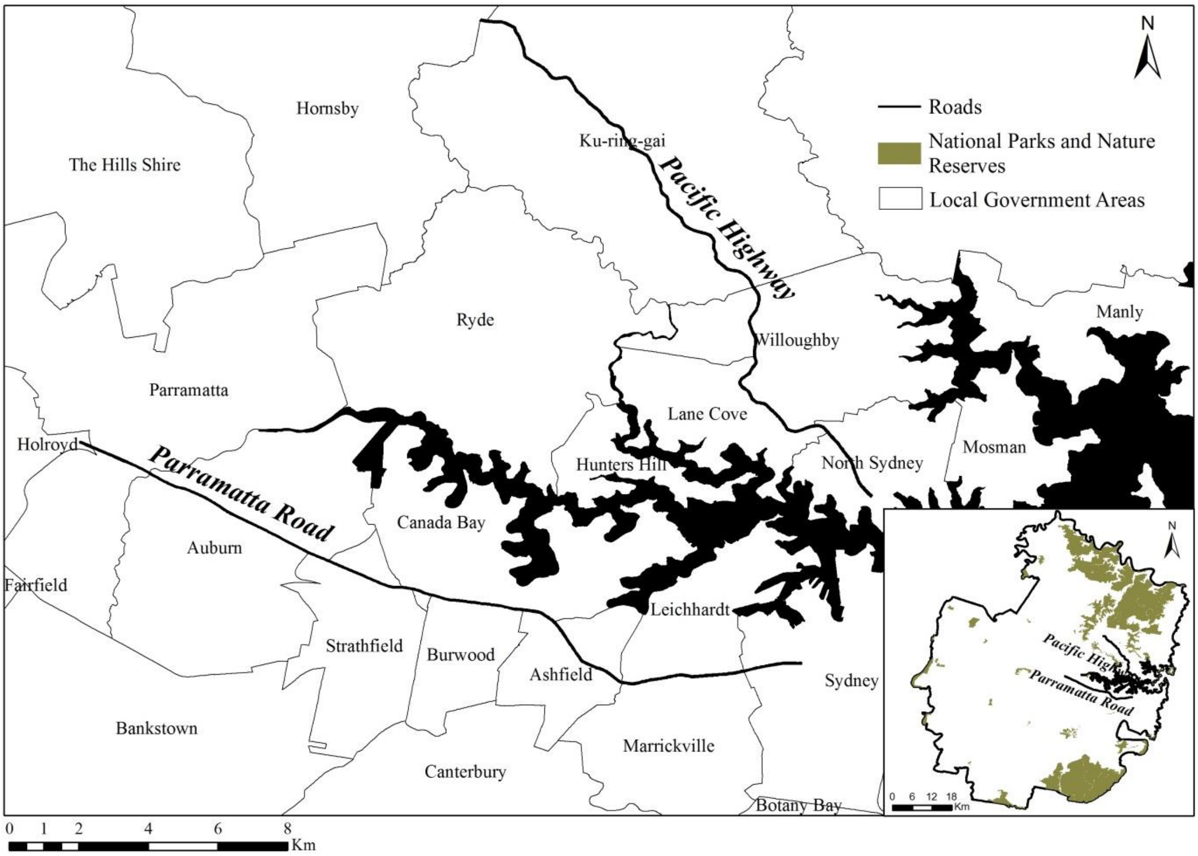


Figure 4-1 Map of inner metropolitan area showing the lengths of Parramatta Road and Pacific Highway surveyed as well as Local Government Area (LGA) boundaries. Insert shows full extent of Sydney Metropolitan Area. *Sources*: *ABS and NSW Lands*

4.2.2 Remote sensing data

The remote sensing data acquisition was carried out by Digital Mapping Australia Pty Ltd (Dimap) in April 2012 before the Autumn leaf-fall. Both LiDAR and hyperspectral sensors were mounted on a Piper Navajo aircraft. The aircraft flew at a nominal altitude of 500m above ground with a flying speed of 240-290 km/h. The data were delivered in the projection of WGS84 UTM Zone 56S.

LiDAR data were acquired using a RIEGL LMS-Q560 full-waveform laser scanner. The system used a pulse rate of 180 kHz, a wavelength of 1550 nm and pulse length of 3.4 ns. Beam divergence was 0.5 mrad with a scanning angle of 60.0°. The shot-to-shot accuracy for measurement of absolute accuracy along structures was 2 cm. The nominal swath width of LiDAR scans was 400 m. The three-dimensional geographic position of LiDAR points was determined. Both ground and non-ground points were classified by TerraScan (Finland, Terrasolid) using raw LiDAR points. The digital terrain models (DTMs) were derived by the interpolation of ground points and digital surface models (DSMs) were derived from the highest points. All models were gridded to 0.4 m spatial resolution. The height models of urban objects were calculated by subtracting DTMs from DSMs.

Hyperspectral images were acquired using Hyspec VNIT 1600/SWIR cameras. The scanners collected the images at electromagnetic wavelengths ranging from 400nm to 1000 nm in 160 small bands of a spectral width of 2.5 nm. Spatial resolution of the images was 0.4 m and the field of view was 32.0° (narrower than the LiDAR sensor scanning angle). The nominal swath width for hyperspectral images was 200 m. This study focuses on areas where LiDAR and hyperspectral data overlapped. The post flight correction for hyperspectral images, including atmospheric and geometric correction, was carried out by Dimap.

4.2.3 Solar radiation data

To model solar radiation in the analysis, local atmospheric conditions need to be considered. The Gridded Hourly Solar Global Horizontal Irradiance (GHI) Metadata were obtained from the Australian Bureau of Meteorology (BOM). Since the two transport corridors extend across the SMA, the averaged global and direct irradiance of the whole SMA over a ten-year period (2003-2012) were used. Representative meteorological data for typical conditions were also taken into account to examine long-term local climate conditions.

4.3 Methods

The main steps involved in subsequent analyses are shown in Figure 4-2 below. In addition, a brief qualitative description of roadside trees on both study sites is provided in Section 4.4.1. This summary emphasises features relevant to shading and relates to the broader context for specific local radiation findings.

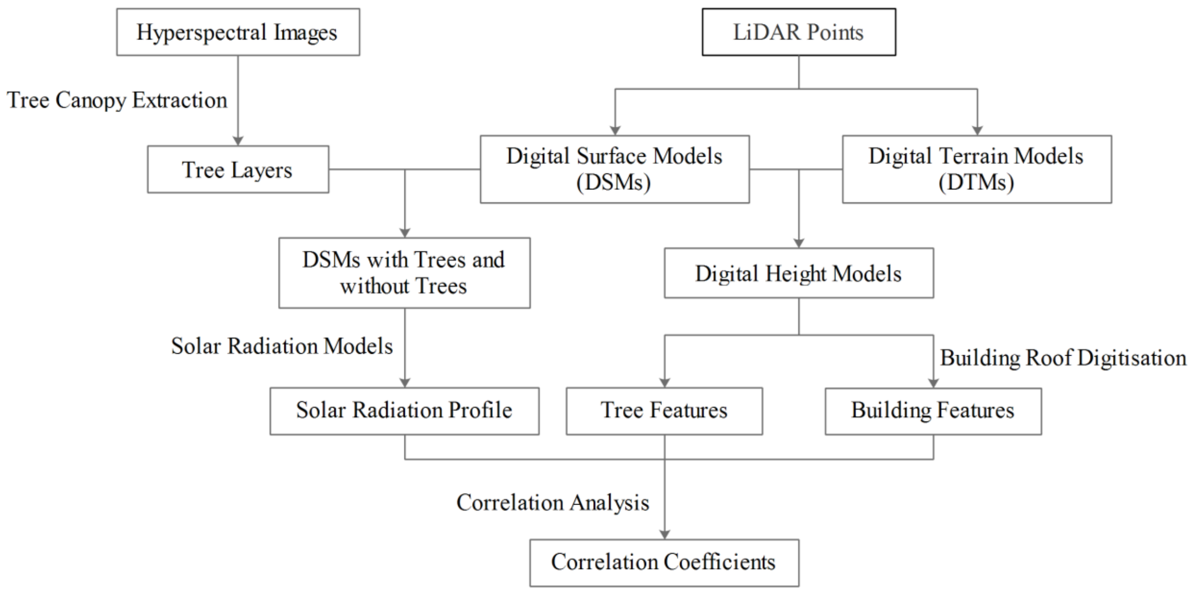


Figure 4-2 Overview of the methodology implemented in this study.

4.3.1 Tree canopy extraction

To assess the impacts of trees on incident solar radiation, tree canopies should be extracted as separate features. From hyperspectral images, the Normalized Difference Vegetation Index

(NDVI) was calculated to generate vegetation masks. NDVI was an indicator, ranging from -1 to 1, for living vegetation which was defined in Eq. (4.1)

$$NDVI = \frac{NIR-R}{NIR+R} \tag{4.1}$$

where NIR was the reflectance value measured in near-infrared channel (858nm), and R was the reflectance value measured in red channel (651nm).

Pixels above a threshold of 0.2 were considered as vegetation features (Fung and Siu, 2001). Combined with height values derived from LiDAR data, grass and shrubs were removed from the vegetation masks by applying a height threshold of 0.5 m. Then the tree masks were produced to show the extent of urban trees within the study areas.

Tree areas were then extracted from the hyperspectral images using the derived tree masks. As all deciduous species within the study sites lose their foliage in winter, they were removed from the winter models to reflect this leaf fall. Spectral analysis was applied to hyperspectral images to differentiate deciduous from evergreen trees. ENVI Classic® was used for classification. To perform the classification, 82 and 259 individual trees were surveyed in the field for Parramatta Road and Pacific Highway respectively. The ground measured tree data were used to locate specific species in the hyperspectral images. The spectral endmembers, which were the ‘pure’ spectra corresponding to each classification class, were then extracted from the hyperspectral data for 21 common evergreen tree species and 6 common deciduous species. Using these as training samples, the Maximum Likelihood supervised classification tool was used to classify the whole urban tree areas into two classes which were deciduous or evergreen species. Based on field tree data, the accuracy of the tree classification model was calculated. For Parramatta Road, 96.3% of trees surveyed were correctly classified and for the Pacific Highway, the accuracy rate was 93.6%. After the spectral analysis, 1.1% of the tree coverage was classified as deciduous species for Parramatta Road and 2.8% for the Pacific Highway.

4.3.2 Building roof digitisation

The building roof extraction was done by TerraScan software using LiDAR points. Since building roofs often reflected the entire laser pulse, we extracted only echo LiDAR returns from the non-ground points. There were some building roofs underneath tree canopies, so the last returns of multiple returns were also extracted from the non-ground points. Then all these specified points were incorporated for routine building classification. In this routine, minimum height above ground was set at 2.5 m, the minimum building area was 100 m^2, and z tolerance was 0.2 m. The building points were extracted and were gridded into original building DSMs. The outlines of building roofs were manually digitised from True Colour images derived from hyperspectral bands. Then the outlines were used to extract exact building roofs from the original building DSMs and so produce more accurate DSMs for further analyses.

4.3.3 Solar radiation model

To quantify tree shading effects, three types of DSMs were used for the solar radiation models: original DSMs with all urban features, DSMs without trees, and DSMs without deciduous trees. Using the tree layer derived from the hyperspectral data, tree areas were masked out from the original DSMs to produce DSMs without trees. Similarly, deciduous trees were removed from the original DSMs to produce new DSMs based on the hyperspectral tree classification. This last type of DSM was only used for winter analysis.

Potential solar radiation was calculated using the ESRI ArcGIS Solar Radiation tool at hourly intervals on four representative days: spring equinox, summer solstice, autumn equinox, and winter solstice. The tool uses hemispherical viewshed algorithm developed by Rich et al.

(1994) and further developed by Fu and Rich (2002). Both direct and diffuse solar radiation was calculated and global solar radiation was the sum of both. This model used the standard overcast diffuse model, in which the incoming diffuse radiation flux varies with zenith angle. The two basic parameters used to calculate solar radiation for a particular area, were clearness index and diffuse proportion. The clearness index was the fraction of radiation that passes through the atmosphere (Eq. (4.2)) and the diffuse proportion was the proportion of global normal radiation flux that is diffuse (Eq. (4.3)).

$$\text{clearness index, } k_t = \frac{I_{global}}{H_0} \tag{4.2}$$

$$\text{diffuse proportion, } d_t = \frac{I_{diffuse}}{I_{global}} \tag{4.3}$$

where H_0 is the extraterrestrial solar radiation, I_{global} is the global solar radiation, and $I_{diffuse}$ is the diffuse solar radiation, on the topographic surface (Boland et al., 2008, Ridley et al., 2010).

The clearness index and diffuse proportion were calculated at 12:00 noon for the four equinox and solstice dates. I_{global} were averaged from the GHI data over a ten-year period from 2003 to 2012. The hourly extraterrestrial solar radiation was given by Eq. (4.4) and Eq. (4.5).

$$H_0 = C \times d_d \times \cos\theta_s \tag{4.4}$$

where C is the solar constant, equal to 1367 W/m^2 (Page, 1986), d_d is the correction to actual solar distance at any specific day in the year, and $\cos\theta_s$ is the Cosine of Solar Zenith Angle.

$$d_d = 1 + 0.0334 \times \cos(0.01721 \times i - 0.0552) \tag{4.5}$$

where i is the day number in the year.

The diffuse proportion was calculated from the clearness index value using the model adapted by Ridley et al. (2010) for Australia as given in Eq. (4.6).

$$d = \frac{1}{1+e^{-5.0033+8.6025k_t}} \quad (4.6)$$

The calculated clearness index and diffuse proportion values are shown in Table 4-1.

Table 4-1 Summary of clearness index and diffuse proportion values on four seasonal dates.

Dates	Clearness Index	Diffuse Proportion
Spring Equinox	0.56	0.54
Summer Solstice	0.65	0.36
Autumn Equinox	0.55	0.58
Winter Solstice	0.50	0.68

The day length values were 13 hours (6:00-19:00), 15 hours (5:00-20:00), 13 hours (7:00-20:00), 10 hours (7:00-17:00) for spring equinox, summer solstice, autumn equinox, and winter solstice respectively. For spring, summer, and autumn analysis, DSMs with all urban structures and DSMs without trees were used as input for the solar radiation model. For the winter analysis, DSMs with deciduous trees removed and DSMs without trees were used as input, and DSMs with all trees were calculated for comparison.

4.3.4 Correlating building and tree features with solar radiation

To understand how the morphology of buildings and trees interact to reduce solar radiation we then examined how tree and building features are correlated with the solar radiation on the building roofs. For example, it may be that the reductions in solar radiation from the trees are a result of large crowns widths, roof areas or tree heights in our selected areas. To examine this, 50 plots were selected using stratified random sampling technique for each road. Land use information obtained from the NSW Mesh Blocks Australian Statistical Geography Standard (ASGS) Ed 2011 was used to create four strata which were commercial, industrial, residential and other. The number of samples for each stratum was calculated based on the land use percentage on each road. The total direct solar radiation received on roofs was calculated for each plot. Then, the modelled radiation was correlated to building and tree features. Three building features were calculated for each plot using the buildings layers. They included:

- average building height,
- average roof area, and
- average building volume

where average building volume was the product of average building height and roof area for each sampling plot.

Seven tree features were calculated for each plot, using the canopy height models, were:

- canopy height metrics including 50th, 75th and 95th Percentile, maximum, mean, standard deviation, and
- canopy coverage,

where canopy height was equivalent to foliated crown height; canopy height standard deviation was the amount of variation from the average canopy height; and canopy coverage was the proportion of each plot area covered by tree crowns, as measured from overhead. This coverage value may be from one tree, or may comprise many tree canopies that overlap to varying degrees.

4.4 Results

4.4.1 Trees, buildings and land use

The roadside forest on both corridors is thin and discontinuous – often consisting of a single row of trees on each side of the road. At the start of Parramatta Road there are large mature fig trees and some dispersed London plane trees; however, along much of this corridor there are very few trees. Where trees are present they may only be on one side of the road at large intervals, so that they do not form continuous habitat or canopy cover. Most trees along this road are small.

At the start of the Pacific Highway there are some mature plane trees; however, most marginal buffer zones have some trees. When present, trees may only be on one side of the road, but they are often in extensive or continuous stands forming connected habitat and significant canopy cover. Much of the forest along this highway consists of mature, long-established large trees.

Adjacent land use along each road shows different patterns (see Figure 4-3). Parramatta Road is known for many motor dealerships and, along the section surveyed, 62.3% is devoted to commercial and industrial use while only 27.0% is residential. On the Pacific Highway, 68.3% of land use is residential and 19.2% is commercial and industrial. The land use differences contribute to the characteristics of trees and buildings along both roads. Average building height along Parramatta Road (7.1 m) is higher than that on the Pacific Highway (5.9 m), while average building roof area on Parramatta Road (358.3 m^2) is also higher than that on Pacific Highway (304.4 m^2). But average tree height on the Pacific Highway (9.8 m) is higher than that on Parramatta Road (8.3 m). The tree coverage on the Pacific Highway (32.0%) is over twice that on Parramatta Road (10.8%).

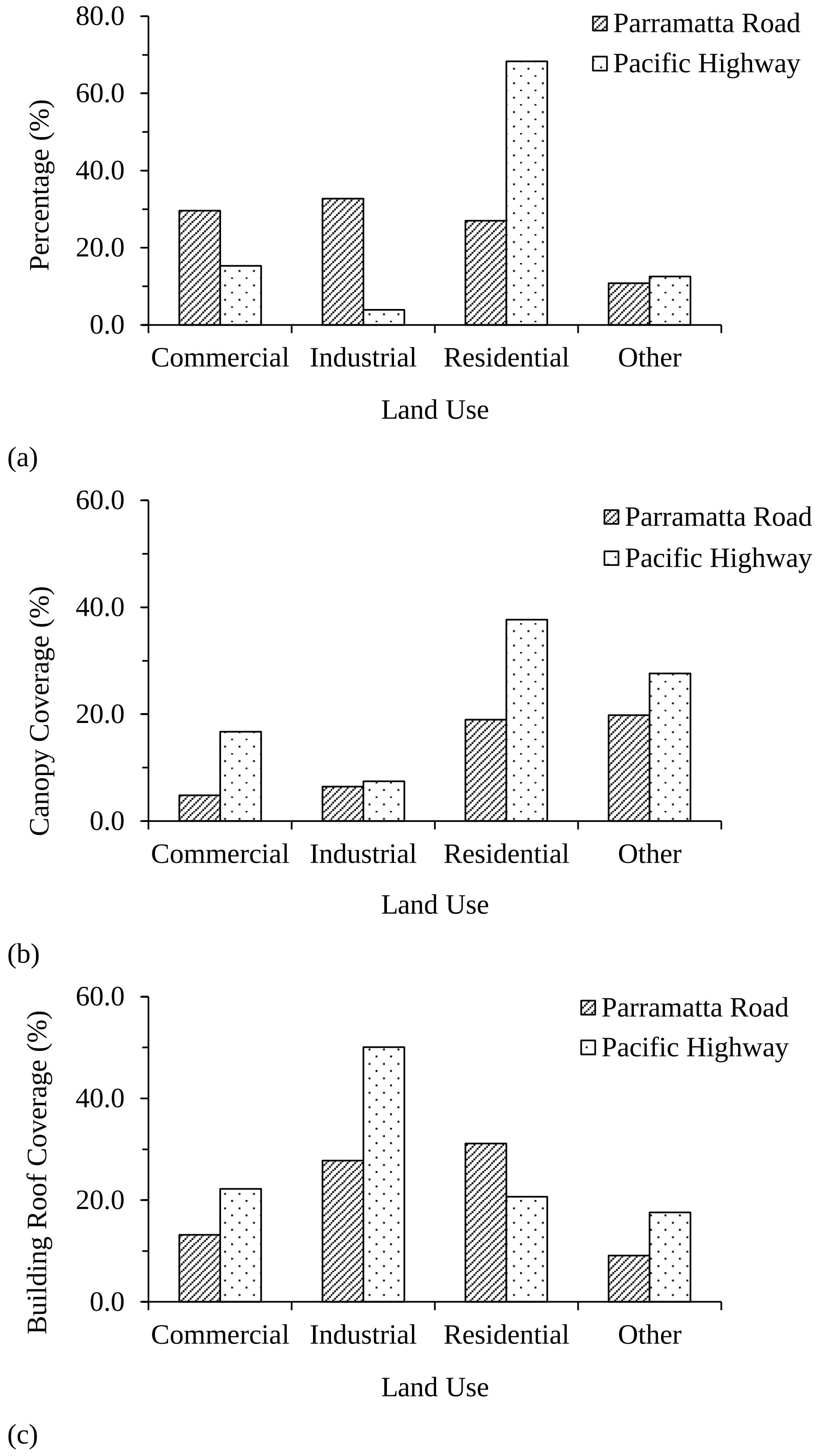
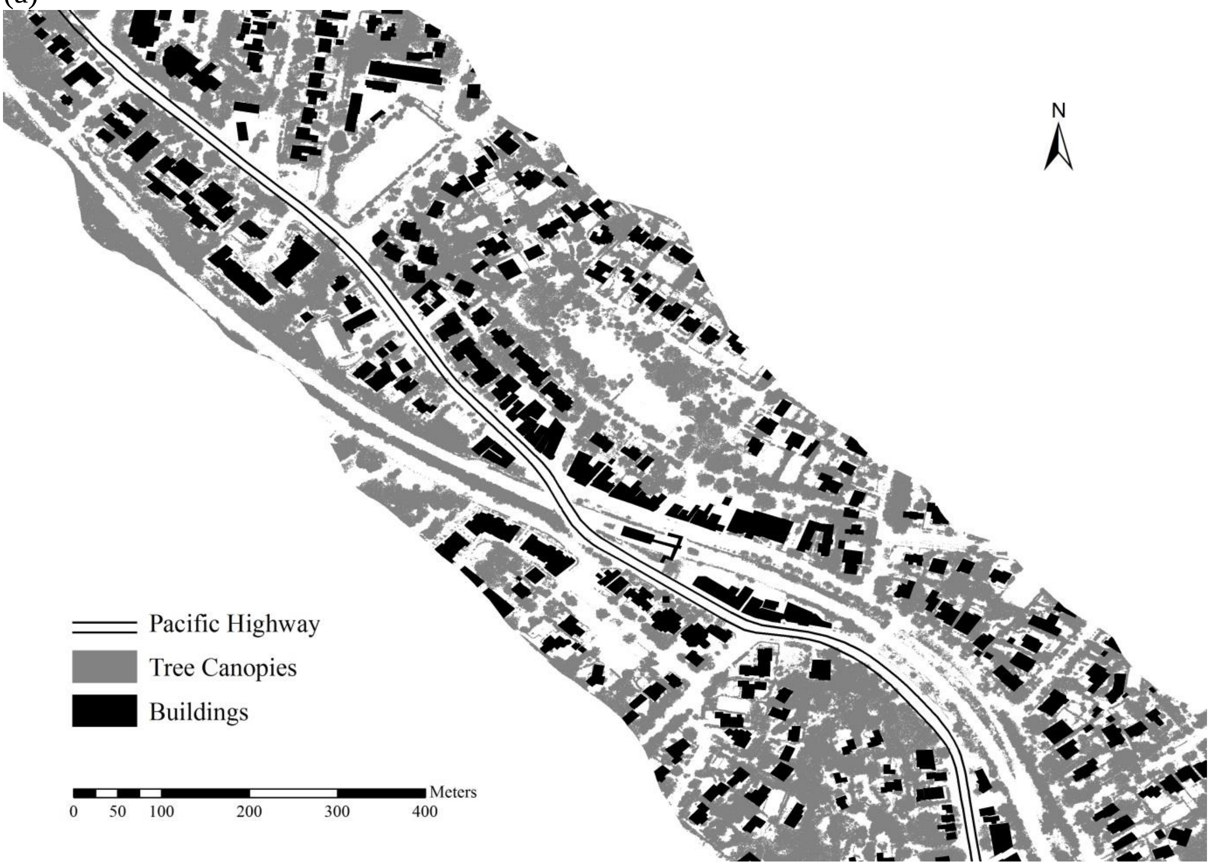


Figure 4-3 Summary of land use, trees and buildings on both roads: (a) land use percentage; (b) canopy coverage; (c) building roof coverage*. *Roof area as proportion of total surveyed area, relating to each land use

As Figure 4-3 (b) and (c) show, for both roads, the canopy coverage of residential areas is much larger than that for commercial or industrial lands. On the Pacific Highway, the industrial areas have much higher densities of building roofs than other land use types, while for Parramatta Road, residential and industrial areas have higher percentages of building roofs.

Based on the remote sensing surveys, examples of distribution of existing trees, at sites on each corridor, are illustrated in Figure 4-4. The segment of Parramatta Road depicted in Figure 4-4 illustrates the very limited roadside trees with gaps of up to 0.5 km between stands; whereas (b) clearly shows the more extensive forest on both sides of the Pacific highway, with very short gaps between stands.

(a)



(b)

Figure 4-4 Distribution of existing roadside trees at sites on each corridor surveyed: (a) Parramatta Road; (b) Pacific Highway.

4.2 Solar Radiation Profiles

Table 4-2 summarises the modelled direct and diffuse solar radiation values received on building roofs. Deciduous trees were masked out during the modelling when simulating the solar radiation values on winter solstice.

Table 4-2 Summary of solar radiation on building roofs on four key seasonal dates.

Season	Solar Radiation ($MJm^{-2}day^{-1}$)			
	Parramatta Road		Pacific Highway	
	Direct	Diffuse	Direct	Diffuse
Spring Equinox	11.0	9.3	9.4	7.7
Summer Solstice	20.0	7.3	17.4	6.0
Autumn Equinox	10.4	10.5	8.9	8.7
Winter Solstice	2.8	6.5	2.3	5.6

The direct radiation of the Pacific Highway is lower than that of Parramatta Road, which could be attributed to a variety of factors including local climate, elevation, aspect and slope of the two roads, as well as different tree coverage and building types. For each road, the radiation for the spring and autumn equinox is similar. Summer radiation is more than seven times the winter radiation and around twice the radiation values for the spring and autumn equinox. As shown in Figure 4-5, the trends of global solar radiation are similar along both corridors in all seasons and are consistent with the trends of direct radiation.

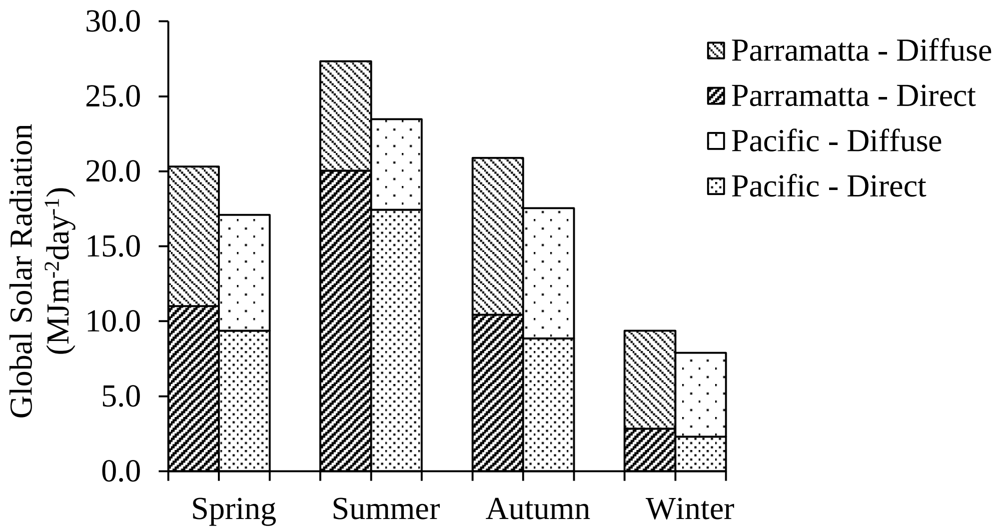


Figure 4-5 Global Solar Radiation (Direct and Diffuse) for both corridors on key equinox and solstice dates.

For the Pacific Highway, the masking of leafed deciduous trees as a proxy for winter leaf fall contributes to an increase of 3.9% in global radiation on building roofs, while for Parramatta Road, the masking of deciduous trees causes a 1.1% increase. This difference reflects the lower deciduous species coverage for the Parramatta Road. Although the percentage of the six deciduous species is not high in the study area, their impacts for winter analysis should not be ignored.

For Parramatta Road, the presence of trees only results in a reduction of 4.0 - 5.4% in direct radiation on building roofs for the four equinox and solstice dates , and a reduction of 4.8 - 5.9% in diffuse radiation. For the Pacific Highway, the presence of trees results in a reduction of 9.7 - 14.0% in direct radiation on building roofs for all seasons , and a reduction of 11.1 - 14.6% in diffuse radiation. The comparison of global solar radiation reduction is shown in Figure 4-6. This reduction along the Pacific Highway corridor is consistent with higher coverage by existing trees, which is substantially higher than that of Parramatta Road. Other factors that may contribute to this reduction include tree and building features.

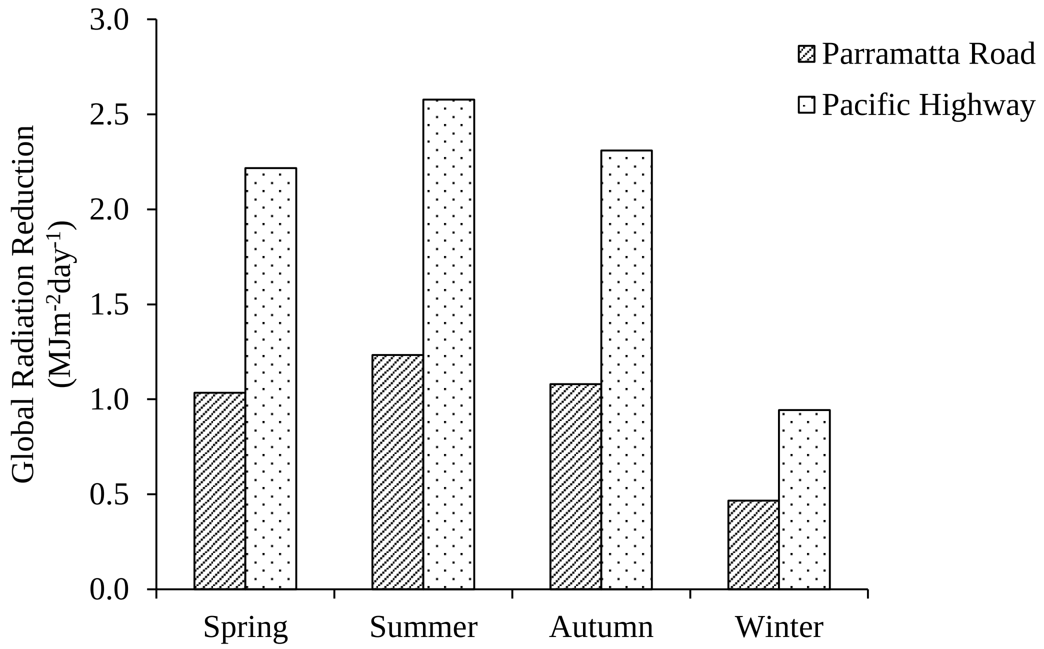


Figure 4-6 Reduction of Global Solar Radiation reduction, for both corridors on four equinox and solstice dates.

Figure 4-7 shows the hourly reduction of direct and diffuse solar radiation received by building roofs. The general trends of four seasons for both sites are similar. The reduction of direct radiation increases rapidly in the early morning and decreases in late afternoon. The radiation reduction in summer shows a different pattern from that in winter. The highest reduction is observed at noon in winter while a concavity is shown in the levels at noon in summer. The high solar altitude in summer results in shorter shadow cast by trees, especially at noon time. Since diffuse radiation is scattered by molecules or aerosol particles in the atmosphere and may travel in any direction, no shadows are produced by diffuse radiation. Therefore, the reduction of diffuse radiation varies with solar zenith angle over a day.

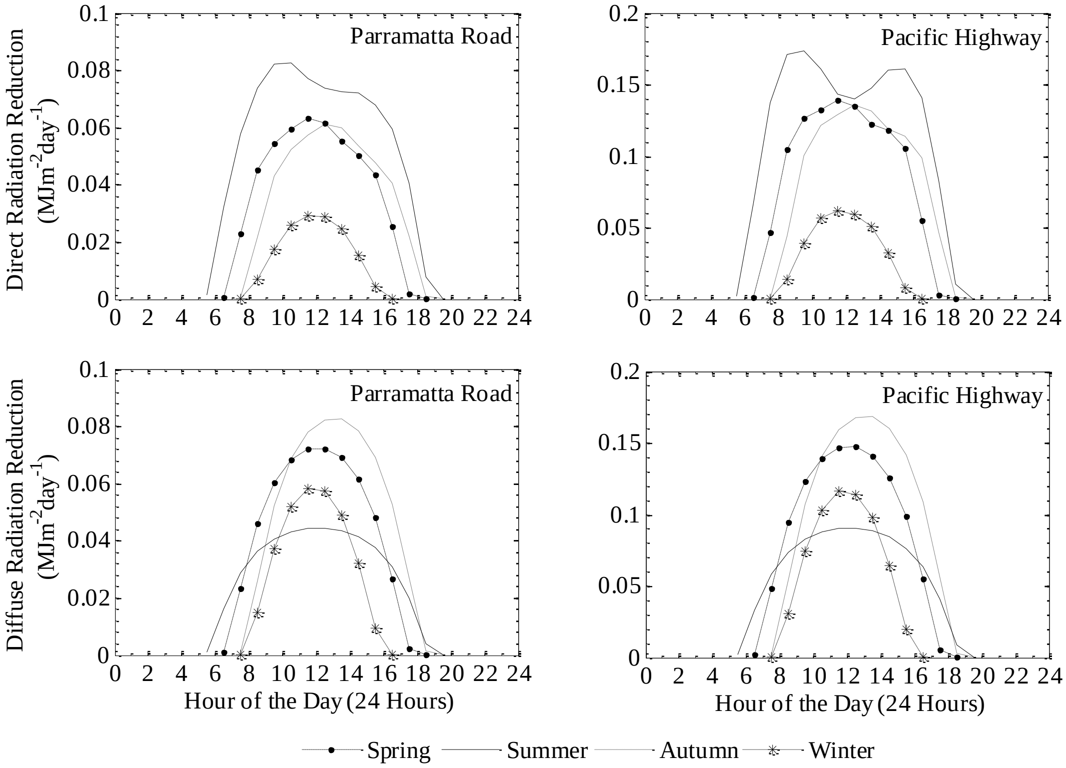


Figure 4-7 Hourly reduction of Direct and Diffuse Solar Radiation received by roofs of buildings along these corridors on key equinox and solstice dates.

4.4.3 Correlation between solar radiation and tree and building features

The correlation analyses summarised in Table 4-3 show the Pearson's correlation coefficient (r) values between the modelled direct and diffuse radiation on building roofs and the tree and building features for spring, autumn equinox and summer, winter solstice. As would be expected, for both roads, as the trees increase in size the roof-received radiation decreases. However, the tree features have a stronger influence compared to the building features. In general, the correlation between these tree features and solar radiation is strongest in summer, and weakest in winter due to lower incident radiation. The results show that tree metrics are strongly correlated with the reduction in solar radiation in the summer, which underscores their role in cooling energy conservation. However, the correlation results also show how dependent these results are on the morphology of the urban environment and its surrounding trees. For Parramatta Road, canopy coverage is the tree attribute which has the greatest influence on solar radiation. For the Pacific Highway, the mean canopy height and canopy coverage show higher impacts than other features. For both roads, none of the building features are significantly related to solar radiation. The Pacific Highway has higher tree coverage and smaller buildings, and impacts of tree features are more pronounced, Parramatta road has smaller trees, larger roof areas but also buildings of one or two storeys, allowing canopy coverage to have a significant effect.

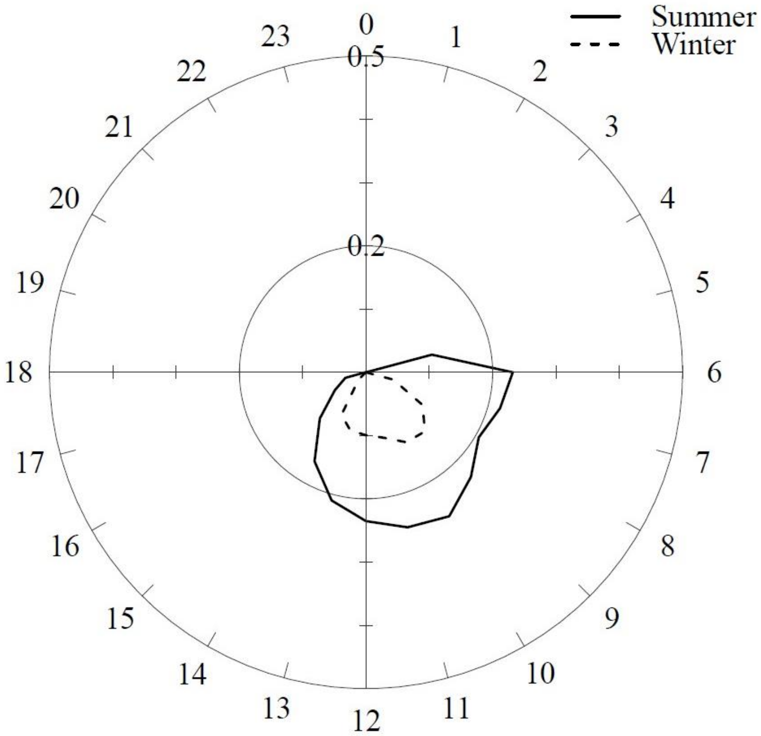
To understand how the morphology of the urban environment affects the reduction in solar radiation at a more detailed level, the correlation of determination (r^2) values were used. As mean canopy height and canopy coverage are the tree features that most strongly relate to solar radiation, they were selected to examine the r^2 values through time on a daily basis for both summer and winter solstice (Figure 4-8 & Figure 4-9). Since the two roads have different tree coverage, they show different patterns of r^2 variation. For Parramatta Road, r^2 variation peaks for both tree features occur at 6:00 on summer solstice. The highest correlations between the same features and winter radiation occur at 8:00 and 9:00. For the Pacific Highway, the strongest correlation between mean canopy height and direct summer radiation is shown at 9:00 and 15:00; the strongest correlation between canopy coverage and direct summer radiation is shown at 15:00. The strongest correlation between canopy coverage and direct winter radiation is shown at 8:00 and 14:00.

Table 4-3 Summary of correlation coefficients (*r*), between solar radiation reduction and two building features and three tree features, by season.

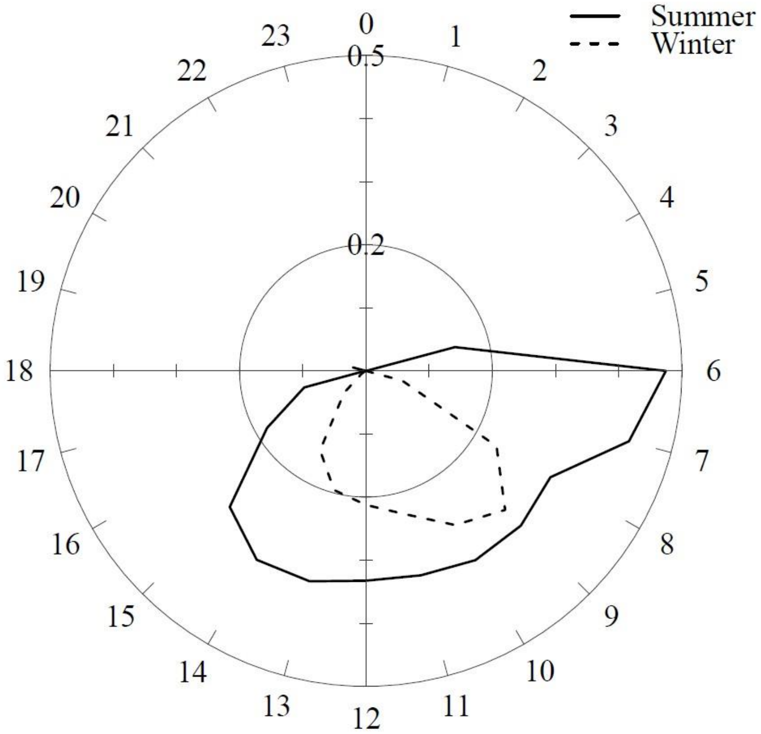
Parramatta Road		Spring		Summer		Autumn		Winter	
		Direct	Diffuse	Direct	Diffuse	Direct	Diffuse	Direct	Diffuse
Canopy Height Metrics	50th Percentile	-0.38	-0.39	-0.45	-0.48	-0.38	-0.39	-0.27	-0.41
	75th Percentile	-0.38	-0.39	-0.45	-0.48	-0.38	-0.39	-0.27	-0.41
	95th Percentile	-0.38	-0.39	-0.45	-0.48	-0.38	-0.39	-0.27	-0.41
	Maximum	-0.38	-0.39	-0.45	-0.48	-0.38	-0.39	-0.27	-0.41
	Mean	-0.47	-0.49	-0.51	-0.54	-0.47	-0.49	-0.34	-0.51
	Standard Deviation	-0.32	-0.35	-0.40	-0.44	-0.31	-0.35	-0.21	-0.37
Canopy Coverage	Canopy Coverage	-0.61	-0.68	-0.67	-0.71	-0.61	-0.68	-0.51	-0.70
Building Features	Average Building Height	0.31	0.42	0.33	0.37	0.31	0.42	0.23	0.44
	Average Roof Area	0.40	0.42	0.44	0.40	0.39	0.42	0.25 n/s	0.43
	Average Building Volume	0.33	0.37	0.36	0.33	0.33	0.37	0.22 n/s	0.38

Pacific Highway		Spring		Summer		Autumn		Winter	
		Direct	Diffuse	Direct	Diffuse	Direct	Diffuse	Direct	Diffuse
Canopy Height Metrics	50th Percentile	-0.42	-0.47	-0.46	-0.53	-0.41	-0.47	-0.39	-0.47
	75th Percentile	-0.42	-0.47	-0.46	-0.53	-0.41	-0.47	-0.39	-0.47
	95th Percentile	-0.42	-0.47	-0.46	-0.53	-0.41	-0.47	-0.39	-0.47
	Maximum	-0.42	-0.47	-0.46	-0.53	-0.41	-0.47	-0.39	-0.47
	Mean	-0.56	-0.61	-0.62	-0.67	-0.56	-0.61	-0.51	-0.61
	Standard Deviation	-0.44	-0.47	-0.47	-0.53	-0.44	-0.47	-0.39	-0.47
Canopy Coverage	Canopy Coverage	-0.50	-0.59	-0.49	-0.59	-0.50	-0.59	-0.54	-0.59
Building Features	Average Building Height	0.12 n/s	0.18 n/s	0.24 n/s	0.25 n/s	0.12 n/s	0.18 n/s	0.01 n/s	0.18 n/s
	Average Roof Area	0.19 n/s	0.19 n/s	0.20 n/s	0.18 n/s	0.19 n/s	0.19 n/s	0.15 n/s	0.19 n/s
	Average Building Volume	0.16 n/s	0.15 n/s	0.16 n/s	0.14 n/s	0.16 n/s	0.15 n/s	0.15 n/s	0.15 n/s

n/s: not significant

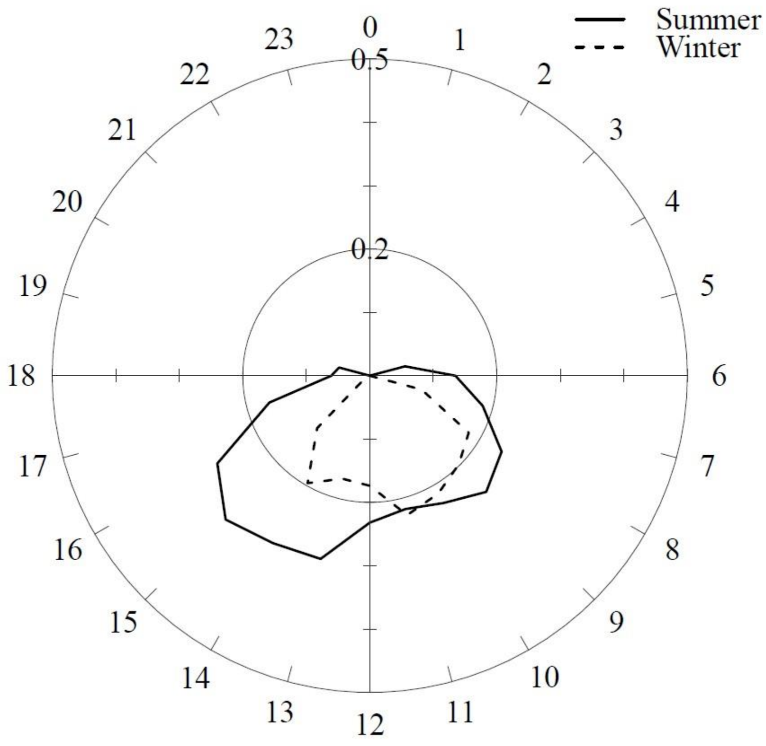


(a)

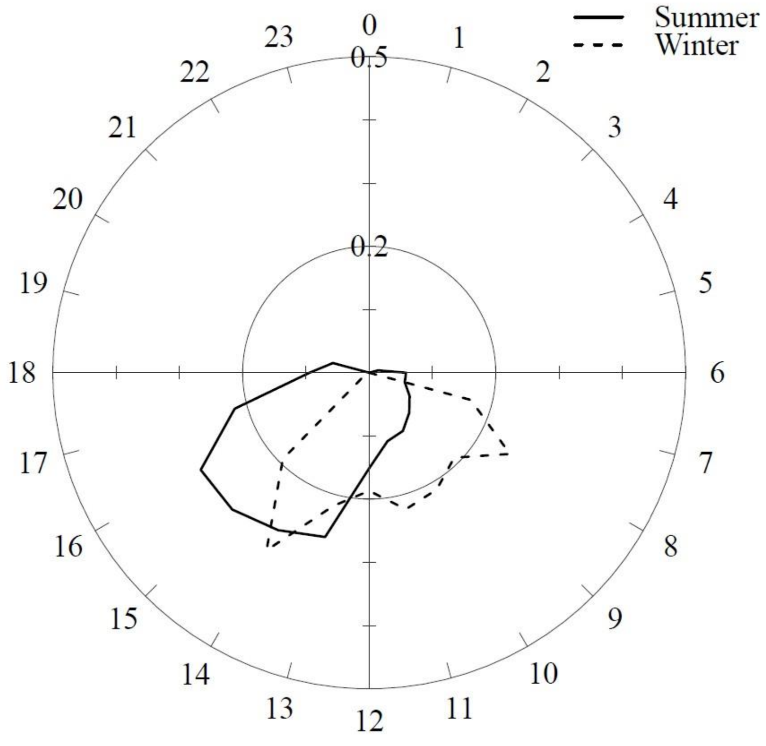


(b)

Figure 4-8 Correlation of determination (r^2) between direct radiation (per hour) and individual tree features for summer and winter on Parramatta Road: (a) mean canopy height; (b) canopy coverage.



(a)



(b)

Figure 4-9 Correlation of determination (r^2) between direct radiation (per hour) and individual tree features for summer and winter on Pacific Highway: (a) mean canopy height; (b) canopy coverage.

4.5 Discussion

The impacts of shading by green infrastructure in urban areas have been recognised for some time (Heisler, 1986). However, currently the most common technique for understanding these impacts are field-based. This study adds to the existing knowledge base on how to quantify the impacts of the urban forest by the means of spatial information science. The analyses reported here are focused on linear transport corridors and give some indications of key comparative values and variables in a temperate geographic location, with a mild coastal climate.

4.5.1 Contribution of tree and building features to radiation received

The radiation received on urban surfaces is dependent on a range of potential variables: distance of the tree stand from the building, building roof orientation etc. as well as the variables looked at in this study. The correlation tests here show that the solar radiation reduction is significantly related to canopy height and coverage, indicating greater benefits from larger trees. Another study of tree shade effects by Gómez-Muñoz et al. (2010) also indicated that economic values of larger trees were greater than those of smaller trees. Economically, planting larger trees can increase the green coverage with fewer individual trees, consequently reducing planting and maintenance costs. While tree size is highly dependent on the species, the growing conditions are also crucial. Harsh environments in urban areas may stunt the growth of trees. Furthermore, roadside trees are under particular threats such as excessive pruning to avoid conflicts with traffic and underground or overhead services as well as high pollution from traffic exhaust fumes.

The size of buildings is another important factor for the variation of solar radiation. Yu et al. (2009) found that the extensive and dense distribution of tall and large buildings can significantly influence the spatial pattern of solar radiation intensity and duration. The correlation analysis in this study shows that as the size of building roofs increase, the amount of radiation reduction from trees decreases. But, building height did not have significant impacts; however, this may be due to specific building characteristics along these two roads. Although there are more and larger buildings along Parramatta Road, the average height of its buildings is similar to that of the Pacific Highway. Since 67% of the adjacent land use along Parramatta Road is related to motor retailing and services, the building floor areas are extensive but the height is relatively low within this corridor.

4.5.2 Correlating radiation and energy use

Figure 4-10 shows that patterns of daily variation in average electricity demand for summer and winter are different. For summer, the demand begins to rise sharply from 5:00 (sunrise) to 9:00 and drops after 16:00 and continues to fall during the night until 4:00 before dawn. The maximum electricity demand shows a peak around 16:00. For winter, two peaks appear at 8:00-10:00 in the morning and 18:00-19:00 in the early evening. In summer, the electricity demand is higher during daytime than night-time. In this study, results demonstrate significant solar radiation reduction on buildings roofs over daytime due to tree shade. This reduction can effectively contribute to energy savings by reducing the use of air-conditioners (Pandit and Laband, 2010).

These results also show that correlations between roof received direct solar radiation and tree features vary with time on a daily basis. The mean canopy height and canopy coverage have strongest influence in the morning or middle afternoon. Both of these times are periods of high electricity demand. It should also be noted that for Parramatta Road, the correlation values during the whole morning are stronger than those during the afternoon, while the Pacific Highway shows the reverse pattern. This means that in summer trees play a more important role in lowering radiation in the morning for Parramatta Road and in the afternoon for the Pacific Highway. This difference could be due to a number of factors; the two roads have different elevations, aspects and slope as well as building types and orientation, tree coverage and tree height distribution. Further research is needed to test how these variables can affect the roles of tree features in shading, but the variation in correlation patterns can provide useful information for regional energy planning. Despite this variation, the strong influences of tree features on solar radiation are observed throughout the entire day, and hence the contribution of tree shade to energy saving is demonstrated to be significant.

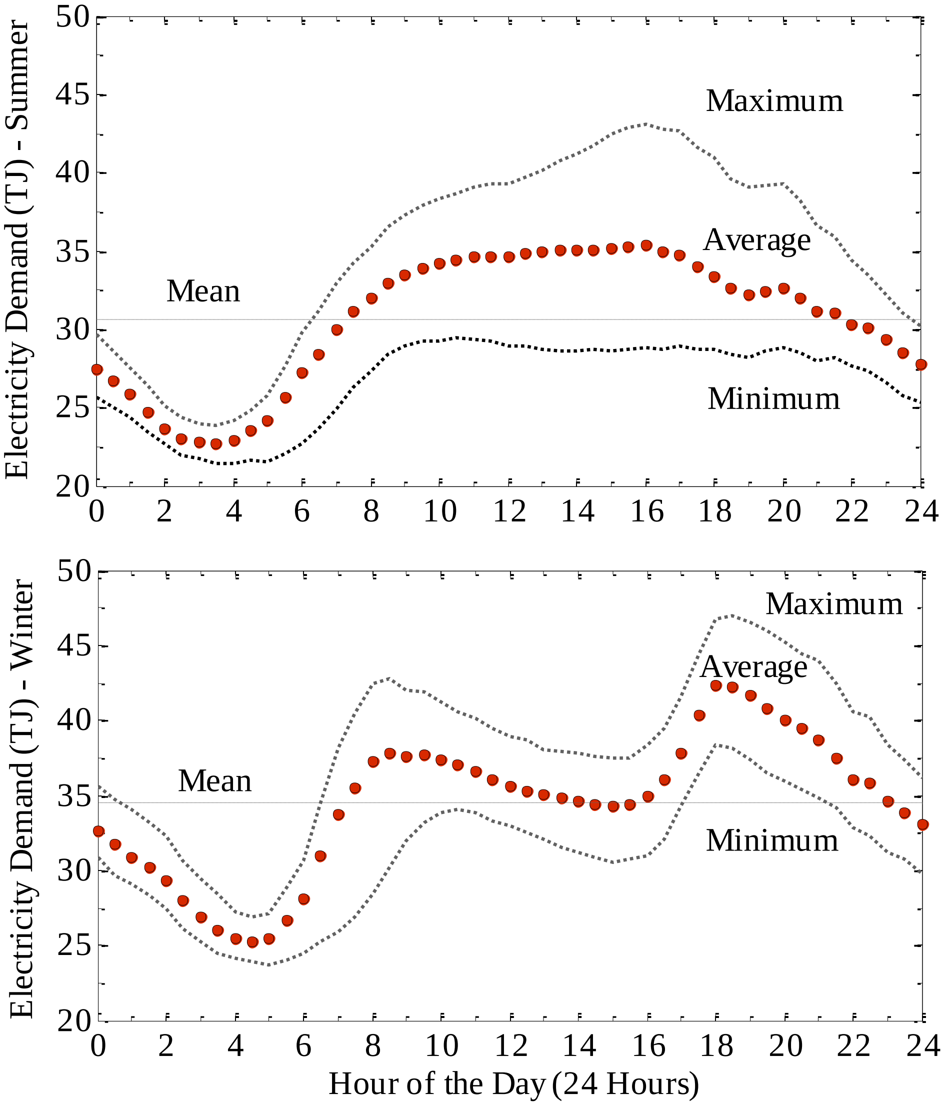


Figure 4-10 Daily variation in average electricity demand on summer and winter solstices over 10 years (2004-2013) in NSW, Australia. *Source: Australian Energy Market Operator (AEMO).*

One aspect of tree shading, impacting energy usage, which warrants further comment is defoliation. In winter, the reduction of solar radiation may increase the energy use for heating, but the presence of deciduous trees which drop leaves in winter allows the transmittance of direct solar radiation (Georgi and Dimitriou, 2010, Nikoofard et al., 2011). This study found the coverage of main deciduous trees along the Pacific Highway is over twice that along Parramatta Road, and that more radiation is received by building roofs along the Pacific Highway. This suggests potential ways to improve energy conservations in areas such as Parramatta Road that have more commercial or industrial land use. Many exotic deciduous trees are fast-growing and more tolerant of paved environments. They also have broad tree canopies that provide extensive dense shading.

These results not only show the impacts of trees on energy saving, but also provide useful information for renewable energy initiatives. The shorter shadow at noon, combined with high solar radiation received by building roofs during this period, indicate the potential for utilisation of solar energy. From the planning point of view, remote sensing technologies present a cost-effective way to minimise the conflicts between trees adjacent to buildings and solar photovoltaic panels. The existing available roofs for solar panels can be detected by modelling the shadow rasters from LiDAR derived DSMs. Additional DSMs can be produced by including the projection of tree growth to predict the shading impacts of existing trees in the medium and long term (Levinson et al., 2009). The radiation and shading models are also able to optimise planting programs. With the shading stimulation of new plantings, recommendations can be made in relation to species choice (height and canopy width), tree locations (orientations and distance to buildings) and tree densities.

4.5.3 Urban forest shading – broader implications

Although focused on Sydney, most of the features, processes and findings are relevant and applicable to other capital cities in Australia and internationally. Transport corridor vegetation often forms the only residual ecological skeleton for basic ecosystem function, in highly developed urban areas. The roadside and railway-side forest has significant impacts on both the roads/railways and adjacent buildings. But with further data it is possible to calculate the extent of this influence and to consider ways of expanding it. Although general urban forestry techniques have been widely documented, management of roadside forests does pose some special challenges; however, for this discussion they are considered as permanent natural shaded areas that need to be conserved.

Both roads surveyed are significant arteries in Sydney, but have distinguishing characteristics in terms of development and urban trees. They both extend over a number of local government areas, which can impose difficulties in coordinating forest management. The tree database of LGAs is not centrally maintained and varies with area; however, as remotely sensed data have become more accessible and affordable, some councils have utilised these technologies to map their urban forests. The NSW Land & Property Information (LPI) provides spatial imagery including LiDAR data to NSW state and local government agencies on a whole of government basis. These LiDAR data collected by LPI can be used by different organisations for many purposes, such as monitoring of climate change, soil degradation and fire risks, as well as detailed quantification of vegetation impacts such as shading. In addition, various digital data are available from Geoscience Australia or the Australian Bureau of Statistics and other international agencies (e.g. NASA). Using remotely sensed information, the investigation of urban forests will not be limited to local government boundaries, but extend to broader natural systems such as catchments or landscapes. Like trees along transport corridors, the riparian vegetation, forest linkages and other kinds of specific vegetation systems can all be effectively assessed and monitored.

4.6 Conclusion

In their work on the Canadian urban forest, Tooke et al. (2011) use similar analysis to show how tree and building properties are correlated with solar radiation. Our results extend this by firstly showing that extreme radiation in summer is reduced even with limited trees and in a coastal temperate climate where seasonal changes are not distinct, with widely differing solar radiation profiles, clearness indices and temperature profiles. Secondly, with a totally different forest composition, the work demonstrates the benefits of lowered radiation in adjacent areas from taller larger trees along permanent corridors of public land. Thirdly, the contrasting land use in the two study areas suggests how large deciduous trees could be used more effectively in industrial or commercial areas. Fourthly, maximum radiation reductions due to trees, in this region, overlap with peaks in daily building energy demands.

Understanding the shading impacts of urban trees is essential for calculating benefits and potential energy savings that urban forests offer. In Sydney, residual areas of forest extend along major transport or utility routes and, although important, management of roadside trees is fragmented or a low priority. Two remote sensing technologies have permitted rapid assessment of shading of variable strips of roadside forest over two chosen study sites in Sydney. Analyses have demonstrated reductions in solar radiation received by building roofs due to tree shade – both with season as well as tree type. Although deciduous trees only form a small fraction of the forests surveyed, and their distribution is more concentrated on sections of the highways concerned, their presence in some areas may have a significant effect on building roof-received energy. Relationships between select building and tree features are useful for field management of these forests as well as planning the best positions for installation of solar panels.

This chapter also shows how integrative analyses of remote sensing data can be used as practical tools for understanding or utilising green infrastructure. We have used an automatic computer solar radiation model to quantify the shading effects over two relatively long linear areas in a cost-effective way. As LiDAR and other types of remotely sensed data such as satellite imagery are widely accessible in Australia, they can be used by local government or other agencies for urban tree management or energy planning. In future studies, LiDAR points will be analysed to include tree transmission of different tree species in the model and provide more accurate results; to date we have only focused on building roofs, but the tree shading on walls and windows could also be assessed in future.

This chapter has focused on the effects of tree shading on solar radiation reduction and tree features used are at plot-level. The next chapter uses the same set of remotely sensed data to identify tree characteristics at individual tree level and links them back to received solar radiation. It provides more accurate estimation of tree features and emphasises their roles in energy conservation and urban environmental planning.

Chapter 5 Identifying Tree Characteristics and Their Contribution to Shading Impacts along Highway Corridors Using Remote Sensing

5.1 Introduction

Accelerating urbanisation in cities is accompanied by a series of environmental problems such as increased air, noise and water pollution, habitat loss, thermal stress and degradation and contamination of urban watersheds (Platt, 2004, Cook-Patton and Bauerle, 2012, Roy et al., 2012). Residual urban forests now play an increasingly significant role in ameliorating these negative impacts by providing climatic, ecological, economic, social and aesthetic benefits (Brack, 2002, Müller and Werner, 2010, Sander et al., 2010). There are different types of green spaces in urban areas and these are commonly remnant natural forests (e.g. national parks), backyard gardens, street trees, neighbourhood parks and reserves, as well as green walls and roofs (Lindenmayer and Burgman, 2005, Small and Lu, 2006, Hall, 2010). But as all these spaces are impacted by urban development, the shape of many vegetation patches in urban areas has now become linear or dendritic (Lindenmayer and Burgman, 2005).

One particular category of urban forests, known as ecological linkages or corridors, is increasing in importance both in their own right and in combination with other small reserves or green spaces (Bennett et al., 1999). In urban areas, due to the high density of road systems, roadside vegetation provides significant habitats for urban wildlife and become major landscape linkages for all urban green areas (Nagendra and Gopal, 2010). This paper chooses forests along two major highway corridors, in Sydney, which run through the metropolitan area from inner central business districts to outer suburbs.

To quantify the services of urban forests, specific tree characteristics and parameters such as tree coverage, species, total height and crown width need to be estimated. The traditional way to measure these tree features is by field survey, however, for large areas, this is very time-consuming and labour-intensive. Highway corridors are often long in length and vegetation assessment therefore requires extensive field work; however, recent advances in remote sensing technologies provide cost-effective alternative ways to acquire accurate and detailed information more quickly. Light detection and ranging (LiDAR) is an important active remote sensing system that uses laser returns to measure elevation values of ground and surface objects. With increased pulse laser rates and point densities, LiDAR is capable of extracting characteristics of individual trees (Roberts et al., 2005).

The original LiDAR products are LiDAR point clouds. Each point has precise x, y and z coordinates. Some earlier studies have directly used these LiDAR points to perform classification and segmentation. An object-based point cloud analysis approach was applied by Rutzinger et al. (2008) to detect tall vegetation in urban areas. Based on different height variances of LiDAR points, vegetation is differentiated from buildings by Goodwin et al. (2009). Liu et al. (2013) apply different algorithms to extract tree points and individual tree crowns in human settlements. Another common method for detecting individual trees is applying raster-based segmentation on 2-dimensional digital canopy height models (CHMs) derived from LiDAR points. Various algorithms have been employed in a number of other studies to estimate individual tree variables including tree height, crown diameter, crown base height and timber volume, using CHMs (Persson et al., 2002, Pouliot et al., 2005, Chen et al., 2006, Kwak et al., 2007, Forzieri et al., 2009, Ørka et al., 2010, Jung et al., 2011). Species of trees can also be further identified for individual tree segments using LiDAR or combined with spectral data (Holmgren and Persson, 2004, Holmgren et al., 2008, Ørka et al., 2009). The leaf area and biomass can also be calculated based on individual tree segmentation (Roberts et al., 2005, Popescu, 2007). When LiDAR data acquired in different years are available, forest growth or loss can be determined (Yu et al., 2004). However, most of the above raster-based segmentation studies have been done in natural forest areas without the interference of other urban objects or structures.

To apply similar tree identification algorithms in urban areas, trees should first be separated from other urban objects such as buildings. Some studies combine the information of LiDAR points and CHMs for urban vegetation mapping. High density LiDAR point clouds can be used for vegetation classification (Höfle et al., 2012). Then tree crowns are delineated from CHMs by detecting concave edges in between objects (Höfle and Hollaus, 2010, Höfle et al., 2012). Kato et al. (2009) utilise both LiDAR points and CHMs in the segmentation procedure and apply a wrapped surface on LiDAR points for individual trees to get tree parameters. Another reliable and widely used way to obtain tree information from urban areas is by integrating LiDAR data with other remote sensing data that provide spectral information such as multispectral or hyperspectral images (Shackelford and Davis, 2003a, Shackelford and Davis, 2003b, Benediktsson et al., 2005, Huang and Zhang, 2009, Zhang and Qiu, 2012). The Normalized Difference Vegetation Index (NDVI) calculated from spectral imagery can effectively indicate vegetation covers within a specific area.

While many studies have investigated tree segmentation and feature extraction, limited research has also begun to link the tree features derived from LiDAR data to wider urban forest effects. As indicated before, the urban tree benefits are very important in socio-economic terms. Since LiDAR data can collect a few samples from one square metre area on the surface, the derived digital surface models (DSMs) are well suited to model shadows and incident solar radiation. Some researchers have used, LiDAR remote sensing to map shadows or available solar irradiation on building roofs to estimate solar photovoltaic potential (Levinson et al., 2009, Yimprayoon and Navvab, 2010, Latif et al., 2012, Dereli et al., 2013). These studies focus on the usage of one clean, and renewable energy option, where trees are considered as an obstruction to solar radiation generation. However, the positive shading impacts of urban trees on energy saving in summer are also recognised (Akbari, 2002, Simpson, 2002, Block et al., 2012). Vegetation, buildings and terrain are the three principal elements of urban landscape structure (Ridd, 1995, Pickett and Cadenasso, 2008). Trees planted around buildings often affect energy usage by providing shading and reducing heat gain in buildings and the need for air conditioning, consequently mitigating urban 'heat island' problems (Shahidan et al., 2010, Block et al., 2012). A series of studies concentrate on the impacts of urban tree shade on urban facets including ground, roofs and walls (Tooke et al., 2009b, Tooke et al., 2011, Tooke et al., 2012). Tooke et al. (2011) extract both trees and buildings from LiDAR data and link their features to rooftop received solar radiation. However, tree areas in the study are not segmented and the tree features used are not calculated from individual trees.

The aims of this study are to: (a) extract individual tree segments and their characteristics using watershed segmentation algorithm; (b) model shadows on building roofs based on urban surfaces with trees in different height categories using LiDAR derived DSMs; (c) model solar radiation including both direct and diffuse radiation with and without the influence of urban trees; (d) relate the rooftop solar radiation to LiDAR derived tree features and building dimensions.

5.2 Study Area and Data

The Sydney Metropolitan Area (SMA) is extensive (12,145 km^2) but the main green areas, including both national parks and nature reserves, are located to the south and north with a number of pocket reserves scattered on the west and south-west outskirts (Wang and Merrick, 2013). The sections of the two long-established transport corridors surveyed were in the central part of the metropolitan area as shown in Figure 5-1, where green areas are very limited(Wang and Merrick, 2013). One survey extended along the Pacific Highway from North Sydney to Hornsby, approximately 20 km. The other extended out along Parramatta Road from Camperdown to Parramatta, approximately 20 km. In another facet of the group research program field tree data were collected to assess the environmental and economic benefits of urban trees along the same transport corridors, using i-Tree software. The tree parameters collected in the field included tree height, crown width, tree location in lat/lon and tree species. There are 82 and 249 trees measured for Parramatta Road and Pacific Highway, respectively.

The remote sensing data acquisition was carried out in April 2012 before the Autumn leaf-fall. Both LiDAR and hyperspectral sensors were mounted on the aircraft. The data were produced in the projection of WGS84 UTM Zone 56S.

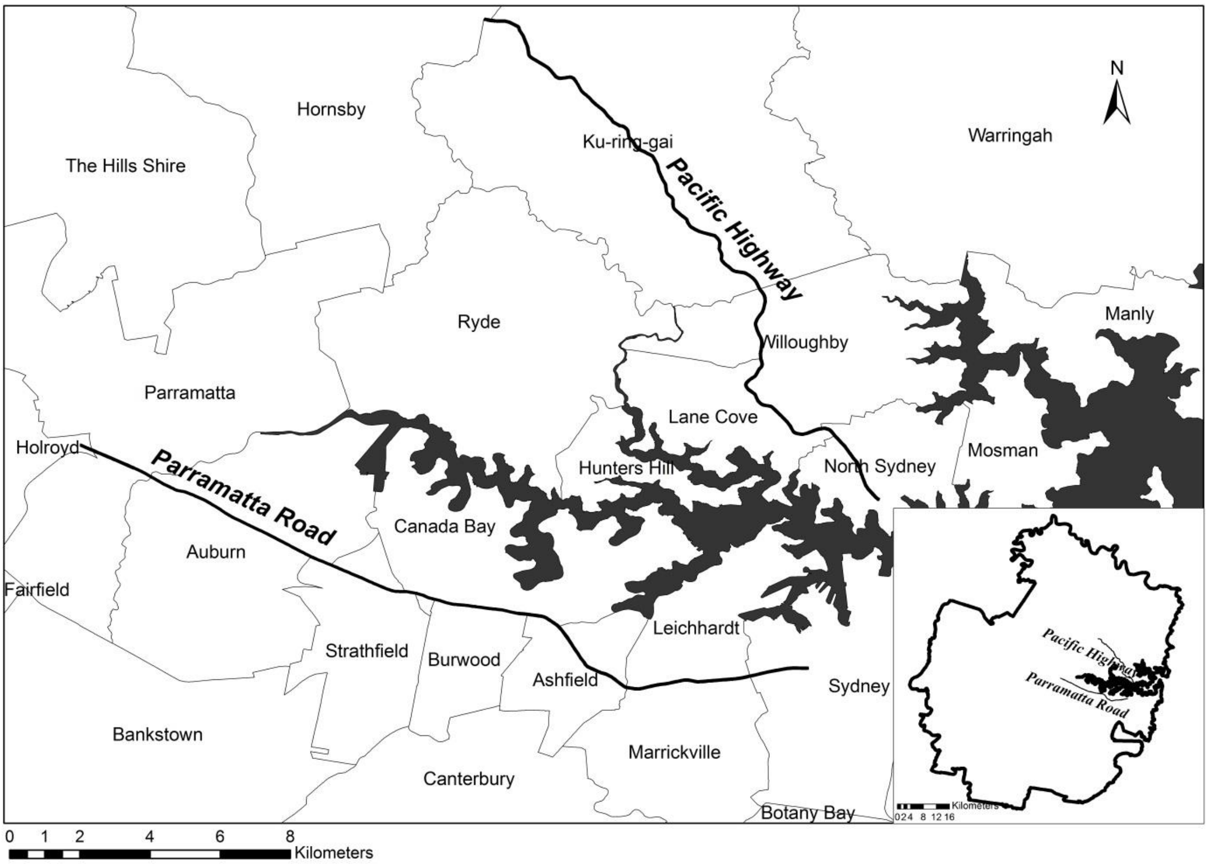


Figure 5-1 Map of inner SMA showing the lengths of Parramatta Road and Pacific Highway surveyed as well as Local Government Area (LGA) boundaries. Insert shows full extent of Sydney Metropolitan Area. *Sources: ABS and NSW Lands*

5.2.1 LiDAR data and hyperspectral imagery

The LiDAR data were acquired using a RIEGL LMS-Q560 full-waveform laser scanner. The system used a pulse rate of 180 kHz, a wavelength of 1550 nm and a pulse length of 3.4 ns.

The shot-to-shot accuracy for measurement of absolute accuracy along structures was 0.02 m. The nominal swath width of the LiDAR data coverage was 400 m. Laser point density was around 5 points/m^2. We classified the raw LiDAR point clouds into ground and non-ground points were classified using TerraScan (Finland, Terrasolid). The digital terrain models (DTMs) were derived by the interpolation of the ground points. The digital surface models (DSMs) were derived from the highest points. All the models were gridded to 0.4 m spatial resolution to match the same image resolution of the hyperspectral products.

Hyperspectral images were acquired using Hyspec VNIT 1600/SWIRcameras. The scanners collected the images with the light at wavelengths ranging from 400nm to 1000 nm in 160 small bands of a spectral width of 2.5 nm. The spatial resolution of the images was 0.4 m. The nominal swath width of Hyperspectral images was 200 m. The hyperspectral products are atmospheric and geometrically corrected. Our analyses focus on the area where LiDAR and Hyperspectral data overlapped.

5.2.2 Cadastral and land use data

The Digital Cadastral Database (DCDB) 2013 was acquired from the NSW Land & Property Information to provide information on the property boundaries over the study sites. The land use information for each property was obtained from the NSW Mesh Blocks Australian Statistical Geography Standard (ASGS) Ed 2011 Digital Boundaries in ESRI Shapefile Format (ABS).

5.3 Methods

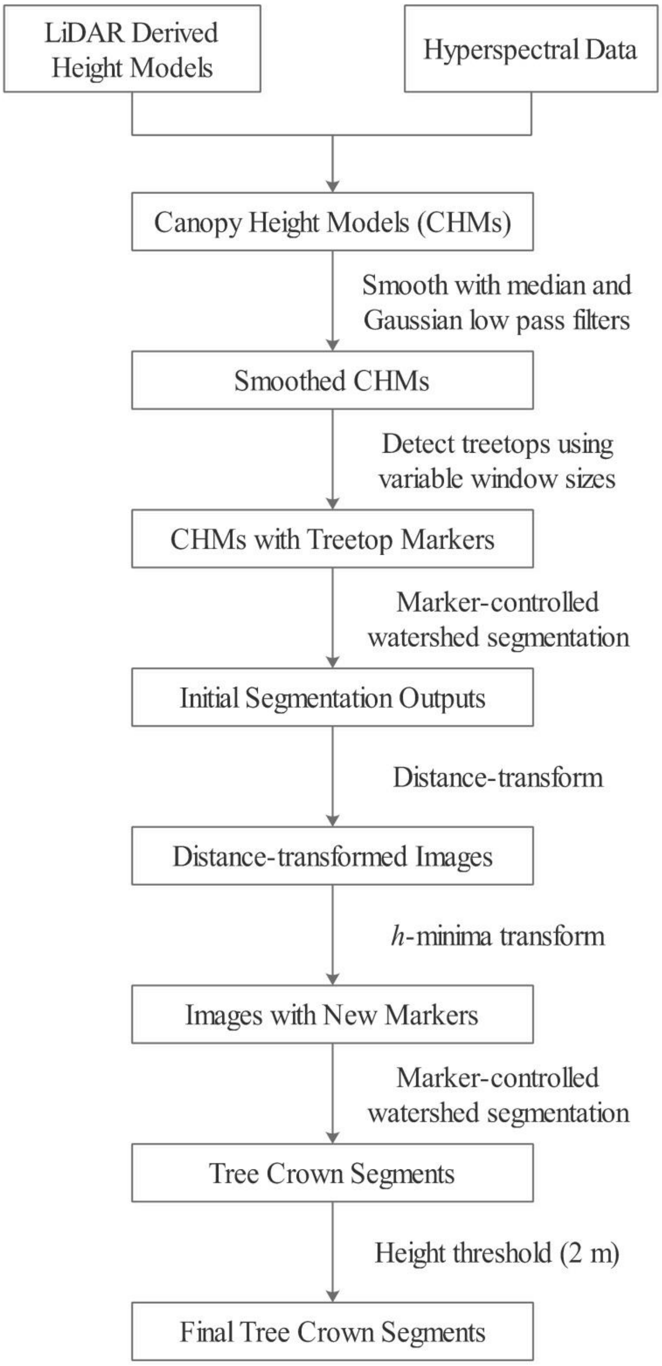


Figure 5-2 Overview of the methods for tree crown segmentation.

Figure 5-2 summaries the key steps used in the methods for tree crown segmentation. The details of these steps will be described in following sections.

5.3.1 Pre-processing

The height models of urban objects were calculated by subtracting DTMs from the DSMs. The NDVI values derived from hyperspectral images were used to extract vegetated areas. Then combined with LiDAR height models, grass and shrubs were removed from the vegetation masks by applying a height threshold of 0.5 m. The tree areas were then overlayed with the digital height models, producing canopy height models (CHMs). The original CHMs presented an uneven and intricate surface of tree crowns (Koch et al., 2006). Large height variation between some tree crowns, especially in large broad leaf trees, can make it difficult to detect a single peak for each tree (Koch et al., 2006). To remove interference and suppress minor height deviations, the CHMs were smoothed with both median and Gaussian low pass filters. Tree crown segmentation was then processed on raster-based and smoothed CHMs.

5.3.2 Treetops detection using variable window sizes

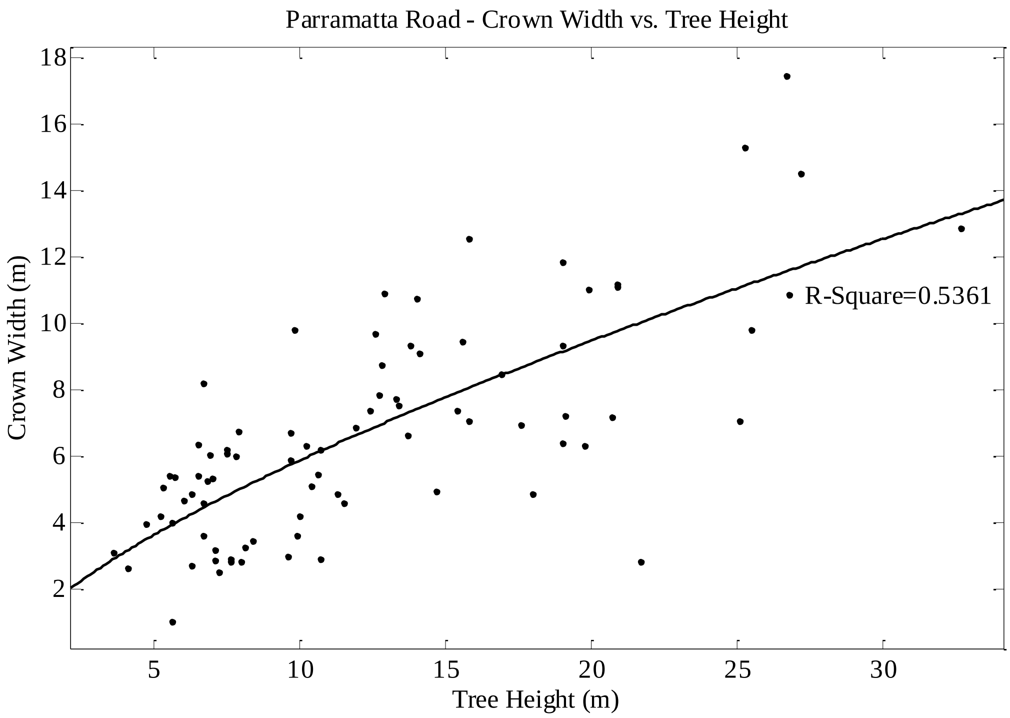
Various methods have been used to detect individual tree crowns. Based on LiDAR-derived CHMs, watershed segmentation, region growing method, and edge-based segmentation are common procedures for tree crown delineation (Hyyppä et al., 2001, Chen et al., 2006, Forzieri et al., 2009, Höfle et al., 2012). In this study, watershed segmentation was applied to delineate the crown boundary of individual trees. The watershed transform derived from geography can be classified as a region-based segmentation approach. This is an powerful tool which works efficiently on gray-scale images including CHMs to solve various segmentation problems (Gonzalez et al., 2009, Jung et al., 2011). The treetops were detected as seed points for tree crown segmentation. A local maximum algorithm was applied on the smoothed CHMs. Local maxima were considered as points or pixels having higher z values (height values) than their neighbours defined by users. Some previous studies have applied local maximum filtering using a moving window with a fixed size. Commonly, a 3 x 3 sliding window is used to compare the value of a point or pixel to its eight neighbours (Hyyppä et al., 2001, Maltamo et al., 2004, Yu et al., 2004, Solberg et al., 2006, Iovan et al., 2007). Based on the pixel size, other window sizes such as 5 x 5 and 7 x 7 have also been used for the local maxima detection (Popescu et al., 2002). This constant local maximum filter presents a relatively easy and automatic method to process CHMs. However, using fixed window size may cause errors of commission, detecting non-treetops as local maxima, or omission, where small treetops are missed, if the filter size is too small or too large (Popescu et al., 2002). So, the performance of local maximum algorithm was determined by the appropriate selection of a moving window size. Another method was to identify tree top locations with a variable window size under the assumption that tree crown size varies with tree height. Essentially, the higher a tree is, the larger the crown width is (Popescu and Wynne, 2004). Based on the relationship between tree height and crown width, the moving window was adjusted to an appropriate size with respect to the height value of each pixel. Some studies used linear regression models or linear regression with a quadratic model to establish the tree height-crown relationship (Popescu et al., 2002, Popescu and Wynne, 2004, Tiede et al., 2005), however, the variability of crown size increased with the tree height (Figure 5-3). In this study, a nonlinear power model adopted by Chen et al. (2006) showed better prediction for crown width using the tree height data collected from the field survey. The nonlinear model was used for both Parramatta Road and Pacific Highway as shown below:

Parramatta Road: $Crown\ Width = 1.2 \times (Tree\ Height)^{0.6898}$ (1)

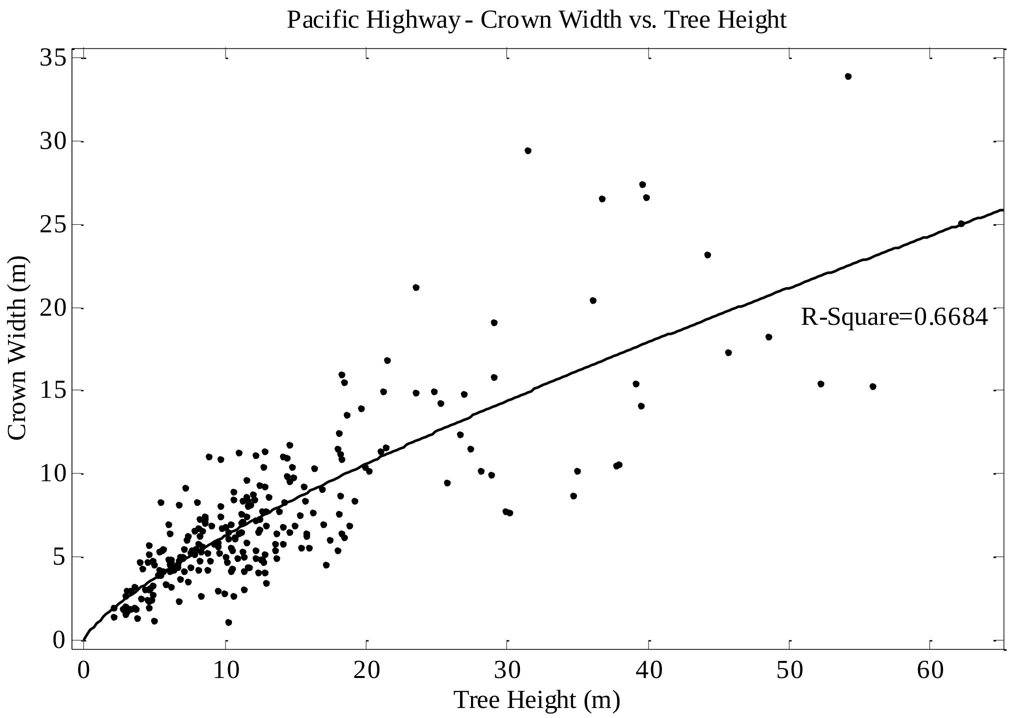
$$(R^2 = 0.5361, RMSE = 2.224)$$

Pacific Highway: $Crown\ Width = 1.096 \times (Tree\ Height)^{0.7567}$ (2)

$$(R^2 = 0.6684, RMSE = 2.926)$$



(a)



(b)

Figure 5-3 The relationship between crown size and tree height based on field data along: (a) Parramatta Road; (b) Pacific Highway.

Based on Eq. (1) and (2), the sizes of the variable windows were calculated corresponding to crown sizes. When filtering the CHMs images with these moving windows, treetops were detected as local maxima for both roads.

5.3.3 Tree crown segmentation and tree parameters

In the process of transformation, the CHMs are inverted so that each tree crown is analogous to a catchment basin. Individual trees can then be delineated by creating watershed ridge lines between any adjacent two basins. If rain is falling exactly on the boundaries, the runoff would be equally likely to flow into either basin (Gonzalez et al., 2009).

These transforms can be operated using different kinds of algorithms such as the morphological watershed algorithm and marker-controlled watershed segmentation algorithm (Forzieri et al., 2009). To overcome over-segmentation issues with watershed methods, we adopted a modified marker-controlled watershed segmentation used by Chen et al. (2006). To apply this segmentation to gray-scale images, the smoothed CHMs were inverted to get the complement of the CHMs. The complemented images were further filtered using a technique called minima imposition (Soille, 2003, Gonzalez et al., 2009). Tree top locations were used as internal markers and minima imposition modified the complement of the CHMs to remove all non-treetop minima, so that regional minima occur only in tree top locations (Chen et al., 2006, Gonzalez et al., 2009). Then the watershed transform was processed with 8 connected neighbourhoods on the filtered complemented CHMs.

The segmentation outputs of the watershed transform contained a number of omission errors because treetops of some species, with a relatively flat canopy surface, were difficult to distinguish from the LiDAR-derived CHMs (Chen et al., 2006). To further clarify tree distribution, watershed segmentation with a distance-transform was employed on the initial outputs. Firstly, the outputs were presented as binary images in which tree canopy areas had the value of 1's and background including initial watershed lines had the value of 0's. The binary images were computed using a distance transform. The transform calculated the distance from each non-zero pixel to its nearest zero pixel (Chen et al., 2006). Then the centres of the tree crowns were assigned higher values compared to the edge. The new pixel values could be used to detect new treetops since treetops were normally located around the crown centre. To perform the watershed segmentation, the distance transformed images were inverted and processed with the *h-minima* transform. The *h-minima* transform suppressed all minima in the images whose depth is less than *h* (Gonzalez et al., 2009). Based on some initial training, *h* was set as 0.5 m in this study. Afterwards, the regional minima of the suppressed images were detected as marked as seed points (treetops). Then, the marker-controlled watershed transform was processed with 8 connected neighbourhoods, using seed points as marker, on the complement of the distance transformed images. Finally, the segmentation outputs were filtered by a height threshold of 2 m to minimise the interference of grassland and small bushes or shrubs.

To evaluate the accuracy of the individual tree segmentation, 51 and 77 trees were measured in the field for Parramatta Road and Pacific Highway respectively. A handheld GPS device, combined with satellite images, was used to record the coordinates of these trees. The distance and directions of each tree to a nearby reference object were also recorded to assist determining the accurate locations of these reference trees. A number of tree parameters were measured in the field including tree height, crown width along two perpendicular directions (North-South and East-West bounds), and tree species. The ground measurements were combined with aerial photos for delineation of tree crowns. The overall segmentation accuracy was 84.3% and 71.4% for Parramatta Road and Pacific Highway, respectively. The trees along Parramatta Road were more sparsely located. However, tree covers were far denser along Pacific Highway where a large number of tree crowns were entwined or overlapped, which increases the difficulties in correctly segmenting individual trees.

Based on the tree crown segments, three tree parameters were estimated. The tree height was extracted as the highest z value within each tree crown boundary, and area of each tree segment was calculated as tree crown area. To examine the combined effects of tree height and crown, one parameter, called the normalised tree volume, was defined as the product of tree height and tree crown area of each tree segment.

5.3.4 Shadow mapping and solar radiation model

Our investigations focused on the shading effects of urban trees in summer and winter. Day length on summer solstice was 15 hours (5am – 8pm) while the winter solstice day length was 10 hours (7am – 5pm). Potential global solar radiation incident on building roofs, including both direct and diffuse solar radiation, was computed using the ESRI ArcGIS Solar Radiation tool at hourly intervals on summer and winter solstice over the entire study sites. The inputs for the models were the DSMs. Two basic parameters used in the radiation models, clearness index and diffuse proportion, were calculated using the Gridded Hourly Solar Global Horizontal Irradiance (GHI) Metadata, obtained from the Australian Bureau of Meteorology (BOM). For comparison, all trees were removed from original DSMs to create DSMs without trees. Solar radiation over the study area was also calculated using the DSMs without trees. The details of the solar radiation model were shown in Chapter 4.

To produce shadow maps over the study areas, the ESRI ArcGIS Hillshade tool was used to model shaded areas on building roofs by adjacent features such as trees, buildings and terrain from DSMs at 8am, 10am, 12pm, 2pm, and 4pm on summer solstice and winter solstice. The trees of the study areas were categorised into four groups based on height: (1) 2 m – 10 m; (2) 10 m – 20m; (3) 20 m – 30 m; (4) 30 m above. Then the DSMs were processed to create new

DSMs: each containing only one tree category. For Parramatta Road, no trees were found over 30 m, so only three types of DSMs were analysed. For Pacific Highway, all four types of DSMs were analysed. The shadows on building roofs were modelled using DSMs for both roads.

5.3.5 Correlation analysis and stratified random sampling

To investigate the relationship between estimated solar radiation and tree and building features, correlation analyses were conducted using stratified random sampling. There were 50 samples (properties) selected for each road. Land use information was used to create four strata which were commercial, industrial, residential and other. The number of samples for each stratum was calculated based on the land use percentage on each road (Table 5-1). Five tree features included average tree height, average tree crown area, sum of tree crown area, average normalised tree volume and sum of normalised tree volume. Five building dimensions were calculated based on building roof extraction summarised in Chapter 4. They included average building height, average building roof area, sum of building roof area, average building volume and sum of building volume. In addition, the ratios between tree and building features were included in the analysis, which were height ratio (trees versus buildings), average and sum area ratios (tree crowns versus building roofs), and average and sum volume ratios (trees versus buildings).

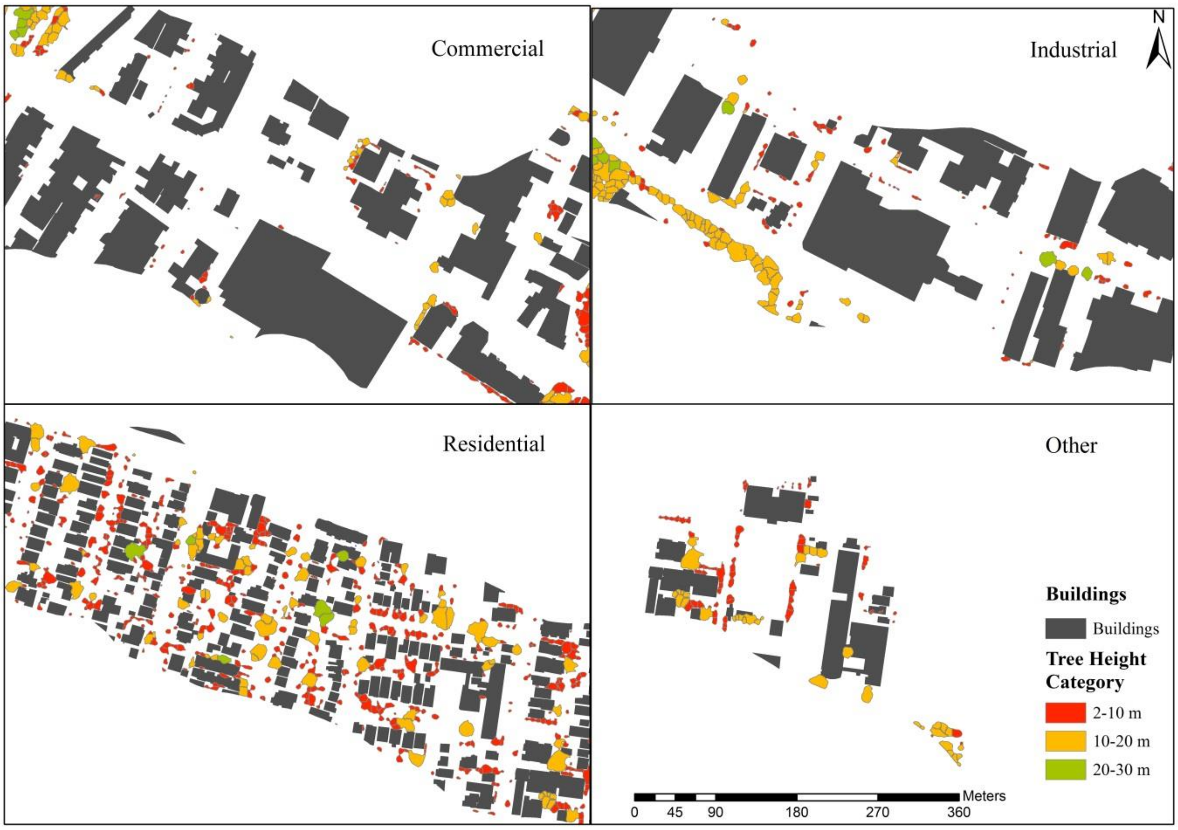
Table 5-1 Land use percentage and number of samples of Parramatta Road and Pacific Highway.

	Parramatta Road		**Pacific Highway**	
Land Use (Strata)	Land Use Percentage (%)	No. of Samples	Land Use Percentage (%)	No. of Samples
Commercial	29.6	15	15.3	8
Industrial	32.7	16	3.9	2
Residential	27.0	14	68.3	34
Other	10.8	5	12.5	6
Total	100.0	50	100.0	50

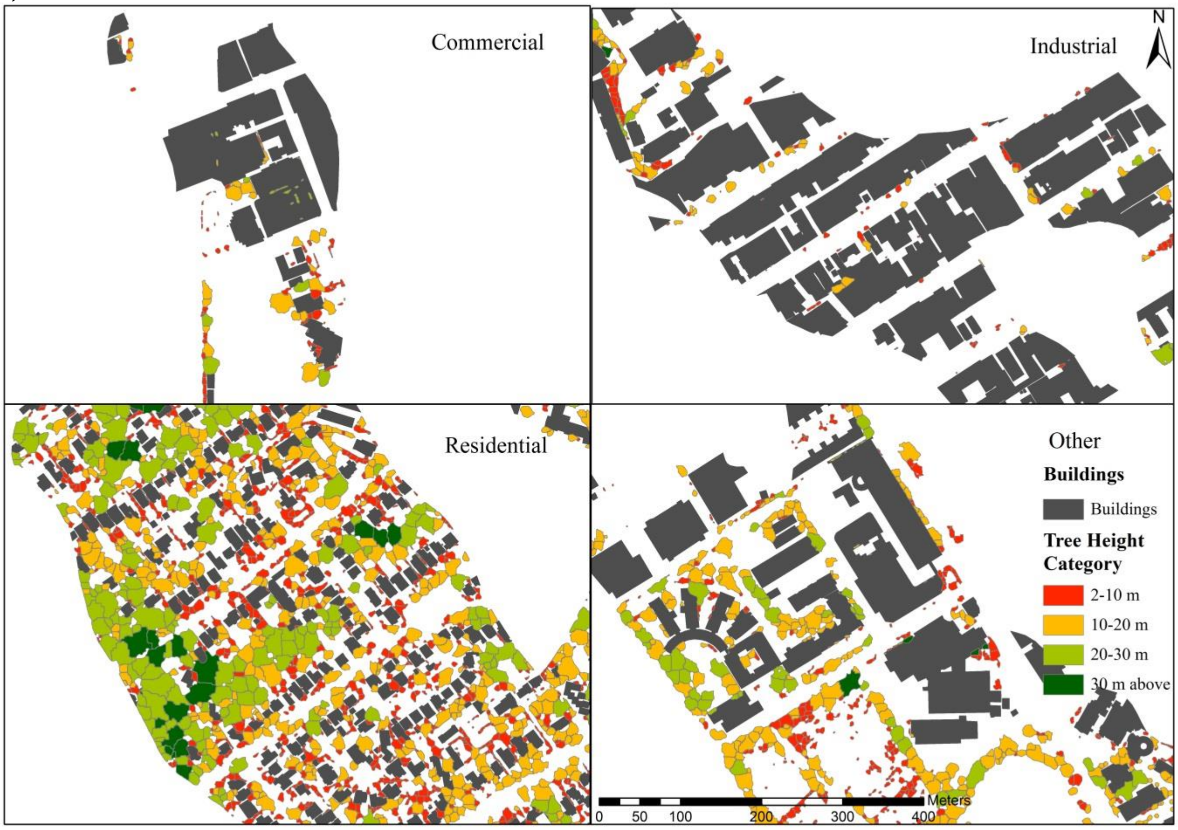
5.4 Results

5.4.1 Tree and building features

The average tree height of Pacific Highway (9.8 m) is higher than that of Parramatta Road (8.3 m). The tree coverage of Pacific Highway (32.0%) is about twice larger than that of Parramatta Road (10.8%). Most tree cover along Parramatta Road is located in residential areas. Larger trees are very limited over the entire length of the road. The Pacific Highway has a much greater tree density and a larger proportion of big trees (e.g. 30m above). The typical areas with trees in various height categories for the four types of land use are shown in Figure 5-4. The different tree features along Parramatta Road and Pacific Highway can be attributed to distinguishable patterns of their adjacent land use (see Table 5-1). Parramatta Road is known as the centre of the motor dealership business in Sydney and, for the part of the road surveyed, 62.3% of land use is devoted to commercial and industrial use. Only 27.0% is residential and residential areas are clustered at each end of the road surveyed while commercial and industrial areas occupy most of the middle part. On the contrary, the areas along Pacific Highway have 68.3% residential and 19.2% is commercial and industrial land use. The differences in land use are also reflected in the features of buildings along both roads. The average building height along Parramatta Road (7.1 m) is higher than that of Pacific Highway (5.9 m) while the average building roof area on Parramatta Road (358.3 m^2) is also higher than that on Pacific Highway (304.4 m^2).



(a)



(b)

Figure 5-4 Tree covers in nominated height categories for four types of land use on (a) Parramatta Road and (b) Pacific Highway.

The features of buildings and trees for different land use are shown in Table 5-2. In general, the average building height, the average building roof area, and tree height are lowest in residential areas while the average roof area is highest for industrial use. The tree coverage of residential areas is much larger than that of commercial and industrial lands. It should also be noted that the building height of commercial and industrial buildings is higher on the Pacific Highway than those on the Parramatta Road. A large number of buildings along Parramatta Road are used for motor retailing and services, they tend to have extensive land area but mostly are one-storey buildings. The commercial and industrial areas along Pacific Highway are minor compared to residential use, but a high proportion of them are business centres which have many high-rise buildings.

Table 5-2 Summary of tree and building features for each land use along both highway corridors.

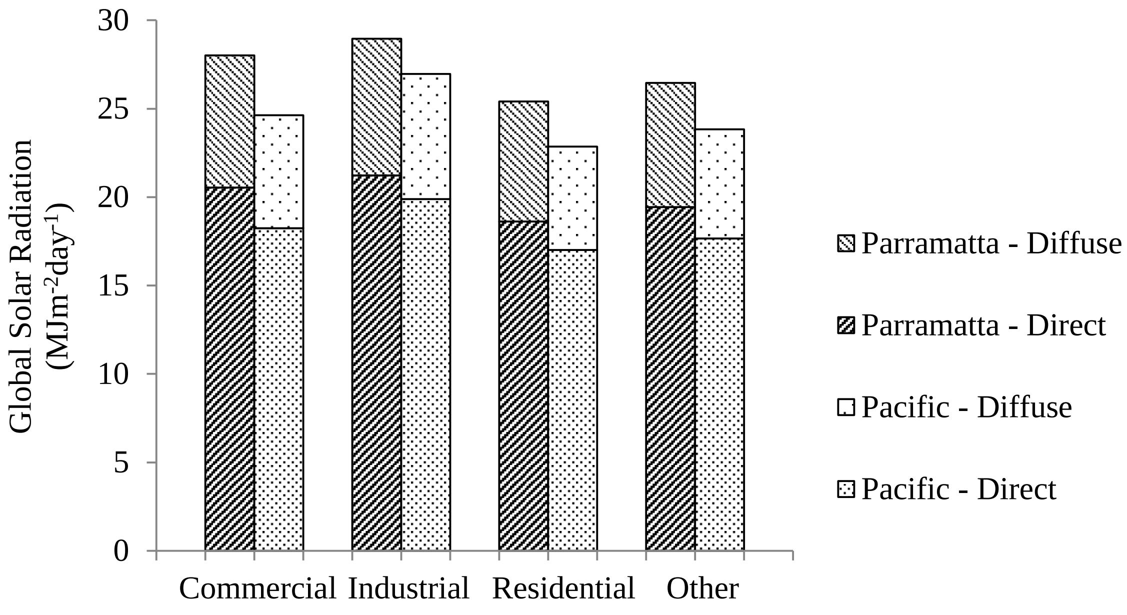
Land Use	Parramatta Road				Pacific Highway			
	Average Building Height (m)	Average Roof Area (m^2)	Average Tree Height (m)	Tree Coverage (%)	Average Building Height (m)	Average Roof Area (m^2)	Average Tree Height (m)	Tree Coverage (%)
Commercial	8.2	587.3	9.1	4.8	12.7	573.2	10.6	16.7
Industrial	8.4	1165.8	9.3	6.5	11.7	807.9	9.8	7.5
Residential	6.8	187.5	7.4	19.0	4.6	239.0	9.6	37.7
Other	6.9	359.9	9.5	19.8	12.2	604.4	11.2	27.6

5.4.2 Solar radiation profiles

Both direct and diffuse solar radiation on summer and winter solstices for Parramatta Road and Pacific Highway is summarised in Table 5-3.

Table 5-3 The direct and diffuse solar radiation on summer and winter solstices for both highway corridors.

	Solar Radiation ($MJm^{-2}day^{-1}$)	Parramatta Road	Pacific Highway
Summer Solstice	Direct Radiation	20.0	17.4
	Diffuse Radiation	7.3	6.0
Winter Solstice	Direct Radiation	2.8	2.2
	Diffuse Radiation	6.5	5.4



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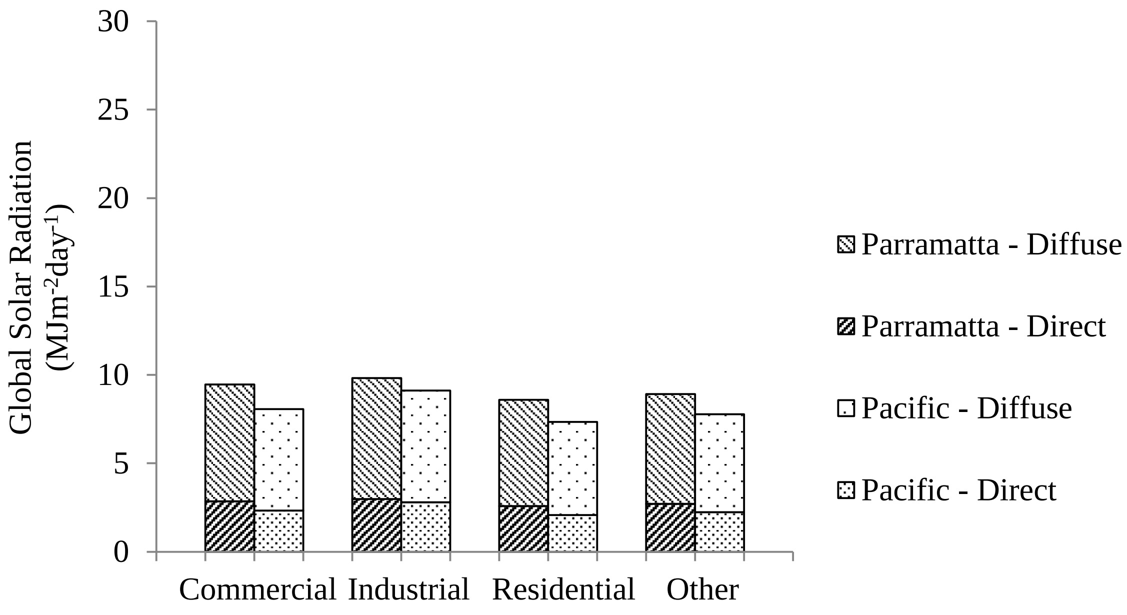


(b)

Figure 5-5 Global Solar Radiation (Direct and Diffuse) on (a) summer and (b) winter solstices for different land use along both corridors.

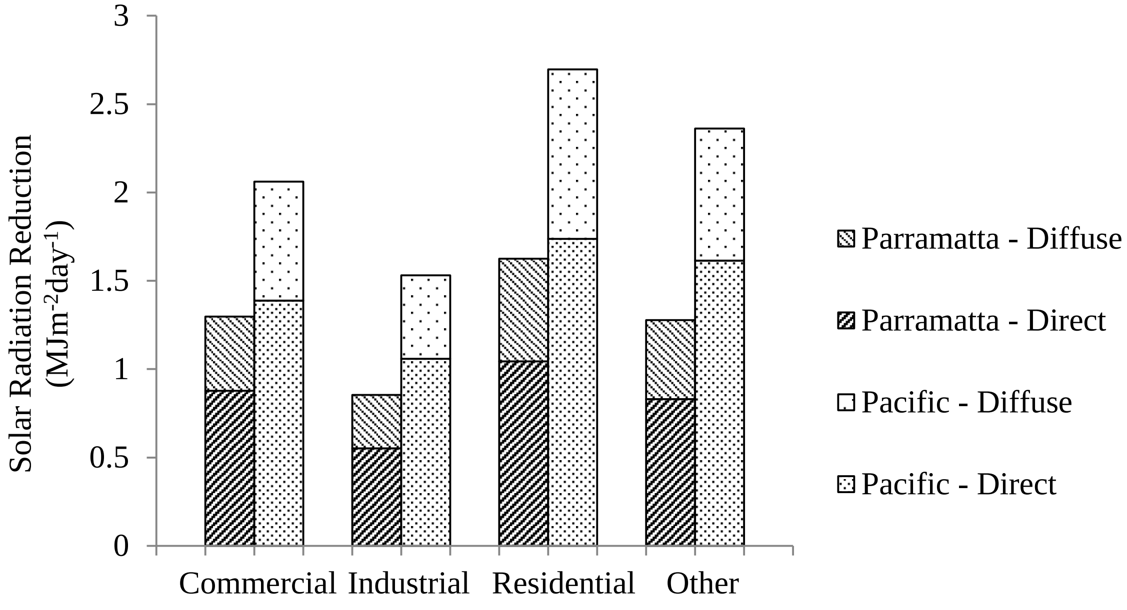
The direct radiation on Pacific Highway is lower than that of Parramatta Road, which can be attributed to a variety of factors including: local topography and climate, elevation, aspect and slope of the two roads, different tree coverage and building types. Table 5-4 presents the solar radiation profile for different land use on summer and winter solstice. For both corridors, the direct solar radiation for these four types of land use shows the same pattern as tree coverage of different land use. Direct radiation over residential areas has the lowest values while commercial and industrial lands have higher direct radiation. This consistency indicates the potential relationship between direct radiation and existence of trees, which can be further verified in Section 5.4.4. The direct radiation is larger than diffuse radiation in summer while this is reversed in winter. Compared to summer radiation, the solar radiation in winter, especially direct radiation, has rather small values (about 10% of the direct radiation in summer).

Solar radiation is modelled using DSMs with and without trees, and their differences are compared to estimate the radiation reduction caused by existing trees for both highway corridors (Table 5-4). The results show reduction of solar radiation for Pacific Highway is always over twice as that for Parramatta Road. This difference can be attributed to the higher tree coverage along Pacific Highway.

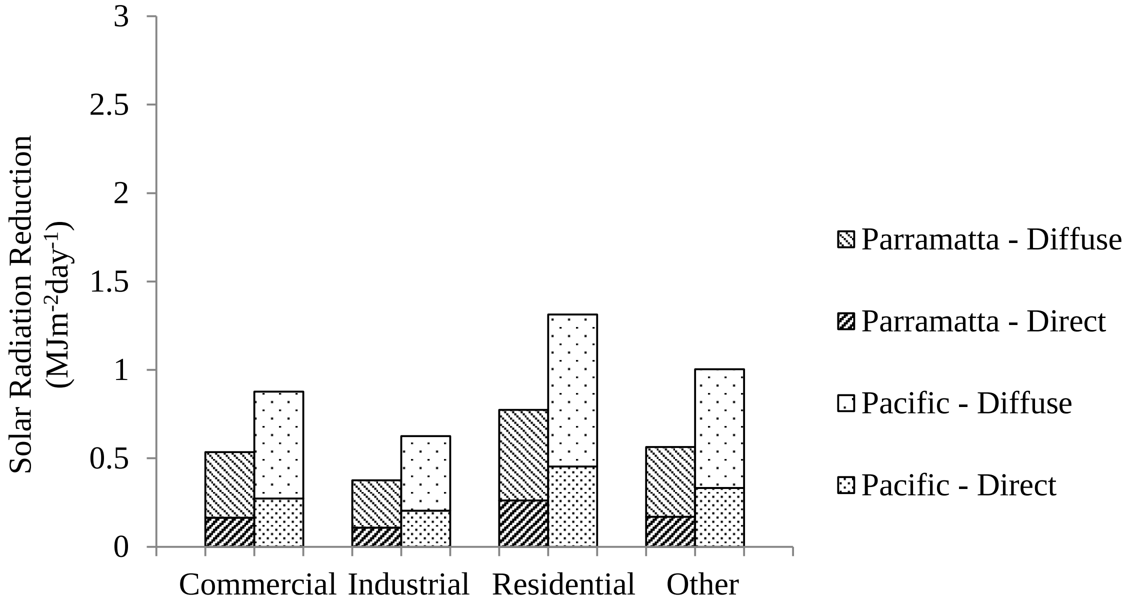
Table 5-4 The Reduction of solar radiation on summer and winter solstices for both highway corridors.

		Reduction of Solar Radiation ($MJm^{-2}day^{-1}$)	
		Parramatta Road	Pacific Highway
Summer Solstice	Direct Radiation	0.8	1.7
	Diffuse Radiation	0.4	0.9
Winter Solstice	Direct Radiation	0.2	0.4
	Diffuse Radiation	0.4	0.8

Figure 5-6 shows the reduction of direct and diffuse solar radiation on summer and winter solstices for four types of land use. The highest reduction occurs in residential areas and lowest in industrial lands. The solar radiation, especially the direct radiation, shows higher reduction in summer than in winter.



(a)



(b)

Figure 5-6 Reduction of Global Solar Radiation (Direct and Diffuse) on (a) summer and (b) winter solstices based on different land use along both corridors.

5.4.3 Shadow mapping

As described earlier, tree height is grouped into four categories. The tree coverage of each tree height category is provided in Figure 5-7. On both roads, the highest coverage is from trees 10-20 m in height. Larger trees are very limited along Parramatta Road: none were found over 30 m and only 0.6% of study areas are covered by trees of 20-30 m in height. The tree coverage in each category is much higher on Pacific Highway than on Parramatta Road. Figure 5-8 and Figure 5-9 plot the percentage of shaded areas on summer and winter solstice at five 2-hourly intervals. For Parramatta Road, the building roofs shaded by trees in 10-20 m show the most shadows, which is consistent with the highest tree coverage in this category. Although the coverage of trees in 20-30 m is much lower than that in 2-10 m, the amounts of shadows on building roofs for both categories are very close. Similarly, the trees in 10-20 m provide the most shadows for building roofs along Pacific Highway. The coverage of 20-30m trees is slightly less than that of 2-10 m height, however, more roof shadows are provided by the larger trees. Trees above 30 m have the lowest coverage (almost one-third of 2-10 m tree coverage), but the shaded areas in this category are almost the same as that in 2-10 m. In general, the shadow maps suggest the greater shading impacts of larger trees on building roofs.

Due to different solar azimuth and altitude in different seasons, roof shadows in winter are much more than in summer. But the solar radiation received in winter is much lower than the radiation in summer, so the larger percentage of shadow by trees does not result in higher reduction in solar radiation.

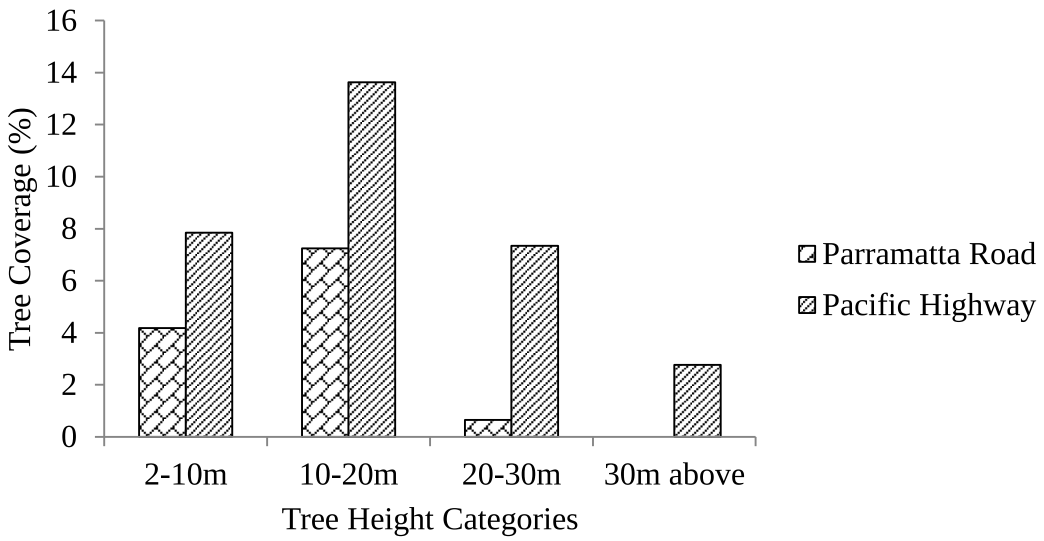
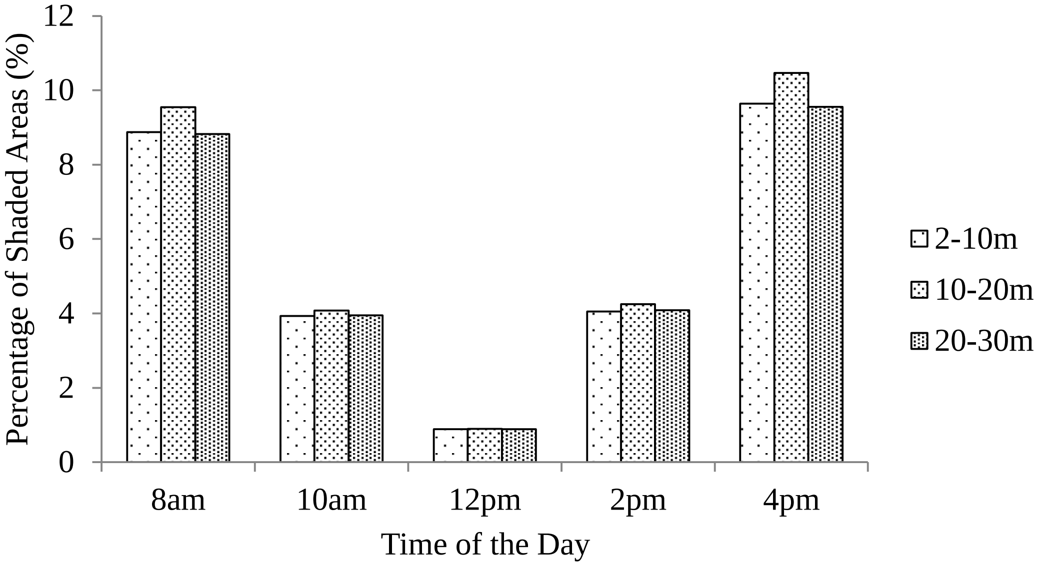
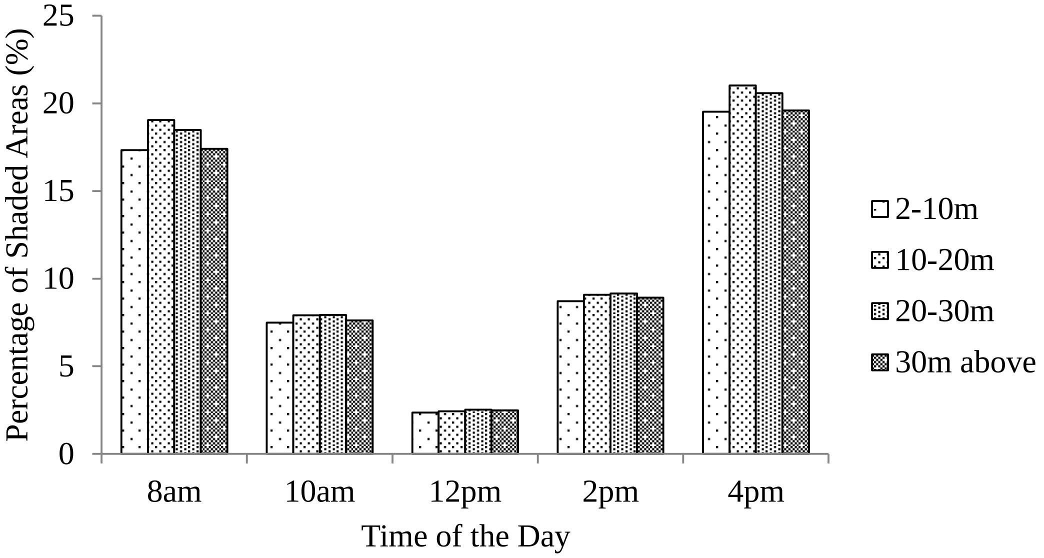


Figure 5-7 Tree coverage of four height categories for both corridors.

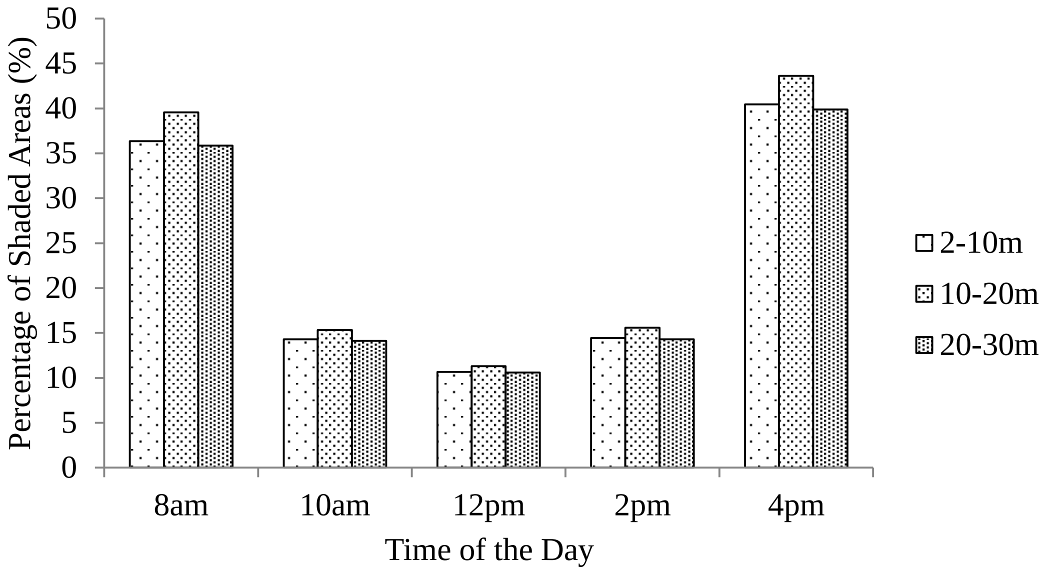


(a)

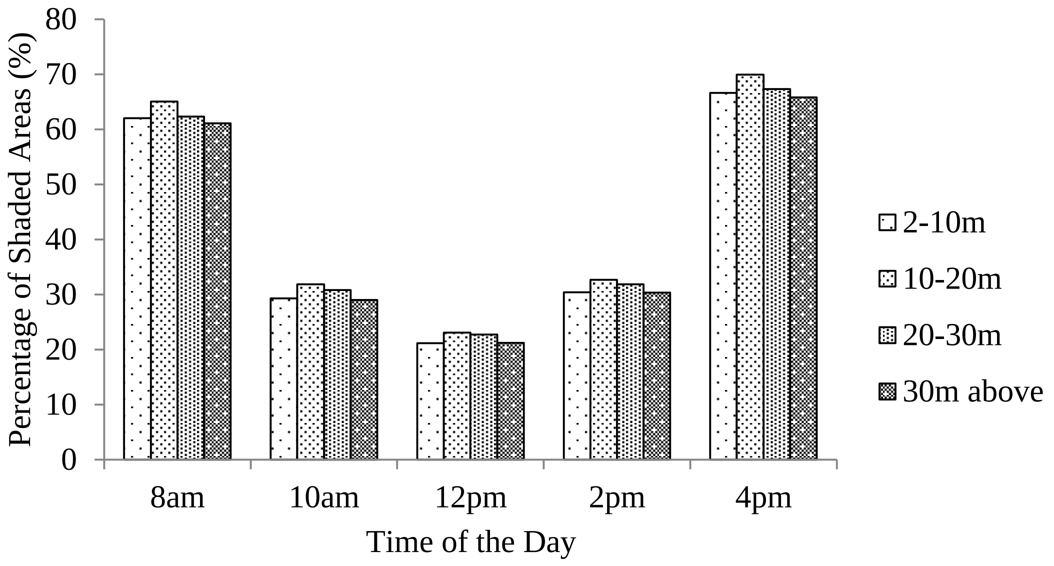


(b)

Figure 5-8 Percentage of shaded areas on summer solstice at 8am, 10am, 12pm, 2pm, 4pm on (a) Parramatta Road and (b) Pacific Highway.



(a)



(b)

Figure 5-9 Percentage of shaded areas on winter solstice at 8am, 10am, 12pm, 2pm, 4pm on (a) Parramatta Road and (b) Pacific Highway.

5.4.4 Correlation of radiation with tree features and building dimensions

Based on the correlation analysis, we can build the relationship between tree and building features with received solar radiation. The calculated correlation values are summarised in Table 5-5. All tree features and ratios are negatively related to solar radiation on building roofs while building dimensions are positively related to roof radiation. For Parramatta Road, the tree features have limited impacts on both direct and diffuse solar radiation, especially the sum of crown area and sum of tree volume, which are not significantly related to radiation. While most building dimensions have significant impacts on solar radiation on building roofs. Conversely, all building dimensions have negligible effects on radiation while tree features significantly affect the radiation received by building roofs. Parramatta Road has a higher number of larger buildings with smaller trees around them. A large area along this road has no vegetation cover, so the effects of trees are suppressed. Pacific Highway has more residential land use. The size of residential buildings is much smaller and trees have greater impacts in reducing solar radiation. The ratios show high impacts for both roads. The larger values the tree features have than building dimensions, the lower the solar radiation is received by building roofs.

Table 5-5 Correlation of determination (r^2) values between features of trees and buildings and solar radiation on building roofs.

		Parramatta Road				Pacific Highway			
		Summer		Winter		Summer		Winter	
		Direct	Diffuse	Direct	Diffuse	Direct	Diffuse	Direct	Diffuse
Tree Features	Average Tree Height	0.07$^{n/s}$	0.13	0.12	0.13	0.23	0.28	0.34	0.29
	Average Crown Area	0.12	0.15	0.18	0.15	0.31	0.35	0.36	0.36
	Sum of Crown Area	0.02$^{n/s}$	0.06$^{n/s}$	0.03$^{n/s}$	0.06$^{n/s}$	0.26	0.32	0.32	0.31
	Average Tree Volume	0.09	0.12	0.14	0.12	0.27	0.32	0.38	0.32
	Sum of Tree Volume	0.02$^{n/s}$	0.05$^{n/s}$	0.03$^{n/s}$	0.05$^{n/s}$	0.31	0.39	0.44	0.39
Building Dimensions	Average Building Height	0.12	0.17	0.06$^{n/s}$	0.17	0.00$^{n/s}$	0.00$^{n/s}$	0.01$^{n/s}$	0.00$^{n/s}$
	Average Roof Area	0.43	0.41	0.20	0.41	0.01$^{n/s}$	0.01$^{n/s}$	0.01$^{n/s}$	0.01$^{n/s}$
	Sum of Roof Area	0.32	0.31	0.18	0.31	0.01$^{n/s}$	0.01$^{n/s}$	0.01$^{n/s}$	0.01$^{n/s}$
	Average Building Volume	0.36	0.35	0.16	0.35	0.00$^{n/s}$	0.00$^{n/s}$	0.00$^{n/s}$	0.00$^{n/s}$
	Sum of Building Volume	0.23	0.24	0.13	0.24	0.00$^{n/s}$	0.00$^{n/s}$	0.00$^{n/s}$	0.00$^{n/s}$
Ratios	Height Ratio	0.17	0.26	0.22	0.26	0.17	0.21	0.28	0.22
	Average Area Ratio	0.35	0.29	0.41	0.29	0.28	0.29	0.29	0.30
	Sum of Area Ratio	0.36	0.39	0.45	0.39	0.36	0.45	0.48	0.45
	Average Volume Ratio	0.30	0.25	0.37	0.25	0.16	0.18	0.24	0.18
	Sum of Volume Ratio	0.33	0.32	0.43	0.32	0.24	0.31	0.42	0.31

n/s: Not Significant ($p > 0.05$)

5.5 Discussion

5.5.1 Tree parameters, radiation reduction and land use

This study has demonstrated that urban trees can be extracted using hyperspectral images and then individual tree crowns may be delineated from LiDAR derived surface models. This provides an efficient method for local government or other relevant organisations to update and maintain their database of urban trees. Specific tree parameters such as tree height and tree crown width calculated from LiDAR data can not only be used for urban tree management, but also be related to broader aspects of urban planning and management. In particular, the various tree characteristics and their shading impacts have been analysed and demonstrated in this paper.

The modelled solar radiation results for both urban corridors show that trees can effectively reduce the direct and diffuse radiation received by building roofs. Summer radiation is substantially greater than winter radiation and solar radiation reduced by trees during the summer is much larger than that during winter. So it is considered that owing to the more intense solar radiation during the summer, the benefits provided by urban trees in summer largely overshadow the radiation loss resulted from tree shadows in winter (Arboit et al., 2008).

The four types of land use investigated in this study are distinct in building and tree features. The differences in solar radiation results between different land use types are distinct. The main differences between Parramatta Road and Pacific Highway stem from the different combinations of land use. Residential areas that feature smaller buildings and denser tree coverage receive lower solar radiation on building roofs, while commercial and industrial lands with larger buildings and sparse tree covers receive higher radiation. The reduction of solar radiation caused by urban trees along the Pacific Highway is much larger than that along Parramatta Road, which can be attributed to the higher percentage of residential use on the former and higher percentage of commercial and industrial use on the latter.

5.5.2 Shadow mapping related to tree size

The shadow mapping demonstrates that trees of 10-20m height produce the largest coverage of tree shadows on building roofs because the highest percentage of trees is in this height category. Interestingly, even though the coverage of higher trees (e.g. 20-30 m or 30 m above) is much less than that of small trees (2-10 m), their shadows on building roofs are similar or greater than trees in the 2-10 m category. This indicates the greater shading impacts of large trees, which has also been supported by correlation analysis. For both roads, inverse relationships are found between solar radiation and tree features including average tree height, average crown area and average tree volume, which means larger trees contribute to the lower radiation. The correlation results for Parramatta Road also show larger building lead to higher radiation. The results show that in the areas with larger buildings as well as less and smaller trees, the impacts of trees on building roofs substantially decrease.

The more significant features that affect both direct and diffuse radiation for both roads are the ratios between trees and buildings features (e.g. height, area, volume) (Table 5-5), but the absolute height of trees is not the most important factor. To reduce the solar radiation, areas with more and larger buildings should be planted with higher, broader and more trees. However, in the study sites along Parramatta Road very few trees are located within roadside areas, particularly around large buildings for commercial or industrial use, and the lack of larger trees (30 m above) exacerbates the problem. While the Pacific Highway already has a much higher vegetation density, areas along Parramatta Road have higher needs and potentials for new tree planting programs.

5.5.3 Practical management considerations

Larger trees are not always the best option, especially in residential areas. Various management issues may occur. For example, the root systems of some vigorous or large growing species can cause damage to underground services, pavements, kerbs and properties; the conflict between crowns of large trees with overhead services such as powerlines; the physical damages caused by trees to buildings or infrastructure; and reduced visibility (Wang and Merrick, 2013, England, 2014). As this study has shown, the ratios between tree and building features significantly affect incident solar radiation. Since the building size, both height and roof area, is relatively small in residential areas, the tree height and crown size do not need to be extremely large to have significant impacts on solar radiation received by building roofs. In addition, some available solar access of rooftops is becoming preferable due to the increasing use of solar photovoltaic systems (Dereli et al., 2013). The solar irradiance can be converted to clean energy, being important for sustainable development. By balancing the environmental costs and benefits of urban forests, trees of moderate size could be more appropriate for residential lands.

Another major management consideration that may affect the emphasis of strategies is conservation. For example, the northern part of the Pacific Highway is located within the Ku-ring-gai Council area and adjacent to Ku-ring-gai National Park, which is one of the major green areas within the Sydney Metropolitan Area (England, 2014). The vegetation along the road connects to wider green reserves and is an important constituent of various native plant communities including some local endangered vegetation communities. Thus, native species are significant within this area.

Conversely, Parramatta Road is located in the central part of the metropolitan area, which has been densely settled for up to a century and where green areas are now very limited (England, 2014). So here the priority is to improve green space quality rather than conservation of nature species. The highly developed and modified areas along Parramatta Road provide harsh living environment for vegetation, particularly native species. Moreover, large buildings especially with large roof areas along this road require an increase of large tree cover. Accordingly, exotic deciduous species with broad leaves such as London Plane trees could be more suitable for this area. These species are more tolerant of pavement roadside conditions but also have additional benefits of providing dense shade in summer and sun access in winter (Wang and Merrick, 2013). As the majority of commercial and industrial areas along Parramatta Road have no tree cover at all, there is great potential for new plantings. Since some big deciduous species have more spreading crowns and provide denser shading over larger areas, the number of individual trees planted can be reduced, which will consequently decrease the future maintenance effort and costs. New tree planting programs should consider both tree growth rates and strategic urban planning for the area. Some large tree species may take several decades to get mature and provide maximum benefits. So if future development proposes zoning or building changes, this needs to be considered in planting strategies.

5.6 Conclusion

Remote sensing technologies show great potential for measuring tree features and estimating environmental functions of urban forests as complementary to the conventional field surveys. Integrating LiDAR and Hyperspectral data provides a cost-effective way to delineate individual tree crowns by using local maxima algorithm and watershed segmentation algorithms. The estimated tree features can then be related to broader environmental functions of urban forests such as their shading effects. The analyses here have demonstrated that tree height, crown area, and tree volume are negatively related to roof received solar radiation, indicating the greater effects of larger trees in reducing radiation. However, tree impacts are substantially decreased within the areas where few trees are present. Ratios between tree and building features are shown most significant impacts on roof radiation. The higher the ratios, the lower the radiation. Tree planting and management programs should be adapted in areas of different land use. Larger trees are more beneficial and preferable in commercial or industrial areas with larger buildings. In residential areas with smaller buildings and intervening areas, the choice of appropriate trees should consider tree benefits in conjunction with various management issues or risks such as litter fall or interference with underground and overhead services.

Future studies could be undertaken to increase the accuracy of individual tree segmentation by including more detailed ground validation, especially in places with dense overlapping canopy cover and diverse tree species. Specific differences relating to canopy characteristics could also be incorporated into shading analyses.

This chapter has investigated various features of trees contributing to shading impacts of roadside forest using remote sensing technologies. The practical management implications of these and earlier radiation findings are discussed in the next chapter that integrates these specific results into a broader urban landscape context or ecosystem network, outlining some the identified and potential management challenges.

Chapter 6 Improving Urban forest Management – A Remote Sensing Approach

6.1 Introduction

Urban forest, as part of green infrastructure, is a primary and distinctive component of complex urban ecosystems (Li et al., 2005). The broad definition of urban forest includes the collection of trees, shrubs, and grass in cities (Roy et al., 2012). In Australia, the New South Wales (NSW) Local Government Associations (2003) defines urban forest as the totality of trees and large woody shrubs on all public and private land in and around urban areas. Compared with other vegetation types, trees generate greater benefits to city dwellers, being the most significant form of urban forest (Hitchmough, 1994). With rapid urbanisation, trees play significant roles in mitigating the increasing environmental problems and challenges (Yang et al., 2009). The benefits delivered by urban trees are reflected at the local, community and global levels (Barrell, 2012). However, it remains challenging to quantify all the environmental, social, and economic values of trees, particularly within complex urban environments, where trees interact with other urban features. Generally, trees in urban areas are an fundamental component of landscape planning (Deb et al., 2013). The roles and functions of trees normally exceed the domain of urban forest management and closely link to the broad aspects of the whole environmental planning regime in Australia (Figure 6-1). However, due to their size and longevity, urban forests can also cause a range of managerial problems and risks (Table 6-1). An effective urban forest management should preserve the values of trees as well as minimise their costs.

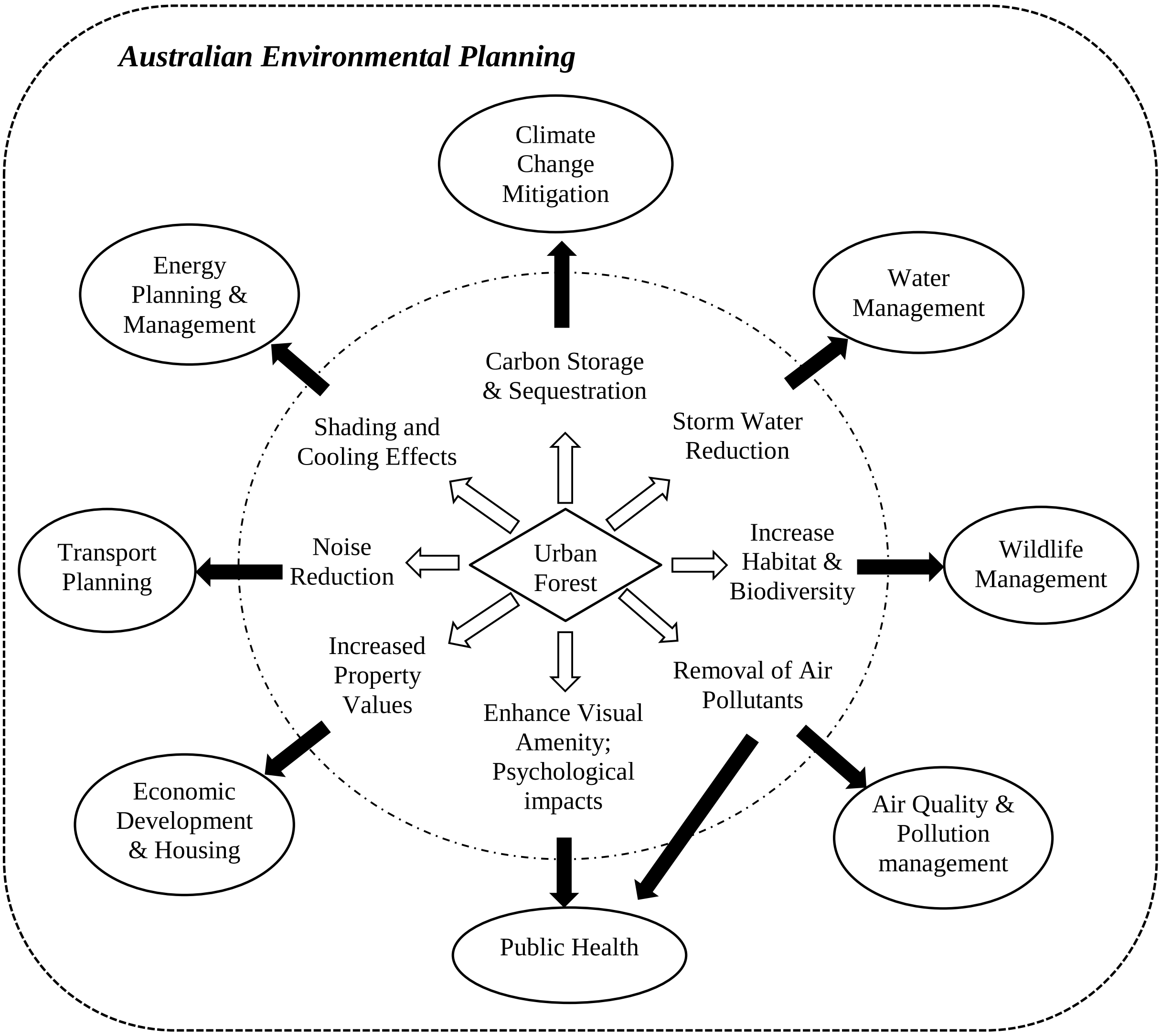


Figure 6-1 The roles and functions of urban forest (inside the oval) within the regime of Australia's Environmental Planning.

Currently, the rapid and ongoing development of remote sensing technologies presents great potentials for the improvement of urban forest management. Remote sensing technologies include two major types, which are passive and active remote sensing defined in Table 6-2. Both types of remote sensing systems have been widely used for tree assessment in natural forest and over large urban areas, but there has been less study of the interaction between trees and urban structures at a small local scale. The details of applications of various remote sensing data for tree management will be discussed in Section 6.2.

Table 6-1 Summary of managerial problems or limitations related to different aspects of urban forest.

Aspects of Urban Forest	Managerial Problems or Limitations
Aging trees or trees in poor condition	High maintenance costs, public safety
New plantings	Higher maintenance costs; Higher mortality rate; Prone to the diseases and pests
Vigorous or large root systems	Potential damage to underground service, pavements, kerbs and properties; Pedestrian walkway hazards, road surface disruption
Large and tall tree canopies	Reduced visibility; Conflicts with overhead powerlines or traffic
Forests adjacent to properties	Bushfire potential and flammability risk; Physical damages to buildings or public infrastructure
Litter fall (shedding leaves, flowers, fruit)	Pedestrian slip hazards, public safety
Tree species	Allergies or irritations; Weeds or invasive species

Table 6-2 Summary of two types of remote sensing technologies.

Types of Remote Sensing	Definitions	Examples
Passive Remote Sensing	Detecting natural radiation emitted or reflected by the imaged objects or area	• Aerial photography • Satellite photography • Thermal imagery • Multispectral imagery • Hyperspectral imagery • Passive microwave sensing
Active Remote Sensing	Emitting energy in order to scan objects and areas then sensors detecting and measuring radiation reflected or backscattered from the target	• Radar imagery • LiDAR point cloud

The prime objectives of this chapter are:

(a) to analyse the key components of urban forest management and to develop a more integrated model using GIS and remote sensing technologies;

(b) using two transport corridor segments as typical case studies, to assess urban forest and their shading impacts based on LiDAR and hyperspectral data;

(c) to improve ecological management of roadside and adjacent forests as a basic structural web for all residual urban forests

6.2 Australian Urban Forest Management and Remote Sensing

6.2.1 Urban forest management system

In Australia, environmental planning and governance fall under three jurisdictions: the Commonwealth; State or Territories; and local government (England, 2014). For most urban areas, local government is largely responsible for day-to-day regulation or management (Humphreys, 1989, Wang and Merrick, 2013). The framework of urban forest management by local government is summarised in Figure 6-2. Tree management policies and strategies are the key components that control the tree management and integrates it within the overall urban planning and management regime (Hitchmough, 1994). The importance of tree inventories is that they provide essential information for the development of tree policies. Detailed tree data such as tree locations, distributions, individual tree size and condition, and required management actions are necessary to determine general status of urban forest and identify managerial problems of small local areas or specific trees (Hitchmough, 1994).

Traditionally, accurate tree inventories are generated by trained and experienced field officers or arboricultural consultants and require extensive time and intensive field work as well as significant financial support. Moreover, these high resource demands reduce frequency updates for the tree database. For example, not all the councils within Sydney Metropolitan Area (SMA) have comprehensive public tree inventories; details and quality of existing tree database of various councils vary to different degrees. Community participation is also a necessary part of the overall tree management. The community contributes to the development of tree policies by providing recommendations based on consultations in the decision-making process about urban forest management; however, the level of this consultation and participations varies widely between LGAs. Recently, the integration of geographic information systems (GIS) and remotely sensed data are becoming an important component part of the database that can be tightly connected to other parts of the tree management system.

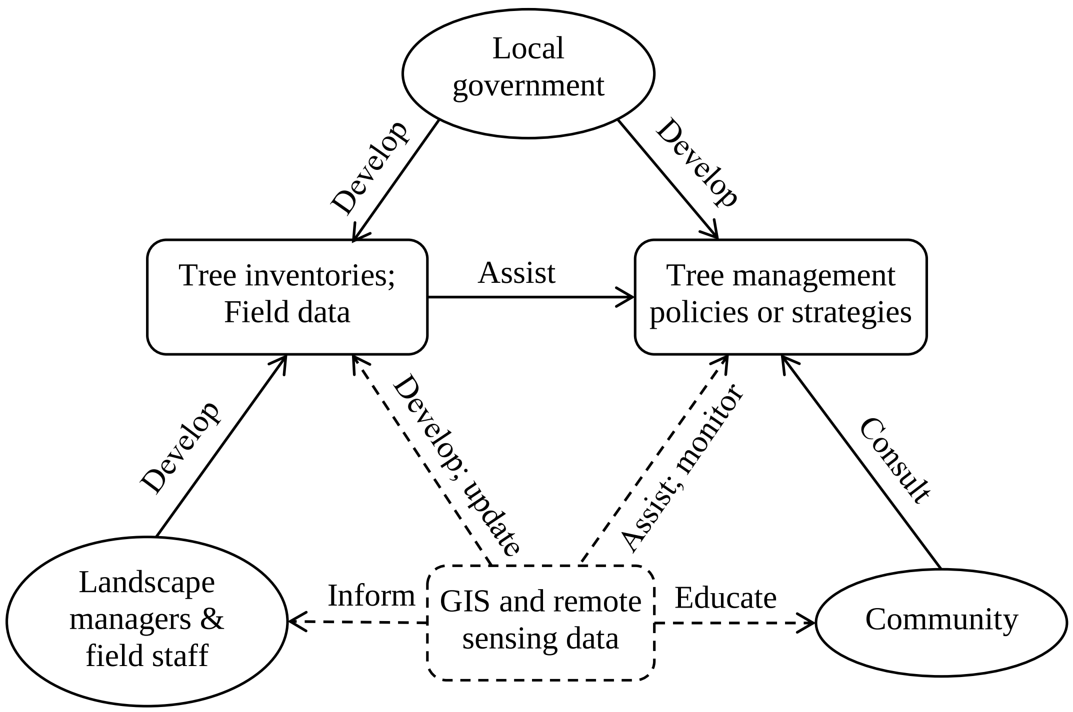


Figure 6-2 Components of urban tree management by local government.

6.2.2 Remote sensing data in urban tree management

GIS has already become one of the most important tools for environmental planning and management (Slocombe, 1993, Goodchild et al., 1996), which can provide a wide range of digital data outputs such as demographic maps, road and railway systems, property boundaries, riparian zones and National Parks. The Australian Bureau of Statistics (ABS) provides various free GIS data. In Sydney, many councils have their own GIS database that stores different kinds of information within their local government areas (LGAs). Remotely sensed data can be interpreted with GIS data and embedded into the database to build a more comprehensive information system.

For local government and other management organisations, aerial photographs and satellite imagery are the most commonly used remote sensing data. They are able to assist in locating trees, identifying tree crowns or monitoring land cover and forest changes. These data are relatively inexpensive and easy to obtain (Secord and Zakhor, 2007). However, they are limited in providing detailed information relating to tree characteristics and require an experienced operator/analyst. There are two other remote sensing technologies which are under-used by tree managers but are of great importance. LiDAR data can measure the elevation of the terrain and all objects on the ground such as trees and buildings. Multispectral or hyperspectral data can be used for image classification to extract tree areas and identify tree species. NSW Land & Property Information (LPI) provides aerial photographs, satellite images, multispectral images, and LiDAR data to local government at relatively low cost. As shown in Figure 6-2, remote sensing data improve the tree management by (a) helping build and update tree inventories; (b) informing landscape managers and the community with the updated information; and (c) assisting and monitoring the development of urban forest policies.

The combination of remote sensing technologies (LiDAR, Hyperspectral Imagery) used in these studies has the advantages and potentials for providing 3-D information from LiDAR and richer spectral characteristics from hyperspectral data to distinguish tree species. It should be also noted that there is a need for further investigation. The current limitations of these technologies include: return frequency; reduced data quality (related to occlusion, flight height, swath); and infrequent data collection. Costs of both collection and skilled personnel to process data have to be considered. Data capture can be more regular using satellites, however the image resolution will be coarser than the airborne data. Another possible way of reducing the costs of collecting high resolution data more frequently, at a local scale, is to use drones.

As mentioned above, the frequency of updating tree inventories can be influenced by limited management resources available. Some councils reassess their tree assets every five years, which means at the end of the five year period, the database is becoming outdated. The development of remote sensing presents an efficient and cost-effective way to update significant information in the database more frequently. LiDAR derived digital height models are proven to be efficient and accurate to measure tree height, crown width and to map interactions between trees and adjacent buildings or powerlines. The changes in tree size or growth rate can then be calculated using multi-temporal data. LiDAR can also be combined with multispectral or preferably hyperspectral data for tree species identification (Holmgren et al., 2008). Hyperspectral images have other advantages in permitting classification of tree species, showing tree health by detecting changes in foliage condition, and indicating fire risk (Voss and Sugumaran, 2008, Wentz et al., 2012).

Publically accessible high resolution hyperspectral data are not as readily available. The U.S Geological Survey provides hyperspectral images (EO-1 Hyperion) with a 30m resolution, but these data only cover a small swath of 7.5 km. Some private surveying and mapping companies can collect commercial hyperspectral imagery with a finer resolution (e.g. 0.4m), which are relatively expensive. While remote sensing data offer local government and environmental managers with more abundant and timely information for decision making, the increasing use of these data can place greater demands on managers. For example, they may now be expected to have ecological knowledge as well as basic or advanced skills for analysing GIS or remotely sensed data.

In addition, the community can be better informed using remote sensing images, as these data can visually show the population and distribution of urban forests or the temporal differences or abnormal changes in urban tree populations. Moreover, effective urban tree management should not only manage trees on an individual basis, but also recognise urban forest as a collective and integrated body of vegetation (City of Sydney, 2013). But remote sensing has the capacity for measuring not only overall canopy attributes but also specific tree characteristics and issues. Assessing existing canopy cover and formulating canopy cover targets are one key element of tree policies and strategies (Szantoi et al., 2012). The calculation of overall canopy cover must include both public and private lands, but trees on private properties are more difficult to access or assess by local government. This is where remotely sensed data can be very useful for assessing the situation. City of Sydney (2013) uses both aerial photography and LiDAR to measure canopy cover reflected in different land uses within its LGA. To develop a more realistic urban forest cover policy and goals, a range of socioeconomic factors such as different land use, local community ethnicity ethnic mix, age profile, income and education demographics, or other planning influences should also be considered (Szantoi et al., 2012). Thus the combination of remote sensing data with related GIS information is becoming increasingly critical and significant.

6.3 Case Study: Sub-systems and Challenges

Within the range of floristic communities that are included in urban forests, one the most important categories or subsystems is roadside forest. With the background of tree management and remote sensing technologies previously described, roadside trees and adjacent forest in Sydney are used as a case study to investigate the management of forest sub-systems, and some issues raised can be extrapolated to the Metropolitan area in general and are relevant elsewhere.

6.3.1 Management of roadside trees and adjacent forest

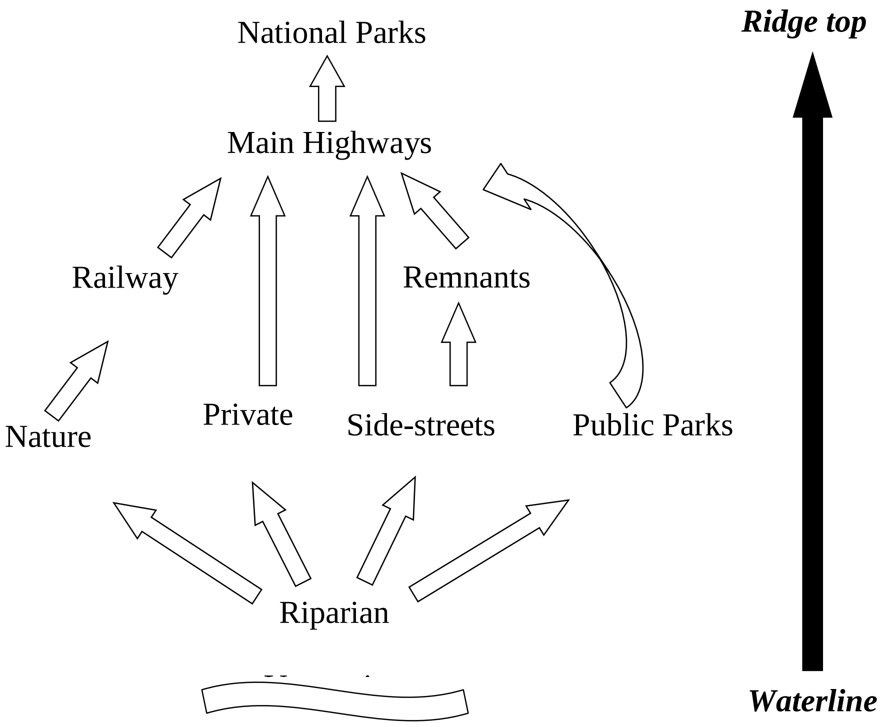


Figure 6-3 Summary of the common categories of urban vegetation that comprise the urban forest complex in Sydney, Australia: this general flow chart shows the connections of urban forest sub-systems from waterline to ridge tops. All vegetation systems can possibly be connected by main transport corridors.

Australia's urban forest includes various forms of plants in parks and gardens, along transport and riparian corridors, as well as on roofs (i.e. green roofs) and walls (Figure 6-3). Linear shape of urban forest has become increasingly common but important in urban environments with the rapid development of public services and infrastructure. In the State of NSW, there are about 180,000 km of public roads and the linear reserves cover around 6% of the State's area (NSW Roadside Environment Committee, 2014a). Roadside forest and reserves are one significant sub-system of urban forest complex. Just as the roads form an essential connecting web, so too the marginal forests can form and essential connecting ecological web. As shown in Figure 6-3, all public and private vegetation systems can be connected by main transport corridors. They are situated on ‘permanent’ reserve areas associated with ‘permanent’ infrastructure and, although there are challenges, they can be managed for multiple-use. These roadside reserves form part of a core system that benefits conservation and alleviates some of the problems created by intensive development, climate change, and reduced permeability in urban areas. In Australia, historically, highways are often built on higher ground and along ridge lines (see Figure 6-3), so roadside vegetation tends to reflect upland woodlands. In NSW, the roadside reserves greatly contribute to native biodiversity by accommodating unique vegetation communities that are not included in other public and private parks or reserves (NSW Roadside Environment Committee, 2014a).

The management of Australia’s roadside forest involves a two-tier system of central road authorities in States and Territories, and local government (Hitchmough, 1994). In NSW, The Roads and Maritime Services are responsible for the management of reserves along main roads while local councils manage local or minor roadside reserves (NSW Roadside Environment Committee, 2014a). Local government has responsibility for most roadside vegetation. The NSW Roadside Environment Committee (REC) was established as an umbrella body of state agencies and environment groups to improve linear reserve environmental management in NSW (NSW Roadside Environment Committee, 2014a). To take effective roadside environmental management, a number of NSW local councils have developed Roadside Vegetation Management Plans (RVMPs). However, only three councils have an RVMP within the SMA (NSW Roadside Environment Committee, 2014b). This is because RVMPs mainly cover remnant native vegetation and not planted street trees. The latter are found on roadsides of much of Sydney’s inner city area. It is only in the outer suburbs where there are significant roadside verges that have remnant native vegetation. Thus for much of Sydney does not have RVMPs, but may have Urban Forest or Street Tree Plans instead. Some peri-urban LGAs may opt not to have a RVMP but use a Biodiversity Plan or similar.

6.3.2 Assessment of roadside forest and allergenic species mapping: Linking to broader management issues

To understand the benefits and management of roadside forest, two major highway corridors are selected which are Parramatta Road and Pacific Highway. These two roads are distinct in adjacent land use (Figure 6-4) as well as vegetation cover. The areas along Parramatta Road are more commercialised and industrialised while Pacific Highway has more residential areas. The tree cover of Pacific Highway is over three times that of Parramatta Road. Two remote sensing technologies, LiDAR and hyperspectral imagery, were integrated to assess the roadside forest and their shading impacts (Wang et al., 2014b).

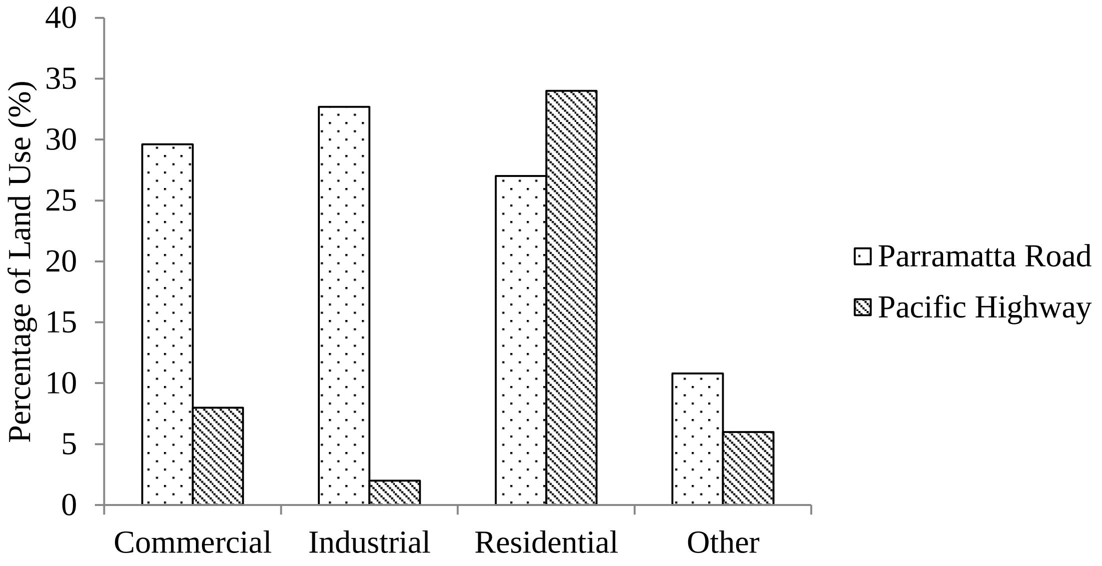


Figure 6-4 The land use percentage of adjacent areas along Parramatta Road and Pacific Highway in Sydney, Australia.

One of the most common reasons for tree planting is to provide valuable shading and to ameliorate microclimate (Tooke et al., 2011, Block et al., 2012, Hansen et al., 2012). Apart from accurately measuring tree characteristics, LiDAR derived digital surface models (DSMs) were well suited to model shadows and solar radiation. Hyperspectral data extracted vegetated areas and LiDAR produced digital height models for these areas. Using local maxima and watershed algorithms, individual tree crowns were delineated. Based on individual tree segments, tree attributes including tree height and crown width were calculated. In this study, DSMs were used to model global solar radiation on building rooftops on both summer and winter solstices. To estimate the impacts of trees, two types of DSMs were modelled which were DSMs with all the urban objects and DSMs without trees (Figure 6-5). Hyperspectral images were also analysed for tree species mapping. Individuals of one of the commonly planted exotic deciduous trees, London Plane Tree (*Platanus × acerifolia*), were located within the study areas by spectral analysis.

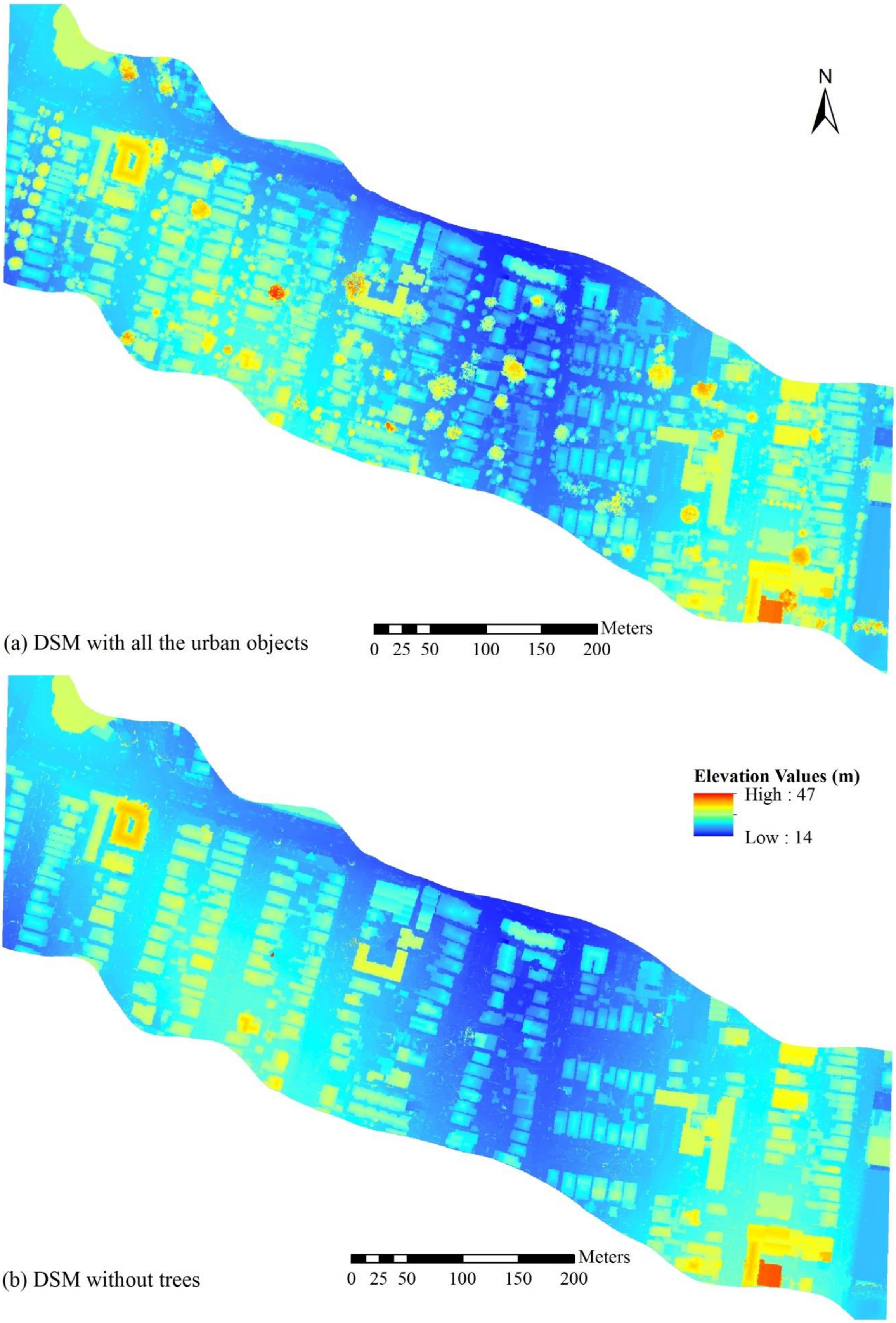


Figure 6-5 The comparison of subsets of digital surface models (a) when trees are present, and (b) when trees are removed.

Among community concerns relating to urban trees, medical issues, such as allergies and irritations caused by some species have become increasingly important in recent years. For example, London Plane trees are often cited as a prime allergenic tree species because it produces of pollen with fine pointed hairs (City of Sydney, 2011). However, Plane trees are also one of the most cost-effective shade species, especially tolerant of harsh urban environments (North Sydney Council, 2006). The particular characteristics and benefits of Plane trees include: high tolerance to most difficult conditions such as formative pruning, heavy pollution, high wind tunnel effects and poor soils; limited maintenance requirement; low purchase rate; and very large tree size with broad leaves (North Sydney Council, 2006, City of Sydney, 2011). The preference for choosing Planes as street trees within inner city areas is thus the reflection of balancing benefits and costs of urban forest. In addition, pollen production of Plane trees is limited to a few weeks in Spring, and according to recent industry reports, the Plane tree pollen causes no more allergy or irritation than many other common urban vegetation species (North Sydney Council, 2006, City of Sydney, 2011). Furthermore, as a deciduous species, Plane trees drop leaves in winter, providing better lighting and sun access when radiation is low.

As the fumes exhausted from road traffic are one of the most important sources of air pollution (Powe and Willis, 2004), these deciduous trees on roadsides significantly contribute to pollution absorption because leaf drop means much pollution is also deposited. New foliage provides new absorption surfaces. In contrast, the pollution absorption capacity of evergreen trees decreases with the increments of pollutants on foliage (North Sydney Council, 2006). Plane trees are still favourable for highly developed areas and major routes such as the Pacific Highway, but require essential management relating to their pollen and dropping fruits.

In this study, the tree mapping along both roads shows that 88.4% and 95.9% of London Plane trees of Parramatta Road and Pacific Highway respectively are used as street or roadside trees. For Pacific Highway, 66.9% of London Plane trees are located within North Sydney LGA that is the beginning of the Pacific Highway and has its unique feature of urban tree plantings. North Sydney is a relatively small and highly urbanised LGA in proximity to Sydney Central Business District (Smith and Smith, 2010). Some species are particularly dominant in this local area. In North Sydney, there are only 4 species have been planted along Pacific Highway – London Plane (*Platanus x acerifolius*), Cocos Palm (*Syagrus romanzoffiana*), Broad Leafed Paperbark (*Melaleuca quinquenervia*) and Oriental Plane (*Platanus Orientalis*). London Plane Trees constitute 86.4% of the trees planted along Pacific Highway and 35.0% of all street trees within North Sydney.

6.3.3 The dilemma: Larger or smaller trees

The remote sensing analyses of roadside forest indicated that larger trees produce more extensive shading on buildings and contribute more to energy saving. Studies also show the greater economic values of larger trees by providing shade (Gómez-Muñoz et al., 2010). Big and long-lived trees are also demonstrated to deliver greater carbon sequestration and air-quality benefits (Sunderland et al., 2012). Large trees are more preferable for large-scale planting, having higher potentials for rapid development of tree canopies within sparsely vegetated areas (Yang and McBride, 2003). Their broad canopies and trunk hollows build better habitat for other urban tree species (Nagendra and Gopal, 2010). Culturally, long-lived large or heritage trees can create the sense or distinctive character to a local area. These particular values of large tree species are also acknowledged by local government in Australia (Auburn City Council, 2012, City of Sydney, 2013). However, there are a number of management issues associated with large trees such as physical damage of their vigorous root systems to underground services and pavements, relatively high maintenance cost, conflicts between large tree crowns with overhead services or traffic, and the obstruction of light (Auburn City Council, 2012, City of Sydney, 2013, Wang et al., 2014a). Moreover, harsh urban environments such as roadside verges are difficult for large trees due to poor soil conditions and limited growing space (Jim, 1997).

Cultural or social preferences are also a significant factor affecting tree species choice. A survey done in England indicates that smaller trees are more preferred by residents (Flannigan, 2005). In Melbourne, Australia, the attitude study shows medium sized trees as the most preferred ones compared to smaller or larger trees (Williams, 2002). Nagendra and Gopal (2010) suggest the size of street trees should be in scale with the road width. Wide roads tend to have wider margins separating them from residential areas with fewer obstacles such as overhead powerlines and containing more growing space, where larger trees can provide more shading or cooling and pollution mitigation benefits. Narrow roads or streets are more likely located adjacent to residential or other buildings, so smaller or medium sized trees are usually more appropriate (Nagendra and Gopal, 2010). This is consistent with the residents' tree preferences. The results of correlation analysis in this case study can also contribute to the justification of these tree species choices. As the ratios between tree and building attributes significantly affect shading impacts, in commercial and industrial areas with larger buildings, bigger trees are more preferable and efficient to alleviate environmental problems. But in residential areas with smaller buildings, smaller or medium trees could be a better option by balancing the benefits and potential issues of urban forests. Additionally, planting large species around areas with extensive paved surface areas can have significant impacts on minimising urban heat island effects.

6.3.4 Protection of existing mature trees and new planting potentials

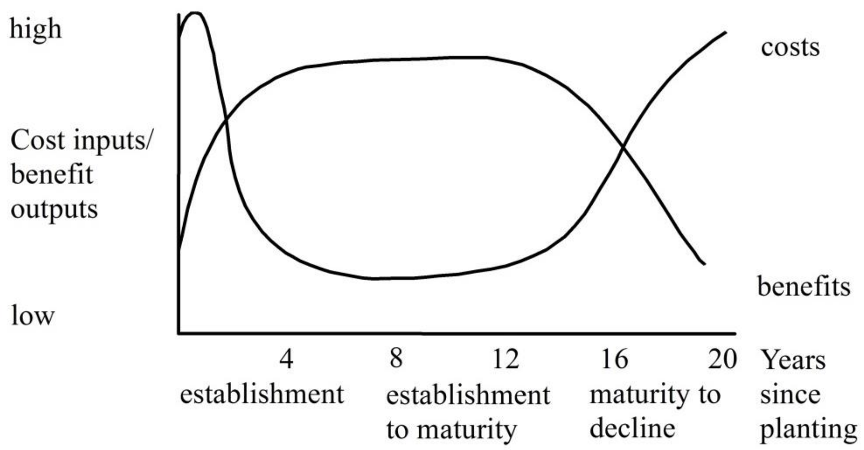


Figure 6-6 Relationship between management costs and functional and aesthetic benefits, in relation to the life cycle of a hypothetical tree. *Source: Hitchmough (1994)*
Note: this is based on a tree species with a life span of 20 years; different species may have different longevity but the overall relationship would apply.

While local governments have concentrated their urban forest management on canopy coverage and various managerial problems, the significance of existing mature trees have often not been adequately recognised or prioritised into the whole planning/management system. The relationships between maintenance costs and environmental and socio-economic benefits have been known for some years (Hitchmough, 1994). Figure 6-6 shows the initial stage of planting and establishment requires high management and maintenance inputs; then the maintenance costs stay at a relatively low level during the mature stage; and when trees begin to decline, the cost inputs to maintain them in a safe and sound condition increase rapidly. Thus, the very early and later phases are the most expensive stages across trees' life cycle (City of Sydney, 2013). The crossover point around the over-maturity and decline phase indicates a reasonable time for tree removal and replacement (Hitchmough, 1994).

As higher urban density usually relates to lower gasoline use per capita (Newman and Kenworthy, 1989), urban consolidation has been a major planning policy in Australia's largest cities since the 1970s (Gray et al., 2010). The primary objective of consolidation policies in Australia is to develop sustainable urbanisation by managing low density urban growth or sprawl (Bunker et al., 2002). However, the debate is growing over whether these policies have achieved their aims (Bunker et al., 2002). This increase in residential housing densities has influenced urban form and structure as existing suburbs have been redeveloped, resulting in a series of environmental problems (Troy, 1996, Low et al., 2005). Moreover, the infill and infrastructure development can considerably affect tree growth, canopy cover, and retention of remnant native vegetation; it has particularly contributed to significant loss of mature urban vegetation (Stovin et al., 2008, Brunner and Cozens, 2013).

Conservation of mature trees, especially those that have just reached maturity phase, should be prioritised due to their high benefits and low maintenance costs (see Figure 6-6). When high management costs associated with tree decline can be avoided by tree removal, the high resource inputs for initial establishment are normally inevitable. If trees are removed at an early stage of maturity, the initial cost inputs are unlikely to be fully compensated. The existing roadside trees are of particular importance because the harsh roadside environment may cause high failure of new tree plantings. Accordingly, protection of established trees should have higher priority for urban forest management, and if possible, these trees on or adjacent to development sites or grey infrastructure should be retained (Hitchmough, 1994). However, the number of existing trees has been inevitably decreasing because of new development, tree aging and vandalism, and natural or anthropogenic hazards. As local government's tree policies and strategies set canopy cover goals and targets, new plantings are essential to protect urban forest against net loss of canopy. But new planted trees are also most vulnerable to pests and diseases, climate change, poor soil conditions, weed competition, and tree vandalism (Hitchmough, 1994).

Redeveloped areas are normally not the best locations for large scale tree planting due to their harsh growing conditions (Brunner and Cozens, 2013). Suitable species selection is undoubtedly one of the most important factors for successful tree planting, but choosing appropriate planting sites is also a key component. Remote sensing data can be used to map urban land cover such as impervious areas, soil surface and vegetated areas (Ridd, 1995, Wu and Murray, 2003, Weng, 2012, Weng and Pu, 2013). This information can then be combined with other GIS data to locate potential planting sites within public parks and reserves, soft road verges, as well as private gardens. Areas with low canopy coverage can be a focus. Occasionally, nodal regeneration can help develop tree covers within these sites by using an isolated large or culturally significant tree as the focus for new extended planting.

Apart from this after-development planting, a more proactive method is integrating the age of tree population into the planning system. If development occurs in areas with large numbers of aging trees, its adverse impacts on local environment can be minimised by incorporating tree placement strategies. The diversity of age groups is also particularly important as a large number of trees declining during a similar period would create high demand on management resources (Hitchmough, 1994). Thus, the mixture of different tree age classes in urban areas should be a key objective; the age information of existing trees is essential and can often be collected with tree inventories. New plantings are best located into areas with trees in different stages (e.g. maturity; over-maturity). For roadside forest, primary challenges are protecting or extending very small natural ranges and utilising narrow road verges for tree plantings. Remote sensing and GIS data can enable rapid assessment of roadside conditions and regular update of tree inventories, and provide recommendations for street tree removal and replacement.

6.4 Conclusion

Urban forest management has become increasingly important with rapid urbanisation and resulting vegetation degradation. As it is entwined with various parts of overall environmental planning and management, optimal tree management needs to balance the benefits and costs of trees. Remote sensing technologies coupled with GIS provide great potential for updating the tree inventory and improving the management from different aspects. Unfortunately, the tiered regulatory/management organisations structure can lead to some inconsistency or unnecessary complexity.

Urban forest is comprised of different forms but linear reserves have grown in importance with the development of urban infrastructure. Roadside forest is one of the most important urban forest types because of extensive road networks. Using remote sensing data, the tree assessment and shading impact analysis along two major highway corridors in this study show the great capacity of urban trees to reduce solar radiation, both at ground level and on building roofs. The choice of appropriate tree size should be tailored to different land use with different building and ground characteristics. Moreover, the values of existing mature trees should be more fully recognised and incorporated accordingly into the planning system. Remote sensing can be an effective tool to monitor existing forest, to model tree benefits, and to locate potential new planting sites. While a large amount of research has been done for urban tree studies using remote sensing, the applications of this tool in tree management can be extended to new aspects.

Based on the tree feature and shading analyses, and management implications discussion, the final chapter provides synthesis and conclusions drawing all stands of the study in a way that the conclusions or abstracts of individual chapters cannot do.

Chapter 7 Synthesis and Conclusions – a New Model and Future Trends

7.1 Introduction

In the broader context of rapid global urbanisation, climate change and development of new planning concepts such as eco-cities, the research documented in this thesis has had three major themes:

1. Accurate assessment of environmental impacts of urban trees and strategies for maximising shading for energy savings;
2. Development of a more integrated urban forest management model primarily based on remotely sensed data; enabling
3. Improved ecological management of roadside and adjacent forests as a basic structural web for all residual urban forests (i.e. improved multi-use systems management).

This final chapter is designed to draw together all the key findings within the context of the new management model and broaden the perspective, by briefly considering how the new model might be used in a complementary or supplementary way with existing frameworks.

The findings discussed here:

(a) build on earlier surveys and analyses of urban forest resources and associated policy influencing management;

(b) complement and supplement the ground-based i-Tree surveys of the same areas (Amati et al., 2013b);

(c) extend recommendations and projections to transport corridors throughout the SMA; and

(d) contribute towards the development of a more comprehensive and integrative model for urban forest management – primarily based on various analyses of high resolution remote sensing data, but also incorporating other diverse information (e.g. ground measurements, socio-economic factors).

In addition, poorly known ecological aspects that currently, or potentially, need urgent attention are identified and trends reflecting local priorities are also briefly outlined.

7.2 Australian Green Infrastructure – Increasing Profile, Fragmented Policy and Management

The growing importance of urban green infrastructure and integration into urban planning is acknowledged although, currently, resources allocated do not necessarily reflect its rising profile. Features of the policy and management structure (summarised in Wang and Merrick (2013)) that can impede progress and efficiency include the large number of organisations involved, bureaucratic inconsistencies and lack of political communication. An example of the latter, which has led to unexpected and undesirable outcomes in the SMA, is the recent 10/50 Legislation.

Following disastrous bushfires in peri-urban areas of the SMA, during the 2013-14 Summer, Fire Authorities pressured the NSW Government to amend legislation relating to vegetation clearance near buildings. Unfortunately the new Rural Fires Amendment (Vegetation Clearing) Act 2014 was too specific, being primarily based on flammability, and it extended to all urban areas. The hasty drafting and approval led to initial confusion and opportunistic abuse (e.g. long-established trees removed for new development or to enhance existing real estate values, by expanding views). These and other problems forced rapid consideration of amendments less than three months after Enactment.

Other urgent urban forest problems being faced by local government (in Sydney), right now are:

- Climate change impacts and how to understand and manage them in the long term
- Competition for land, or loss of allocated land, available for canopy tree planting
- Community misunderstanding and negative reactions to tree removal and replacement programs
- The management and protection of trees during utility or other infrastructure construction works
- Minimising the impact of pruning by utility companies, clearing trees from their overhead powerlines

More data are also urgently needed to address the following issues.

- Identification of tree and plant species that will thrive in changed conditions (including impacts from pests and diseases).
- Identification of the thresholds for canopy cover, and the spatial distribution required to achieve the most environmental, social and economic benefits.
- Improved stakeholder communication, providing clear examples of the tree removal issues and the benefits of replacement tree at specific sites.
- Australian quantitative data on the benefits of trees (Sweeney, 2014, pers. comm.).

Another general observation relating to management was discussed at a recent Green Infrastructure Research Forum at Macquarie University attended by the author. It was explained that the ‘green infrastructure industry’ (including green roofs, green walls, etc.) is, in many respects, at an early stage of development in Australia. It consists of many individual practitioners and small enterprises undertaking a wide range of innovative activities, but not communicating sufficiently to facilitate rapid progress. It was suggested that a co-ordinating or hub organisation might be beneficial to provide advice, expedite information transfer and maintain a central database.

7.3 Radiation and Shading related to Tree and Building Features

The LiDAR–derived models are well suited to model solar radiation to assess the shading impacts of trees. One of the most significant results of the shading analysis is that even a limited presence of trees (<32% coverage) results in substantial reductions (up to 14%) of solar radiation on building roofs. The radiation reduction along the Pacific Highway is around 2.5 times that along Parramatta Road and can be related to the increased tree coverage. If generally applied to the whole SMA, the findings indicate major importance relating to land use, tree coverage, building features and energy conservation.

Without going into details, this clearly has major economic implications. As roof radiation reductions can be related to building energy demand profiles, these results can be combined with future solar radiation analyses to develop more comprehensive energy planning initiatives.

Another general observation, about the importance of deciduous trees, is relevant at this point. The research highlighted the benefits, and potential, of using deciduous species in some situations where it was important to be able to utilise reduced radiation in winter (see Chapter 6). Discussion of deciduous trees usually focuses on species, such as the London Plane tree, that shed leaves in winter; however, there are a number of alternatives available that may be suitable substitutes in specific locations. In the SMA there are a number of 'semi-deciduous' trees present; these species (e.g. Jacaranda) have variable and short-term seasonal defoliation (Downing, 2014, pers. comm.).

7.4 Conservation and Management

For the reasons previously outlined in Chapter 6 these roadside forests are viewed as a very important sub-system of urban forest (see Figure 6-3, summarising the situation in the SMA), connecting other biological systems. Clearly management has to be consistent throughout the system, necessitating co-ordination between jurisdictions and organisations. These public roadside forests are an essential connecting web – and the main transport corridors can connect all public and private vegetation systems. They are situated on permanent ‘reserve’ areas (associated with permanent infrastructure) and, although there are challenges, they can be managed for multi-use - forming part of a core system that benefits conservation and alleviates some of the problems created by intensive development and reduced permeability in urban areas.

One aspect that deserves further comment relates to large trees. As this and other research has indicated large tall trees have major benefits, but also pose major challenges especially when an area is being managed for multiple purposes. For example, in Chapter 6 it is explained that older trees become more expensive to maintain and an efficient management strategy would be to implement a phased removal and replacement program; however, long-lived trees change their ecological roles with age and this may modify management, depending on local conservation priorities. Many of the large eucalypts common in Australian ecosystems have lifespans of several centuries. They do not mature for some decades and then, later in the life cycle, branch atrophy results in the formation of many nesting hollows utilised by a variety of native fauna. Management must be flexible and very long-term; although some problems can be minimised by positioning plantings so that, at least some, older trees can be left standing indefinitely and not create safety hazards.

In summary, the following planting recommendations can be made, based on this research.

- Prioritise new plantings to connect existing stands.
- More deciduous trees may be appropriate in commercial and industrial zones.
- Implement active management and encourage community engagement.
- For main highways and wide roads (large trees > 20m height):
    - New or replacement planting at low density (average spacing 1 per 8-10 m)

    - Where space permits, plant more than one row – alternately spaced.

- For side streets and narrow roads (medium trees < 20m height):
    - New or replacement planting at medium density (average spacing 1 per 4-5 m).

These recommendations are designed to maximize the use of a public resource for mutual benefit – they do not conflict with existing conservation or energy initiatives, they enhance them. In addition to the advantages of co-ordinated vegetation management on public land there is no inhibition to co-operative, complementary initiatives on private lands for further benefits.

Urban forest management is an important component of the whole environmental planning system and includes diverse aspects. As this research shows, remotely sensed data, combined with GIS analyses, can be used to refine all major facets of urban tree management at local level – for example, (a) in terms of inventories, these data can assist measurement of tree parameters (such as tree height and crown width), mapping tree conditions and distribution, and calculating growth rate, and (b) in terms of monitoring, these data can quickly detect changes in tree coverage and assess the effectiveness of tree policies. As policies and strategies are refined there should be better long-term planning outcomes relating to tree species selection, increasing new plantings and practical tree removal and replacement strategies.

The management of urban forest is not only important on its own, but also correlates to broader issues such as ecological permeability, green corridors, catchment management, and urban management. Remote sensing technologies also provide powerful tools in terms of monitoring the impacts of climate change, measuring ground litter loads (fire fuel), catchment monitoring, managing soil degradation and erosion, mapping physical assets and natural resources, risk assessment of natural hazards and temporal and change analysis.

7.5 LiDAR-based Integrative Management Model

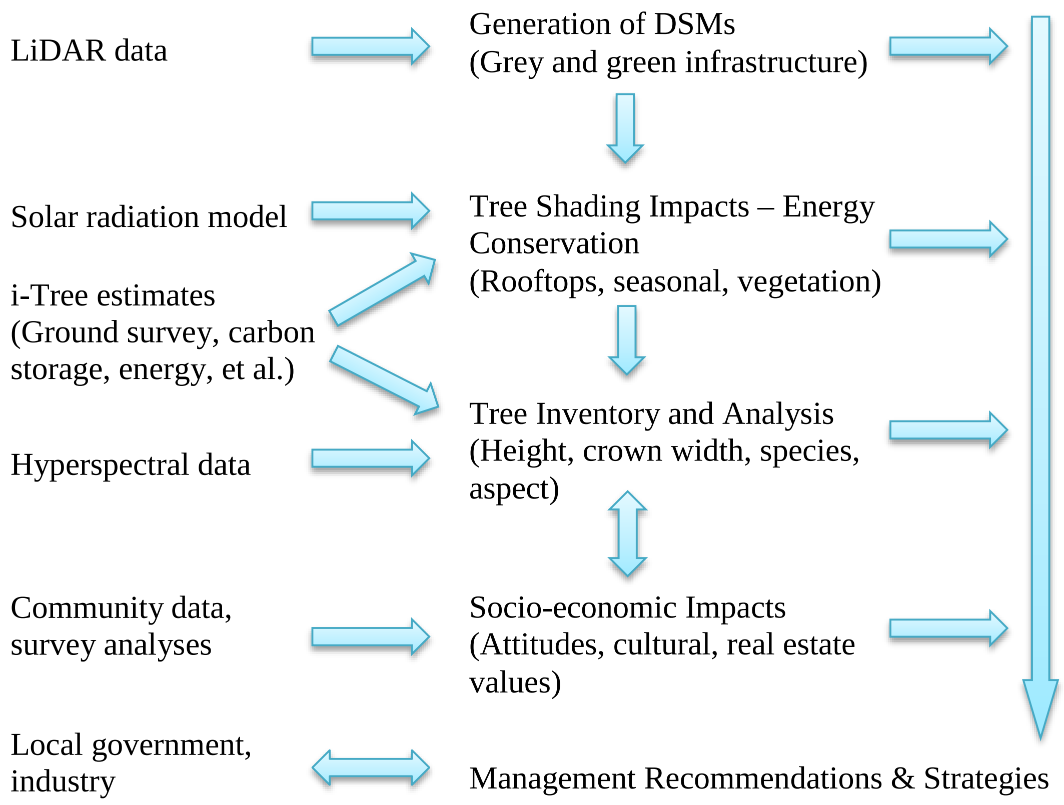


Figure 7-1 LiDAR-based integrative management model for urban forests

The relative advantages and disadvantages (see 6.2.2) of LiDAR (and remote sensing in general) have been discussed previously and will not be repeated here. But it is important to emphasise that LiDAR datasets can be used as the basis for a sequence of analyses, which enable development of 3D pictorial and predictive optional models, which contribute to improvement of on-going management of an urban forest resource – at a local level.

This research has demonstrated that a LiDAR-based integrative management model can be developed for urban forests (Figure 7-1). The model incorporates grey and green infrastructure mapping, tree shading impact modelling, and tree inventory development by using remotely sensed data and ground surveys. It also includes more diverse input from the community, industry and local government sectors. Although LiDAR data have recently become increasingly available and affordable for tree management and other planning or management issues; unfortunately hyperspectral images, especially high resolution hyperspectral data, are still limited in availability or very expensive (see 6.2.2). Furthermore, current remote sensing analyses usually require the assistance or validation from ground-based data. So they are complementary to each other rather than exclusive alternatives.

7.6 Conclusions and Future Directions

It is emphasised that the studies reported here show that, with very limited resources and relatively small numbers of additional large trees, environmental conditions in the central SMA could be significantly improved.

General consideration of socio-economic comments should include objections to trees. These are expressed in surveys as: traffic hazards, obstruction of advertising, reduced views, or nuisance litter drop. These are essentially based on commercial concerns and may well be reduced or dropped when the economic benefits of trees are fully explained. For example, increased customer flows to pleasant, cool areas and major savings on air-conditioning costs. As with so many environmental issues, community engagement has to be increased and interactive participation maintained – this can be achieved by campaigns such as 'adopt a tree'.

There are several ways to expand the studies reported here in future:

1. Incorporate different characteristics (e.g. leaf shape, texture) of different tree species in the solar radiation models;
2. Include building walls and windows in shading analyses based on LiDAR derived 3-D models and other resources such as field surveys and building data;
3. Use hyperspectral imaging to link building roof reflectance to reduction in solar radiation caused by trees;

4. Extend the assessment of roadside forests to other biological systems, and then to the whole SMA as an integrated region.

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Appendix A – Statement of Authorship

Chapter 2

Title of Paper	Chapter 9 Urban vegetation
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Name of Principal Author	Mingzhu Wang
Contribution to the Paper	Collected filed survey data, conducted interviews with local government, wrote manuscript
Name of Co-Author	A/Prof. Marco Amati
Contribution to the Paper	Helped to evaluate and edit the manuscript
Name of Co-Author	A/Prof. Jason Byrne
Contribution to the Paper	Helped to edit the manuscript

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Name of Co-Author	Dr. John Merrick
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Name of Principal Author	Mingzhu Wang
Contribution to the Paper	Perform data analysis, wrote manuscript and acted as corresponding author
Name of Co-Author	Dr. Hsing-Chung Chang
Contribution to the Paper	Helped to evaluate and edit the manuscript
Name of Co-Author	Dr. John Merrick
Contribution to the Paper	Helped to evaluate and edit the manuscript
Name of Co-Author	A/Prof. Marco Amati
Contribution to the Paper	Helped to evaluate and edit the manuscript

Chapter 5

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Contribution to the Paper	Perform data analysis, wrote manuscript and acted as corresponding author
Name of Co-Author	Dr. Hsing-Chung Chang
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Name of Co-Author	Dr. John Merrick
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Contribution to the Paper	Perform data analysis, wrote manuscript and acted as corresponding author
Name of Co-Author	Dr. John Merrick
Contribution to the Paper	Helped to evaluate and edit the manuscript
Name of Co-Author	Dr. Hsing-Chung Chang
Contribution to the Paper	Helped to evaluate and edit the manuscript

Appendix B - Australia and New Zealand Association of Planning Schools (ANZAPS) Conference Paper

Urban Forests along Sydney Transport Corridors: the Possible Role of LiDAR in Future Planning and Management

Authors: Wang, M-Z., Merrick, J. R. and Amati, M.

Graduate School of the Environment, Department of Environment and Geography, Faculty of Science, Macquarie University

Contact: mingzhu.wang@students.mq.edu.au

Abstract: In the context of expanding urbanisation, climate change and peak oil, the maintenance and extension of connected vegetation corridors has become an essential component of urban planning and environmental management. In addition to ecological benefits, urban forests improve air quality, save on energy (cooling and heating) and mitigate greenhouse emissions. As part of broader studies on the use of Light Detection and Ranging (LiDAR) technology in urban tree management, the work reported here focuses on initial surveys of urban forests bordering two highway corridors in Sydney. These are used to demonstrate the potential and technical aspects of working with LiDAR in densely developed areas. Aspects of planning and management for urban forests are briefly discussed. Limitations of resolution of this technology and new ways in which LiDAR might be utilised are suggested.

Key Words: urban forests, urban forests planning, remote sensing technologies, improved management strategies, public areas.

Introduction

General Background

Among the expanding range of socio-economic and environmental issues that have to be considered in planning now is that of green infrastructure, which presents a range of planning challenges. This paper presents initial findings into the factors that affect the quality of green infrastructure and the potential for new technologies to facilitate the management of urban forests.

Remote sensing has been a stock in trade among planners for several decades. The technologies are known to enable the survey of large areas in a short time. The utility of remote sensing is reflected in the incorporation of geographic information system (GIS) units as a core component of all planning programs in Australia. While GIS has found an application in a range of domains its application to green infrastructure has been overlooked.

Light detection and ranging (LiDAR) is one such remote sensing technology. It produces a comprehensive database for subsequent analysis; giving accurate assessments of tree extent and condition. It is non-invasive which minimises the problem of access or privacy; permitting identification of changes or problems that, if necessary, can be investigated by on-ground staff. These advantages, in turn, contribute to more efficient use of limited field equipment and finite human resources.

Importance of Planning Green Infrastructure

Clearly, although threatened globally by accelerating urbanisation, urban trees and green spaces are becoming increasingly valuable resources, performing both socio-economic and environmental functions that are summarised in Table 1. Urban environments have been highly transformed by anthropogenic activities and have specific climatic conditions due to high levels of fossil fuel combustion (Nowak and Crane, 2002). The remaining and new vegetation within urban areas provides various crucial environmental benefits (Brack, 2002). It should be noted at this stage that most studies of green infrastructure have focused on, or emphasised, trees. Accordingly much of the discussion here relates to trees or urban forests.

Table 1 Summary of environmental and socio-economic functions of urban forest trees- some of these overlap between role categories.

Role	Function (Source)
ECOLGICAL	• Refuges and additional habitat, enhancing usage of remaining fragmented habitat (Bennett et al., 1999, Bennett et al., 2006) • Corridors and reserve network for limited biodiversity in landscape (Bennett et al., 1999) • Lower or moderate ambient temperatures by evapotranspiration • Carbon storage and sequestration mitigates climate change (Nowak and Crane, 2002) • Intercept rainfall increasing soil absorption and reducing surface runoff as well as erosion (Brack, 2002) – in turn, reducing sedimentation in waterways
SOCIOECONOMIC	• Mitigates air pollution - remove gaseous pollutants, intercept airborne particles (Beckett et al., 2000a, Beckett et al., 2000b, McPherson, 2000, Nowak et al., 2006, Nowak et al., 1998) • Shading decreases incident solar radiation - reduces local air temperature lowering need for air conditioning in summer (McPherson, 2000) • Reduced wind speed reduces building heating demand in winter (McPherson, 2000) • Street trees protect pedestrians from wind, rain or sunlight (Nagendra and Gopal, 2010) • Combined effects of shading and evapotranspiration directly modify building energy use (Simpson, 2002) • Combined effects of shading and evapotranspiration indirectly reduces carbon emissions and air pollutants from lowered power plant emissions (Simpson, 2002). • Carbon storage and sequestration mitigate local and global climate change (Nowak and Crane, 2002) • Reduce rapid surface runoff – reducing transport of pollutants from anthropogenic activities into waterways (Brack, 2002) • Increased aesthetic qualities and health benefits (Powe and Willis, 2004) • Improved property values in immediate area (Anderson and Cordell, 1988, Laverne and Winson-Geideman, 2003, Sander et al., 2010)

While many beneficial roles have been identified for urban trees, there are some problems as well. These include: bushfire potential, increased risk of physical tree damage to buildings or infrastructure due to storms, reduced visibility and increased risk of collision with street trees. Effective management has to consider these benefits and costs.

Objectives

The overall goal of this project is to better understand the environmental benefits of urban forests in Australian cities. While emphasising the necessity of including urban forests in medium and long-term planning, the objectives of this paper are: (1) to outline the broad stages in development of urban forests planning and strategies in Sydney; (2) to briefly explain some of the technical aspects of working with a remote sensing technology, to measure parameters to facilitate improvement in urban planning; (3) to point to the factors and limitations that need to be considered in urban forest management.

Development of Urban Forest Plans - Phases and Planning

Before undertaking any field surveys it was necessary to collate and review the existing data and management processes relating to urban forests. A number of the key background points summarised in Figure 1 are considered in subsequent discussion. But, in summary, the most important findings are that: a wide range of land uses and stakeholder requirements have to be accommodated; a wide range of technologies are currently used to assess urban forests – to varying degrees in different local areas; the development of comprehensive urban forest plans is a long-term process.

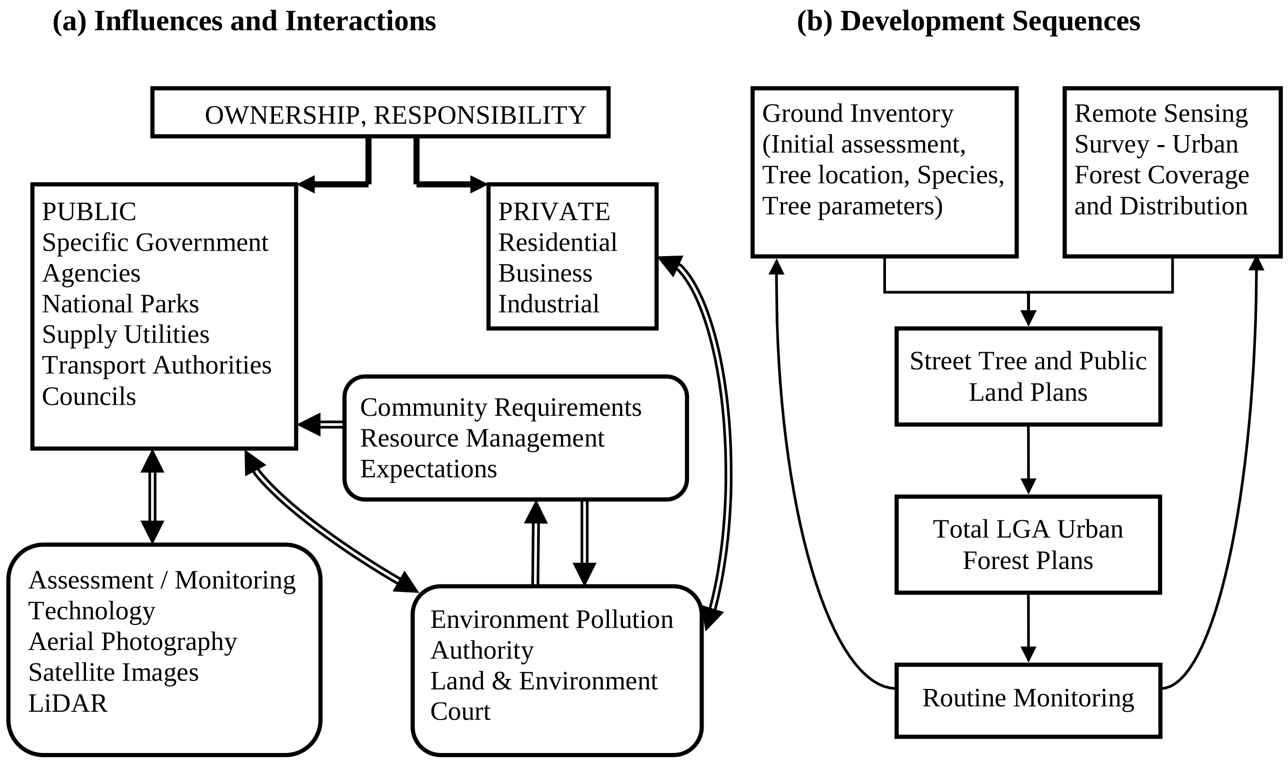

Figure 1 General summary of: (a) influences and interactions; and (b) stages in the development of Urban Forest Plans, in the Sydney Metropolitan Area

The Potential for Remote Sensing

Recently, passive remote sensing technologies such as aerial photography or satellite images have been used for tree studies because they are relatively inexpensive and easy to obtain (Secord and Zakhor, 2007). But these methods are sensitive to weather, season, and the time of day when data is collected, and limited in providing three-dimensional information (Jung et al., 2011, Patenaude et al., 2004, Shan and Sampath, 2005). Figure 2 reveals the types of distributional, size and canopy cover data yielded by aerial photography.

(a) **(b)**

Figure 2 Samples of North Sydney Tree Canopy Cover Data: (a) shows the beginning of the Pacific Highway in a business area; and (b) shows the middle part of the highway within the North Sydney LGA, where there is mixed commercial and residential development.

LiDAR Features and Limitations

Light detection and ranging (LiDAR) is one of the most important active remote sensing technologies. The airborne LiDAR system emits laser pulses towards the ground surface and the pulses are reflected back to the sensor by objects such as trees, buildings and the ground. The LiDAR device measures the time-delay between pulse emission and return, converting it to distance measurement (Popescu, 2007). In this way, an accurate three-dimensional model of natural and man-made structures, as well as underlying topography, can be created. Compared to other photogrammetric approaches, LiDAR has several distinct advantages for environmental studies: it is less dependent on weather conditions or sun angles (Patenaude et al., 2004, Shan and Sampath, 2005); it can collect both vertical and horizontal information at high density (Jung et al., 2011); it can generate high density airborne data to produce digital surface models with high spatial resolution (Kato, 2008, Patenaude et al., 2004); it is a more effective tool with higher accuracy than field or passive remote sensing approaches (Jung et al., 2011, Secord and Zakhor, 2007); and for tree measurements it can penetrate the tree canopy, capturing its vertical structure as well as underlying terrain (Hollaus et al., 2009).

These features are already used by councils to map the terrain surface, however the potential for LiDAR in urban forest management is under utilised.

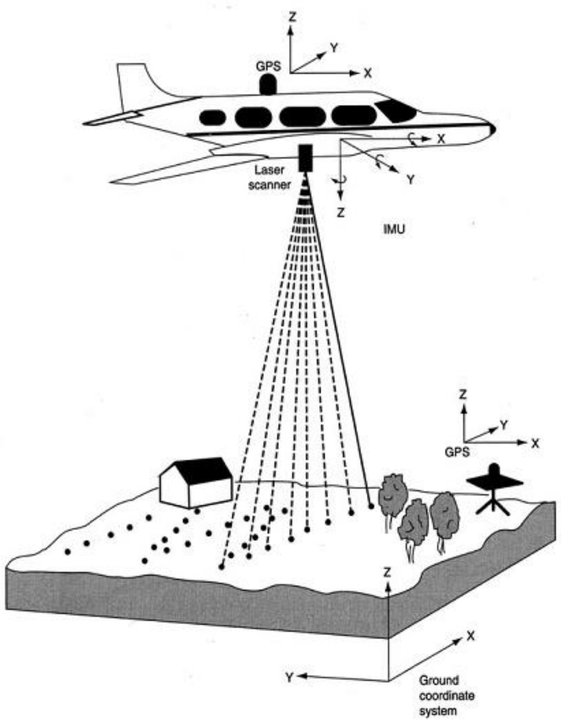

Figure 3 Airborne LiDAR System and how it works

Source: Zhang et al. (2011)

The two aspects of the general advantages listed above, that are most important in this context are: (a) greatly increased resolution; and (b) the capacity to interpret and visualise the environment in three dimensions. This assists assessments / management of forests in several ways.

First, unlike previous technologies, LiDAR has the capacity to differentiate different types of tree (Hollaus et al., 2009, Moffiet et al., 2005, Zhang et al., 2011), so it can identify diversity and assemblages in a way not previously possible. What is unclear at present is the level of botanical diversity that can be reliably distinguished: whether it can only delineate different families or whether it can distinguish genera or species. However, the combination of LiDAR and hyperspectral or multispectral images which provide the spectral information of forests can greatly increase the accuracy of extracting tree parameters including tree height, location and tree species (Holmgren et al., 2008). If the spatial and spectral resolution is high, it also raises the possibility of detecting differences in condition of individual or groups of trees – perhaps giving an early indication of drainage or pollution problem or critically, a potential danger to powerlines.

Second, associated with this improved recognition of different tree types, is the ability to detect an expansion or reduction (in numbers) of a particular species between successive surveys. Differences in understorey structure should also be detectable – even in steep inaccessible sites.

The capacity to illustrate the spatial interrelationships of forest and infrastructure or buildings is critical in management and development. For example, the assessment of shading impacts is highly dependent on the relative positions of trees and buildings, together with relative heights and aspects. In the case of transport corridors, the effectiveness of pollution mitigation is highly correlated with tree type, density of planting and proximity to the fume source (Baldauf et al., 2008, Beckett et al., 2000a, Nagendra and Gopal, 2010).

Perceived limitations of this technology, at present, are:

(a) the volume of data generated requires extensive computer storage and analysis resources;

(b) effective analysis and working outputs are dependent on trained specialist personnel;

(c) some uncertainty as to the level of resolution possible;

(d) the relative expense of the aerial surveys.

Highway Corridors – Study Areas

Parts of two major highway corridors were surveyed. In each case the survey length was around 20 km – running from inner central business districts to outer suburbs. One survey extended along the Pacific Highway – from North Sydney to Hornsby. The other extended out along Parramatta Road – from Camperdown to Parramatta (Figure 4). The survey band included the road with an overlap of about 150m either side of it.

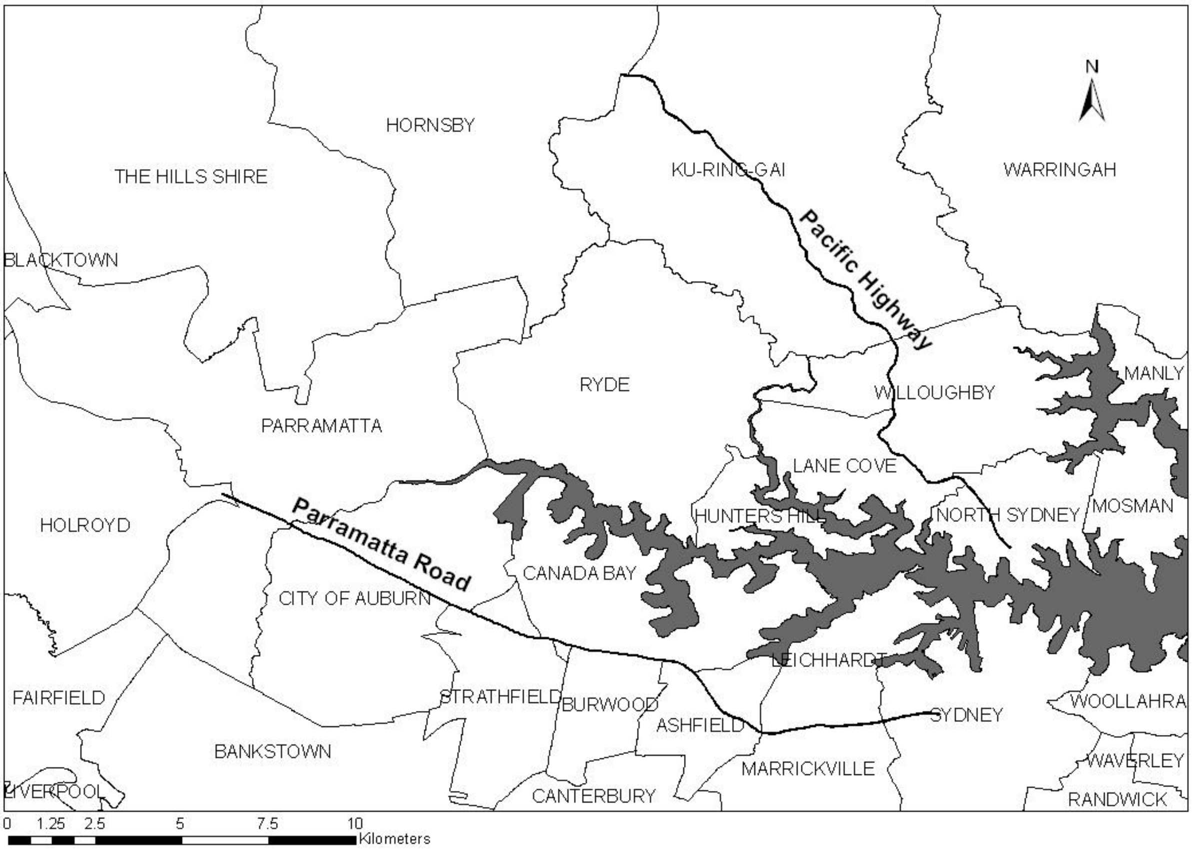

Figure 4 Map of inner metropolitan area showing the lengths of Parramatta Road and Pacific Highway surveyed as well as Local Government Area (LGA) boundaries. Data Source: ABS and NSW Lands

In the absence of combined or comprehensive tree species lists for these corridors (and ground-truthing check for the planned aerial survey), a preliminary field survey was carried out to investigate the diversity of roadside trees along Parramatta Road and the Pacific Highway. A car was driven slowly along these two roads while a botanist identified tree species on the road verge. All tree species (> 2.0m in height) were recorded and identified to generic or specific level. Further information about trees on public lands within the 150m buffers, including species in parks and street tree databases, was provided by tree officers from relevant councils.

Results and Discussion

Urban Forest Resource – Initial Transport Corridor Surveys

The benefits of the urban forest resource are widely recognised; however, this recognition has not always been matched with appropriate monitoring or management resources. It should also be noted that the generalised sequence in the development of comprehensive urban forest plans (Figure 1), has largely evolved in response to a perceived need and demand for conservation of a specific resource that is dwindling and poorly-documented; so objectives to date have largely focused on basic features of the urban forest complex. But initial plans and on-going management will be increasingly modified as a result of integration of urban planning issues – and the extent of socio-economic and ecological interactions are fully realised.

Understandably, urban forest strategies for public land are usually applied throughout the LGA and adequate baseline data for particular zones, such as transport corridors, are often not available. The field surveys reported here demonstrated the following:

(a) unexpected diversity – beneficial from a conservation point-of-view, but needing more intensive management;

(b) wide variation in overall species diversity and component species within local areas and between different sections of each corridor;

(c) very patchy tree distribution in some areas;

(d) planting and maintenance of some species that did not contribute to conservation, shading or pollution mitigation.

The follow-up enquiries indicated that, while the street-tree strategies were at varying levels of development, most councils were upgrading databases and management plans for this category of vegetation. It should also be noted that some of the limitations or problems, associated with urban tree management, have only become apparent in recent years (see Table 2).

Table 2 Summary of factors, limitations or problems that need to be considered in urban tree management

Factor, Limitation or Problem	Source
1. Maximum benefits from urban forests are only achieved when density of the tree canopy is appropriate and when each individual tree is properly maintained and replaced when necessary.	North Sydney Council (2006)
2. Inappropriate plantings in unsuitable conditions or locations can cause different kinds of problems in local environments or communities. For example: particular tree or grass species can cause allergies or irritations by producing a greater pollen load leaf or fruit droppings can increase litter problems or make ground slippery when fleshy fruits or leaves decompose	City of Sydney (2011) City of Sydney (2011).
3. Root systems of some vigorous or large growing species can cause damage to underground services, pavements, kerbs and properties	Pittendrigh Shinkfield Bruce Pty Ltd (2005), City of Sydney (2011)
4. Maintenance costs may outweigh benefits when urban trees reach a certain stage or life span (over-maturity) or are in poor condition	North Sydney Council (2006)
5. Species selection – especially for new plantings of street trees – should consider: (a) local climate, geology, soil and topography (especially in relation to drainage); (b) growing space – relating to overhead / underground services; (c) height, maturation size, foliage (deciduous / evergreen) and physiology; (d) tolerance to pruning	Pittendrigh Shinkfield Bruce Pty Ltd (2005) North Sydney Council (2006)

For effective tree management, to improve local environments, comprehensive and current inventory data are essential. For example, Council tree officers can predict potential problems caused by larger trees using knowledge of growth rates and maturation height. Considerations in the selection of species for new (or replacement) plantings are summarised in Table 2. Other factors to be considered include: if the species is native – relating to disease resistance; and street width – in relation to traffic and ability to alleviate impacts (City of Sydney, 2011, Nagendra and Gopal, 2010).

Common native species like *Eucalyptus* are often adapted to soils with low nutrient levels and rapid drainage (City of Sydney, 2011). But the growing conditions in an urbanised area are quite different from natural conditions (North Sydney Council, 2006) so these species may not do well in some urban areas. Conversely, exotic deciduous species are more popular in inner urban contexts, like North Sydney, because they are more tolerant of paved areas. Deciduous trees also have the advantages of being energy saving by providing shade in summer and sun access in winter (North Sydney Council, 2006). In highly developed areas, native vegetation communities are limited and their scale is negligible. Clusters of trees are largely planted around places such as schools, churches and parks. While in less developed areas, the density of native vegetation is much higher.

With reduced green reserves in urban areas, the parks around transport corridors have become more important. Compared to paved streetscapes, parks provide better growing conditions, consequently trees in parks normally have longer life spans and are healthier (Marrickville Council, 2010). As public parks are now the few urban habitats remaining that are suitable for trees, it is logical that they be used more intensively for this purpose. However, a lack of data or tree management strategies in some LGAs, as well as the need to maintain other traditional recreational functions of parks, will slow progress towards more intensive management.

Although trees planted along transport corridors are playing a significant role in pollution mitigation, they have often been undervalued in urban planning (Nagendra and Gopal, 2010). In the long term, effective urban forest management requires the local governments to increase expenditure on the renewal and maintenance of street trees and re-planting of trees that are removed by infrastructure development (Nagendra and Gopal, 2010).

Managing and Monitoring with Remote Sensing Technologies

Except in particular circumstances, local government cannot carry out work on trees on private land. But tree data from private land are important in developing urban forest strategies for the whole LGA. Remote sensing provides an accurate, efficient and cost-effective way to collect this information. Aerial photographs are commonly used to map and calculate canopy coverage and i-Tree is another tool used by local government to estimate the environmental benefits provided by their urban forest. But i-Tree has limitations, it can only provide averaged value estimates, usually based on local weather and pollution data and location databases for a whole city. As physical environments within LGAs vary widely, using i-Tree cannot provide accurate information for small local environments and it is difficult to identify problems at a specific location.

Remote sensing technologies are currently used in various ways in different LGAs and although some methods are relatively expensive, they show great potential for wider usage. North Sydney Council uses remote sensing data, such as aerial photographs, to get information on overall canopy cover within its area (North Sydney Council, 2006). Lane Cove Council uses aerial photography only to locate trees, prior to site inspections, and does not use LiDAR for tree management. Ku-ring-gai Council uses aerial photography and LiDAR to map woody vegetation coverage of its LGA; LiDAR data is also used to determine height of its vegetation communities. The Urban Forest Strategy of Marrickville Council set a high priority on using aerial photographs to assess the existing percentage of urban forest canopy cover and change each decade from 1980 until 2010 (Marrickville Council, 2010). Strathfield Council has an aerial photo of the municipality with the trees being roughly plotted and with notes from an inspection undertaken in 2005.

These technologies are now capable of providing faster, efficient monitoring of urban forest dynamics at landscape level (Myeong et al., 2006). Aerial photographs are now readily available and inexpensive, providing a cost effective tool to assist urban forest management by local government. LiDAR shows greater potential in future planning and management since it can provide precise data of tree height, crown width, basal area, crown base height and crown volume (Kato, 2008).

Summary and Recommendations

Management of urban forests is another issue that will inevitably grow in significance in planning. In combination with traditional field measurements, remote sensing techniques can be used to build comprehensive urban forests inventories more rapidly. Using this multi-temporal data not only enables forest changes to be monitored (Myeong et al., 2006) but, for the first time, permits detailed investigation of interrelationships between urban forests and structures. This will improve planning for pollution mitigation and energy use.

This paper uses the findings of preliminary surveys and analyses of roadside forests along major road corridors in Sydney, to demonstrate the current situation and types of challenges faced in management of this resource. Based on these initial studies, several general recommendations, for all councils along these corridors, can be made:

(a) that adequate resources be allocated to upgrading and/or updating inventory databases, for both roadside and park trees;

(b) that remote sensing technologies be considered to rapidly accelerate the development of databases and assist in monitoring for more effective management in future;

(c) that comprehensive programmes of maintenance and new plantings be retained or extended;

(d) that long-term strategic plans be developed or implemented to expand urban forest on public land in each LGA – by extending plantings of appropriate species on roadsides and increasing connections with park or reserve forest communities.

Much of the discussion is focused at LGA level, as councils have prime responsibility for urban forests; however, the potential of remote sensing, as well as many of the management criteria or strategies and challenges identified, apply equally at broader scales.

Acknowledgements

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Appendix C - Institute of Foresters of Australia (IFA) Conference Paper

Understanding the Carbon and Pollution Mitigation Potential of Sydney's Urban Forest

Amati, M[1], Brack, C.[2], Ghosh, S.[3], Kachenko, A.[4], McManus, P.[5], Shrestha, K.[6], Wang, M.[7], Yung, S-. H.[3]

1) Faculty of Human and Social Sciences, La Trobe University, Bendigo. 2) Fenner School of Environment and Society, Australian National University, Canberra. 3) Faculty of Design, Architecture and Building, University of Technology, Sydney. 4) Nursery and Garden Industry Australia, Castle Hill. 5) Faculty of Science, University of Sydney. 6) Faculty of Arts and Social Sciences, University of New South Wales, Sydney. 7) Department of Environment and Geography, Macquarie University, Sydney.

Abstract: The most widely used technique internationally to map and model the benefits of urban forest is i-Tree Eco. This study aims to show how remote sensing through hyperspectal imaging and LIDAR can add to this tool. LIDAR data is frequently collected by local councils to map topography for example. Sampling along two major highways in Sydney was used to collect both the LIDAR and hyperspectral data. These transects cross different suburbs, land uses and different local government areas. A plot sample study was made using the i-Tree Eco method. The results show that the Pacific Highway has a canopy coverage of 40.3% while the Parramatta Road's coverage is 14.2%. Furthermore, a given tree along the Pacific Highway is 1.7 times more effective at removing pollution, 5.0 times more effective at saving energy from buildings and therefore 5.0 times more effective at avoiding carbon emissions when compared to those along the Parramatta Road. On the other hand, trees along the Parramatta Road are more effective at sequestering carbon and producing oxygen than those of the Pacific Highway. These differences in the value that a given tree will deliver to the urban environment on average are reflective of the species planted but also the health of the tree and its age. The discussion focuses on how these results can be supplemented using remotely-sensed LiDAR data. Overall we argue that local councils can employ these two tools to calculate the impact of planning decisions such as increasing development density and set priorities for more effective environmental decision-making.

Introduction

Sydney's population is expected to reach six million by 2036, with infill development along existing urban corridors containing most of this growth. Eighty percent of Australia's population now live in urban areas which will be affected by peak oil prices and climate change, particularly rising temperatures and urban heat islands. A number of measurement tools exist to analyse the contribution that urban trees can have in mitigating the effect of these changes on urban areas. i-Tree Eco is one of the most prominent of these measurement tools and is based on the Urban Forest Effects (UFORE) model developed by the US Department of Agriculture Forest Service (Nowak and Crane, 2002). i-Tree Eco can model the urban forest's rate of carbon sequestration, air pollution mitigation and energy savings. It employs field measurements, typically using a sample of randomised plot measurements over the whole of a city's area, stratified by land use.

Remotely sensed data such as LiDAR is also a well-known tool for measuring trees. Unlike i-Tree Eco it requires little fieldwork. While some studies in Australia have utilised LiDAR data for tree stem and crown mapping, forest structure quantifying, biomass calculation and species classification (Moffiet et al., 2005, Lucas et al., 2006, Tickle et al., 2006, Lee and Lucas, 2007), in urban areas LiDAR has been used for extracting urban features (road, building etc.) and land cover classification. Few studies focus on tree detection, tree height measuring and urban green volume estimation in urban areas (Imai et al., 2004, Secord and Zakhor, 2007, Sugumaran and Voss, 2007, Hecht et al., 2008). However, little work has been done to use LiDAR derived parameters to estimate environmental benefits of urban forest.

This research fits in with a broad concern to understand the adaptability and usability of these measurement tools and models to Australasian conditions. For example, Cavanagh and Clemons (2006) note the limited applicability of Northern Hemisphere studies and models because of their reliance on deciduous tree species. Brack and Richards (2002) discuss the influence of the Australian climate (especially drought) on the accuracy of the internationally available models. Saunders et al. (2011) used UFORE in 2008 to examine the benefits of trees on public land in western Perth. More recently, work by the arboricultural and environmental consultants ENSPEC, partially funded by the Nursery Garden Industry of Australia (NGIA), has produced Version 5 of i-Tree Eco that is adapted to Australian conditions.

There are several reasons why it is important to adapt these tools to Australian conditions. Australian cities, and especially the Sydney metropolitan area, are fragmented in their land cover and their governance. There is no metropolitan governance, rather, Sydney like most Australian capital cities, is fragmented into a large number of local governments. State involvement in planning is highly contingent. For example the major physical infrastructure of major highways receives attention being of strategic importance for the State government while planning for green infrastructure is left to local governments and private individuals. Yet, the areas of urban forestry that are typically under threat from urban development lie along the major highways of the city. Here, trees provide a significant amount of value through removing the pollution generated by commuter traffic. Trees along these corridors are under threat from urban consolidation and densification (Ruming et al. 2012).

Trees along the major infrastructure routes such as highways are critically important, but their management is fragmented. We have taken this into account through our research. Our sampling sites of the Pacific Highway and the Parramatta Road run through a total of 5 and 10 local government authorities (LGA) respectively.

While a great deal of research exists internationally on urban forests, so far no peer reviewed study has compared the usability of i-Tree Eco and remotely sensed methods to measure the environmental benefits of urban forests. This is important for local governments who need to decide to invest either in extensive field work or remotely sensed data gathering in order to better manage their green asset and build resilient liveable communities.

Aim

The aim of this research was to compare the information about urban trees that can be obtained from remote sensing (LiDAR) and i-Tree Eco survey of the same linear sample. While it is inevitable that both techniques will produce different results, we wish to explain more broadly which technique can be applied in which instance and why. This paper presents some preliminary results from the i-Tree Eco and LiDAR surveys.

Method

Sampling method

To compare both remotely sensed and i-Tree techniques it was necessary to use a linear sampling method. LiDAR and hyperspectral data was collected by aeroplane along both corridors collecting. The path width and line was then used to sample according to the i-Tree Eco manual (i-Tree, n. d.).

Two major highways, Pacific Highway and Parramatta Road were selected as sampling sites. The Pacific Highway selection corridor was 19 km in length, from North Sydney to Hornsby on Sydney's north shore. Land use activity varied extensively and included the business district in the North Sydney local government authority (LGA) through to suburban land use in the LGAs of Lane Cove, Willoughby, Ku-ring-gai, and Hornsby. The selection corridor along Parramatta Road was 11 km in length, from Central Sydney heading west to Parramatta. This corridor was comprised of more densely urbanised LGAs of Sydney, Marrickville, Leichhardt, Ashfield, Burwood, Canada Bay, Strathfield, and the more industrial areas of Auburn, Lidcombe, Parramatta, and Holroyd (see Figure 1).

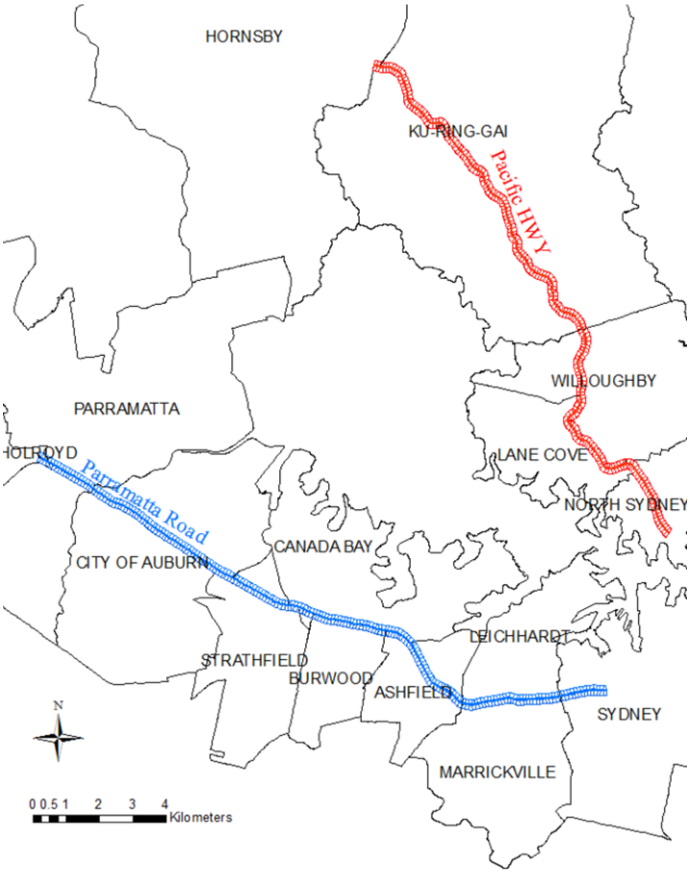

Figure 1: Map of the study sites. Prepared by: S. Yung, University of Technology Sydney (UTS); Data source: Australian Bureau of Statistics (ABS), 2006

i-Tree methodology

i-Tree Eco 5 was used in this study to quantify the environmental services that trees provide, which is suitable for the Australian context. The main steps of the research methodology are:

1. Determination of an 'Area of Interest'

A GIS map layer on the project boundary was created with complete project area data such as spatial distribution of different land use categories. The land use layer was trimmed using the area of hyperspectral data that had been captured to form the AOI (Area of Interest). The spatial features of both AOIs were analysed to estimate the important attributes of the two study areas.

2. Stratification

The study areas were stratified using ‘pre-stratification by land use‘ approach. For the stratification by land use, three major land uses were adopted: ’Residential‘, ’Commercial‘ and ’Institution, Recreation and Other uses (IRO)’. The task was done using GIS and assigning stratification names and remarks into two separate columns in attribute tables of the property polygon layer, according to land uses on zoning maps from various Local Environmental Plans and Planning Schemes.

3. Sampling of plots

Following the i-Tree Eco methodology, the plot size used was 0.1 acre (0.04ha) with 20 plots in each stratum providing a total of 60 plots along the Pacific Highway corridor. Thirty plots were sampled proportionately in the three strata along the Parramatta Road corridor. These plots were randomly generated from each stratum using ArcGIS following i-Tree Eco guidelines. The sampling method was discussed with i-Tree Eco staff to further confirm the appropriateness of the method. A buffer area with a radius of 11.34 meter around the sampled plot was then generated as the plot boundary. Selection criteria for sample plots were:

- sampled plots should lie within LiDAR/Hyper spectral coverage in order to complement the data derived from the parallel analysis using remote sensing data;
- plots with no trees were discarded through cross checking and superimposition with aerial photo imagery with plot boundaries.

4. Nil/Negligible risk ethics approval

In addition, and in according to university protocols, a nil/negligible risk ethics approval from Human Research Ethics Committee (HREC) was obtained prior to conducting the field work. Before conducting the field work, consent forms for permission to access private properties for data collection were obtained via telephone, email, or other personal communication.

5. Field survey

Field work was conducted following the i-Tree Eco manual and guidelines (i-Tree, n. d.). The field crews used handheld GPS accompanied with plot maps to accurately locate the plot centres. The data was first recorded in paper form and then manually typed into the i-Tree Eco application. Tree specimens were collected and identified by the Plant Identification Service Team in the Royal Botanic Garden, Sydney.

6. i-Tree data input and analysis

A total of 332 trees (250 trees along Pacific Highway and 82 trees along Parramatta Road) across 91 plots along the two corridors were surveyed between July to December in 2012. Field data were incorporated in i-Tree Eco data input system and submitted for analysis to the USDA.

7. LiDAR methodology

In parallel with the data collection according to the i-Tree Eco manual an aerial survey was conducted along the same routes. The aerial survey collected LiDAR point clouds for the study area and hyperspectral data. The data were then processed by building digital surface models (DSMs) from LiDAR points digitising the buildings and identifying evergreen and deciduous species using the hyperspectral data. Then the DSMs with trees, evergreen trees and no trees were produced for potential solar radiation analysis. This process was to enable a more precise understanding of the impact of shading of the trees on surrounding buildings.

Results

This research produced important results that are presented below (see Table 1). First, comparisons are presented of the urban forest structure and composition for the two highway corridors. Second, specific results relating to each method are presented, leading to a discussion and conclusions about urban forestry and its relationship to urban amenity and the ability to contribute to important issues such as climate change adaptation.

Table 1: Comparison of the i-Tree Eco results for both sites

Items	Pacific Highway (19 km sample length)	Parramatta Road (11 km sample length)	Effectiveness of a single tree on average on the Pac Hwy compared to Parr Rd* (as a multiple)*
Number of trees	30,500	9,580	N/A
Tree cover	40.3%	14.2%	N/A
Top three most common species**	1.*Syagrus romanzoffiana* (Queen palm) (10.5%) 2.Camellia reticulata (9.8%) 3.*Eucalyptus saligna* (Sydney blue gum) (9.2%)	1.*Eucalyptus paniculata* (Gray ironbark) (14.0%) 2.*Callistemon viminalis* (Weeping bottlebrush) (9.8%) 3.*Eucalyptus microcorys* (Australian tallowwood) (9.7%)	N/A
Pollution removal	11 tonnes/year (A$5.22 thousand/year)	2 tonnes/year (A$857/year)	1.7
Carbon storage	71,700 tonnes (A$1.65 million)	22,600 tonnes (A$520 thousand)	1.0
Carbon sequestration	1,220 tonnes/year (A$28.0 thousand/year)	573 tonnes/year (A$13.2 thousand/year)	0.7
Oxygen production	2,120 tonnes/year	1,060 tonnes/year	0.6
Building energy savings	A$55.7 thousand/year	A$3.49 thousand/year	5.0
Avoided carbon emissions	A$8.85 thousand/year	A$547/year	5.0
Structural values	A$640 million	A$206 million	1.0
* The multiplier was calculated by dividing the results for the Pacific Highway and the Parramatta Road by each of their estimated number of trees and then dividing the result for the Pacific Highway by that for the Parramatta Road. This allows the comparison of			

the average individual effectiveness of a single tree in removing pollution removal and other factors. Where the number is >1 the Pacific Highway tree is more effective. Where it is <1 the Parramatta Road tree is more effective.
** In both sample sites 'Other' trees constituted the highest proportion of trees with Pacific Highway at 44% and Parramatta Road at 28%

- Carbon storage: the amount of carbon bound up in the above-ground and below-ground parts of woody vegetation
- Carbon sequestration: the removal of carbon dioxide from the air by plants
- Carbon storage and carbon sequestration values are calculated based on A$23 per tonne.
- Structural value: value based on the physical resource itself (e.g., the cost of having to replace a tree with a similar tree)
- Pollution removal value is calculated based on the prices of A$23 per tonne (carbon monoxide), A$673 per tonne (Ozone), A$673 per tonne (nitrogen dioxide), A$471 per tonne (sulfur dioxide), A$185 per tonne (PM10)
- Energy saving value is calculated based on the prices of A$37.3 per MWH and A$2.97 per MBTU **(i-Tree, n. d.)**

Urban forest structure and composition

An initial comparison of both sites in Table 1 illustrates that the Pacific Highway has a much larger coverage of trees when compared to Parramatta Road (40.3% versus 14.2%). This means that at a basic road or kilometre by kilometre comparison, the Pacific Highway performs better. While it is always desirable to have more trees, the urban forest along the Pacific Highway corridor is also adding more value per tree than for its Parramatta Road counterparts across most factors. It is in the areas of pollution removal and building energy savings (and therefore avoided carbon emissions) where the biggest differences between both sites are seen. The trees along the Pacific Highway are 1.7 times more effective at removing pollution when compared to those along the Parramatta Road. Building energy savings are 5 times higher for the Pacific Highway than for the Parramatta Road. On the other hand, a single tree along Parramatta Road is (1/0.7= 1.4) times more effective at sequestering carbon than a tree along Pacific Highway. The value for oxygen production is very low, so this has been discounted.

A large amount of data is produced from the i-Tree software which can also show differences between both sites. Firstly, the most prevalent species along the Pacific Highway is *Syagrus romanzoffiana* (Queen Palm) which typically has a sparse canopy. The i-Tree Eco model however calibrates the importance of this tree by adding the percent leaf area and the species percentage. This means that trees, such as the third most prevalent species *Eucalyptus saligna* (Sydney Blue Gum), which are larger and have a denser canopy and a higher leaf area contribute proportionately more to pollution removal and building energy savings. Saunders et al. (2011) also note the importance of the leaf area index in contributing to the importance of a tree species, as shown by the UFORE model. In their study they found that *Araucaria heterophylla* (Norfolk Island Pine) and other species with small needle like leaves were most effective at removing pollution.

In general the institutional, recreational and other (IRO) land uses are where the largest density of trees are found (112 tree/ha for Pacific Highway and 92 tree/ha for Parramatta Road). It is in these schools, parks and other open spaces such as hospital grounds where trees are able to flourish and where a large amount of control can be exerted on planting and maintenance by governmental authorities. Along the more urbanised Parramatta Road corridor, trees on IRO lands constitute islands of native vegetation. Along the Parramatta Road corridor, the IRO tree density is significantly higher than for residential land uses (92 tree/ha compared with 42 trees/ha residential), whereas along the Pacific Highway the residential tree density is comparable to the IRO tree density (110 tree/ha).These numbers point to where the trees are planted along both roads: predominantly on residential and IRO land uses on the Pacific Highway corridor, predominantly on the IRO land use on the Parramatta corridor. A consideration of the land use is important since this will affect the overall management of the urban forest canopy.

Implications for State and local government from the i-Tree Eco analysis

The results point to some areas where the local governments can take action along both sample sites. Firstly, along the Pacific Highway corridor, given the significant role that communities have to play in urban forests, the data from this study can be used to inform and educate the population about the value of vegetation. Comparisons between the studied species can be used to highlight preferred species based on attributes such as carbon sequestration, pollution removal and provision of shade through a greater leaf area. Secondly, along the Parramatta Road corridor there is a clear need to recognise the importance that institutional and recreational open spaces provide as sites for growing trees. The benefits of urban forest cover are mainly located on these land uses.

In 2012 the NSW State government released the 'State Infrastructure Strategy' for NSW (Infrastructure NSW, 2012). One of the areas targeted for redevelopment is the Parramatta Road, which is planned to be redeveloped as 'WestConnex', an extension of the M4 motorway which will connect with M5 East via the Sydney International Airport. The report describes WestConnex as 'more than a motorway. It is a scheme designed to act as a catalyst to renew and transform the parts of Sydney through which it passes' (Infrastructure NSW, 2012, 88). Much of the 'Design Considerations' in the plan are devoted to justifying the proposed design of a 'slot-road' which is a cheaper alternative to a tunnel. However the proposal includes a sketch of this slot-road with a large amount of greenery and planting buffering a projected corridor of high-density buildings from the pollution and noise of the motorway (Infrastructure NSW, 2012, 89). Given the controversy that the 'State Infrastructure Strategy' generated on its release it is debatable whether or which parts of WestConnex will eventually see the light. However the present study provides a basic understanding of the value of the greenery along the Parramatta Road and proposes the Pacific Highway to act as a potential benchmark for this development, with i-Tree being used as a guide for offsetting some of the effects of the slot road enabling it to reach vaunted goal as a catalyst for re-development.

LiDAR and hyperspectral data preliminary results

Given the importance of the energy savings that urban forests can deliver through shading, LiDAR Data was used to calculate more precisely the impact of shading from the trees in winter (21 June) and summer (21 December) when compared with the i-Tree model (see Figure 2).

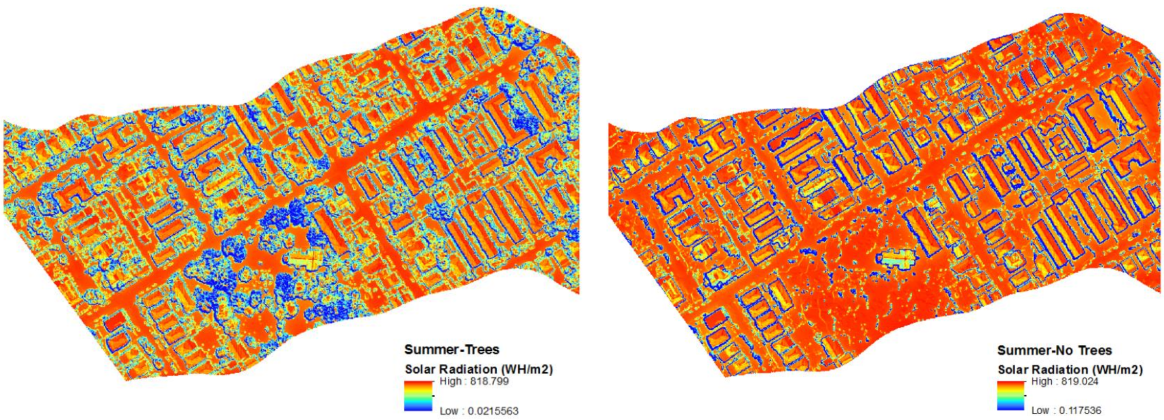

Figure 2: Preliminary results showing the effect of tree shading on two sample sites along the Pacific Highway corridor. Prepared by M. Wang, Macquarie University

Figure 2 and Table 2 present preliminary LiDAR data.. According to this small sample site the trees can reduce the incident solar radiation by 20% across the entire study area and by 8.6% across building roofs. These figures indicate that it is possible to calculate the impact of such a reduction in incident solar radiation on building energy saving.

Table 2: Difference in the solar radiation calculated from the LiDAR (Figure 2)

	Summer Solar Radiation (All figures in $WHm^{-2}day^{-1}$)*		
	No Trees	**Trees**	**Decrease of potential solar**

			radiation
Whole Study Areas	4627	3676	951
Building Roof Areas	4881	4459	422
	Winter Solar Radiation (All figures in $WHm^{-2}day^{-1}$)		
	No Trees	**Trees**	**Decrease of potential solar radiation**
Whole Study Areas	980	707	273
Building Roof Areas	1154	1006	148

***$WHm^{-2}day^{-1}$: Watt Hours per metre square per day. The number of watt-hours that accumulate over the course of a day hitting a surface of 1 m^{-2}. A heater typically uses 1000 watts in one hour of use.**

Discussion and Conclusions

These results illustrate the impacts that urban trees can have on urban amenity. The i-Tree Eco survey provides some clear indications of differences between two major highways in Sydney in terms of the pollution removal by trees and building energy savings. It is important to note some of the reasons why the site selection is likely to underestimate these figures. Firstly, i-Tree Eco pollution removal figures are based on the background pollution source. However with the trees being located along two major highway corridors it is possible that the value generated by the pollution removal was significantly higher.

The most striking differences between the two sites is shown in the building energy savings. Here we propose a way that LiDAR can be used to provide a way of understanding why these differences exist through a detailed analysis of the buildings along both roads and the amount of shade that the trees offer.

Further detailed analysis is required to explore the differences between both sites and provide guidelines for LGAs in planting, maintenance and community education. In addition, research on the social and cultural factors that determine different tree planting will also inform the reasons for the differences between both sampling locations. The significant differences between the benefits generated by the trees in these two case studies that were observed in relation to carbon uptake, storage and release potential are dependent on various tree and shrub variables (e.g. crown height, crown diameter and diameter at breast height), age, species, total tree canopy cover and quality of the environment. Appropriate planning policies and urban tree strategies will therefore be essential for efficient planning and maintenance of these urban areas in the future.

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Appendix D - Abstract for Natural Resources Forum Paper

Urban forest corridors in Australia: Policy, management and technology

Authors: M-Z Wang and J.R. Merrick

Abstract:

This paper demonstrates the importance of the remaining urban forests, and the related policy and management issues, by reviewing the current situation in Sydney, Australia. Transport corridor vegetation surveys are used to show challenges and implications for the future.

The process of medium to long-term policy formulation, with initial management strategy development at the local level, is outlined. This study also addresses the increasing need for integration with other urban issues, including the existing general urban forest strategies. The benefits of using active remote sensing technologies are illustrated by using light detection and ranging (LiDAR) data to generate a high resolution, 3-dimensional surface model.

Among the major transport corridors in the Sydney metropolitan area, segments of two long-established main roads were selected for detailed studies of the roadside forest resource. Data analysis indicated that roadside trees are very diverse and distributed in a patchy way. Some areas are treeless and some have dense stands. The results also showed high variability in species composition between local areas, with canopy cover and shading varying widely. We identify a number of issues and lessons from conservation, pollution and socio-economic perspectives, which have broader applications, and relate these findings back to policies and planning.

Keywords: Essential corridor networks; conservation implications; policy development; remote sensing; roadside vegetation; field management resources, LiDAR; urban forests.

Appendix E - Abstract for the XXIV IUFRO World Congress

Improving urban forest management using remote sensing technologies along major transport corridors in Sydney, Australia

Authors: Mingzhu Wang (Presenting Author), John R. Merrick, Hsing-Chung Chang

Department of Environment and Geography, Faculty of Science, Macquarie University, North Ryde, NSW, 2109, Australia. *Email address*: mingzhu.wang@students.mq.edu.au

Key Words: LiDAR, Hyperspectral imagery, Solar Radiation Model, Tree Features, Urban Forest Sub-systems

Abstract: With global warming and extensive urbanization, it is essential to refine urban forest management models for larger areas, which retain the capacity for detailed monitoring of forest variability at very small, local levels. In Sydney, the effect of urban forest on surrounding areas is not clearly documented. This study aims to investigate trees along two long-established transport corridors in the Sydney Metropolitan Area, using light detection and ranging (LiDAR) and Hyperspectral Imaging sensors. Integrating the two remote sensing technologies permitted rapid assessment of tree features including diversity of tree species, overall distributions and canopy parameters, even in small, inaccessible areas. Incorporating the same data in seasonal solar radiation models allowed shading analysis, which demonstrated the local variation of received radiation in the presence of trees and the respective contributions of evergreen and deciduous species. The shading impacts were significantly related to adjacent forest features. These studies highlighted the importance of trees around buildings and larger, taller trees that provided extensive shading. Remote sensing technologies can be used to indicate ways of planning shading and improving management and connectivity of all urban forest sub-systems. The basic management framework also allows inclusion of diverse data from multiple resources to enhance government decision-making.