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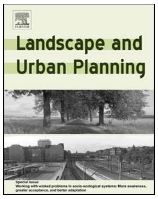

Research Paper

The influence of climate and drought on urban tree growth in southeast Australia and the implications for future growth under climate change

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ABSTRACT

The recent decline in the health of the City of Melbourne's deciduous tree species to a recent drought event has led to concerns about the vulnerability of the city's trees to future climate change. Understanding the response of tree growth to past climate is critical for determining the likely impacts of climate change on future growth and can provide insights into the suitability of current species to future climates. We used dendrochronological approaches to determine the relationships between climate and tree radial growth for common deciduous tree species in Melbourne's urban forest. Chronologies were successfully developed for *Quercus robur*, *Ulmus procera*, *Ulmus* L. and *Platanus acerifolia* with all found to be sensitive to past climatic variability. All four species showed radial growth in a given year was negatively impacted by arid conditions in the previous autumn and arid conditions in the spring orearly summer of that year. Interspecific differences in climate – growth relationships, consistent with xylem anatomy trait differences (ring vs. diffuse porous), were observed. Successive years of drought had a significant negative influence on radial tree growth. Future climate change scenario testing suggested that a shift towards a warmer, drier climate would exacerbate declines in radial growth, and thereby health, highlighting that the studied species are vulnerable to climate change. From a planning perspective, a balance between (a) conserving these vulnerable tree species through proactive management; and, (b) planting more drought and heat tolerant species is likely the best approach towards adapting Melbourne's urban forest to climate change.

1. Introduction

Urban trees are silent assets within our cities as they provide social, health, economic, and environmental benefits (Moore, 2013). Urban trees provide multiple services that include: aesthetics, amenity, air pollution mitigation, climate amelioration, stormwater interception and use, carbon sequestration, noise reduction, habitat for fauna and flora, medical and health benefits, recreational, contact with nature, increased property values, and cultural, heritage, social and psychological benefits (Coutts, White, Tapper, Beringer, & Livesley, 2016; Dobbs, Kendal, & Nitschke, 2013; Jim, 2004; May, Livesley, & Shears, 2013; Moore, 2013; Sæbø et al., 2012; Sanusi, Johnstone, May, & Livesley, 2016; Scharenbroch, Morgenroth, & Maule, 2016; Tyrväinen, 1997). The composition of an urban forest (all trees within a municipality) is influenced by the geography, climate, urban development history and society cultural norms (Jim, 2004; Jim & Liu, 2001). The interplay between these factors has created a broad spectrum of urban forest characteristics that comprise exotic and native trees planted within highly urbanized and modified city centres, to streetscapes in suburban areas, to parks and reserves of more natural habitat (Jim, 2004; Jim & Liu, 2001; White, Antos, Fitzsimons, & Plamer, 2005). The structure and composition of urban forests, in turn, exerts a strong influence on environmental quality and the provisioning of the aforementioned ecosystem services (Dobbs et al., 2013).

Concerns over the impacts of climate change on urban trees is increasing due to the observed decline in the health and vitality of natural forests in a variety of biomes around the globe that have been associated with drought events and high temperatures (Allen et al., 2010; Allen, Breshears, & McDowell, 2015). Recent cases of drought induced forest decline have been reported in the Mediterranean Basin (Girard et al., 2012), Central Europe (Dolezal, Mazurek, & Klimesova, 2010), tropical forests in Ghana (Fauset et al., 2012) and south-western Australia (Matusick, Ruthrof, Brouwers, Dell, & Hardy, 2013). Tree decline is not limited to natural forests, but has also occurred in urban

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landscapes (Gillner, Braüning, & Roloff, 2014). Drought induced tree health decline and mortality has been reported in Melbourne, Australia (May et al., 2013) and Helsinki, Finland (Helama, Läänelaid, Raisio, & Tuomenvirta, 2009, [Helama et al., 2012]2012). Drought can be viewed as an inciting factor (Manion, 1981) that generates adverse growth conditions and a loss of vitality that can make the tree(s) susceptible to secondary stressors; such as pest and pathogens, which concurrently can lead to mortality in both natural and urban forest situations (Gillner, Vogt, & Roloff, 2013; Pedersen, 1998). Our current understanding of the future impacts of climate change on the growth and mortality of urban trees is sparse which limits the ability of urban forest managers to develop adaptive management practices (May et al., 2013). An increased understanding of the response of common urban tree species to extreme climate change and variation is critical for sustainably managing and planning our urban forests (Gillner et al., 2013).

Variability in southeast (SE) Australia's climate can be extreme and environmental changes of similar or even greater magnitude are expected in the coming decades (Hennessy et al., 2007). Projections by the Intergovernmental Panel on Climate Change (IPCC) for SE Australia predict increases in mean annual temperatures ranging from 0.6 to 0.7 °C by 2020 and from 0.9 to 3.7 °C by the 2080s, with a concurrent 1–18% decline in annual precipitation (CSIRO and Bureau of Meteorology, 2015). These forecasts suggest that SE Australia will encounter more frequent and intense droughts in summer (Hennessy et al., 2007) that could detrimentally effect tree growth (Allen et al., 2010, 2015). The degree of predicted climate change suggests that it is likely that many tree species in Melbourne may find themselves in a climate that exceeds their environmental tolerances, which will have implications for their growth and vitality. The Millennium drought (1998–2010) left the City of Melbourne's exotic, broad-leaved, deciduous tree species in a state of unprecedented decline (May et al., 2013; Moore et al., 2013). It has been estimated that, as a consequence of future drought events, up to 23% of the city's existing tree population may be lost within the next decade, and 39% lost in the next 20 years (City of Melbourne, 2012). This presents a challenge as European angiosperms comprise over 35% of the City of Melbourne's tree population (Dobbs et al., 2013; May et al., 2013). The European deciduous trees are amongst the oldest and largest trees in the City of Melbourne, many having been given heritage status (May et al., 2013). A future climate that selectively impacts tree health or mortality, because of species differences in susceptibility to drought or heat, could therefore alter the compositional and structural characteristics of Melbourne's urban forest, which in turn could affect ecosystem services and benefits (Moore, 2013). It also could have conservation implications for *Ulmus* species as the ∼6500 elms in the City of Melbourne have never been affected by Dutch elm disease (*Ophiostoma* spp.) which has devastated *Ulmus* populations around the world.

Tree rings are commonly examined to investigate the extent of environmental and climatic influences respectively on the radial growth of trees (Fritts, 1976, 2001; Rozas, Lamas, & García-González, 2009). Dendrochronological analyses can also be used to determine the importance of climatic variables on observed changes in tree health (Helama et al., 2012). In Australia, many native tree species are evergreen and grow opportunistically in response to favourable conditions, which limits the use of traditional dendrochronology approaches (Heinrich & Allen, 2013). However, many Australian cities contain large tree populations of Northern Hemisphere deciduous species, which typically produce distinct annual growth rings. The mix of exotic, deciduous species planted in Australian cities comprises both ring-porous and diffuse-porous species. Differences in wood anatomy between tree species can lead to differential responses of radial growth to climate and vulnerability to drought (Bush et al., 2008; Gillner et al., 2014; Michelot, Bréda, Damesin, & Dufrêne, 2012; Michelot, Simard, Rathgeber, Dufrene, & Damesin, 2012).

Dendrochronology has been increasingly used in an urban forest context across North America, China, Europe and South America to detect changes in air quality over time and space (Battipaglia et al., 2010; Chen et al., 2011a; Djuricin, Xu, & Pataki, 2012; Dongarra & Varrica, 2002; Doucet et al., 2012; Ragsdale & Berish, 1988; Sirito de Vives, Moreira, Boscolo Brienza, Zucchi, & Filho, 2006; Watmough & Hutchinson, 2003). To a lesser extent dendrochronology has been utilised to determine the role that climate may have on urban tree growth and health with a handful of studies looking at urban tree health and decline (Bednarz & Scheffler 2008; Catton, George, & Remphrey, 2007; Helama et al., 2009, 2012) or at climate-growth relationships (Bartens, Grissino-Mayer, & Day, 2012; Chen et al., 2011a, 2011b; Gillner et al., 2013, 2014; He et al., 2007; Moser, Rötzer, Pauleit, & Pretzsch, 2016). One of the reasons why so few studies have been conducted in urban areas is that urban environmental stresses, not related to climatic variation, can confound the dendrochronology approach (Bartens et al., 2012). For example; trees in urban areas are exposed to many pollutants and higher temperatures compared to those in non-urban areas which can have positive or negative influences on tree growth (Gregg, Jones, & Dawson, 2003). The relationship between tree growth and climate can also change in comparison to relationships that exist in adjacent rural or peri-urban areas (Chen et al., 2011a; Gillner et al., 2013). Chen et al. (2011a) also highlighted that availability and access to suitable samples has limited the application of this technique. Despite these limitations, urban trees can provide valuable information on the impact of climate on tree growth (Bartens et al., 2012; Gillner et al., 2013). The response of urban tree growth to climate could increase our understanding of the future impact of climate change on species growing in natural or managed forest areas as enhanced temperatures in urban centres, due to the urban heat island effect, already elevate temperatures by 3.5–4.5 °C over those observed in surrounding rural areas (Coburn, 2009; Farrell, Szota, & Arndt, 2015). Conversely, the predicted response of species growing in non-urban areas may underestimate the vulnerability of urban trees in a region due to the urban heat island effect (Farrell et al., 2015) which is predicted to intensify under climate change (Coburn, 2009).

Understanding the vulnerabilities of forests, and the tree species that constitute them, to climate is important for managing the risks and uncertainty associated with climatic change (Nitschke & Innes, 2008). Identifying the vulnerability of tree species is therefore a critical step for sustainably managing and planning our urban forests (Gillner et al., 2013). Quantifying the response of tree growth to past climate variability is a crucial first step towards defining vulnerability to future climates (Michelot, Bréda et al., 2012) and will therefore provide critical knowledge to urban planners and forest managers on management actions required to integrate mitigation and adaptation strategies into long-term planning (Nitschke & Innes, 2008). The aim of this research is to quantify of the role of climate, particularly drought, on tree growth and then to use this understanding to determine the vulnerability of tree species to climate change. The outcomes of this study will provide guidance to the City of Melbourne's planning efforts to adapt their urban forest to climate change. To achieve this aim we specifically seek to (1) quantify climate – radial growth relationships for key deciduous European tree species in Melbourne's urban forest; (2) determine the role of drought on radial growth patterns; and, (3) analyse the vulnerability of the studied tree species to climate change.

2. Methods

2.1. Species selection

In this study, tree ring samples were obtained from five deciduous European tree species that make up a significant proportion of the City of Melbourne's parklands and streetscape tree plantings (Dobbs et al., 2013). The sampled species included: London planes (*Platanus acerifolia* (Ait.) Willd), English elm (*Ulmus procera* Salisb.), green leaf elm (*Ulmus*