Arboriculture & Urban Forestry 2020. 46(2):135–147

ARBORICULTURE & URBAN FORESTRY
Scientific Journal of the International Society of Arboriculture

The Effect of a Heat Wave on Urban Tree Pests in Melbourne, Australia: Examples that May Inform Climate Change Tree Management

By G.M. Moore and G. Lefoe

Abstract. Climate change will have profound deleterious effects on many trees in urban environments; however, as in any biological system undergoing change, there will be benefits. On 7 February 2009, the Australian city of Melbourne experienced its hottest day on record (46.4 °C [115.5 °F]) after a heat wave. In the days that followed, the foliage of native Australian mistletoes, *Amyema miquelii* and *A. pendula*, growing on *Eucalyptus camaldulensis* were observed to lose their green color and turn gray. In large numbers, the mistletoes can cause significant stress, leading to tree death. In the aftermath of the record hot day, large numbers of mistletoes died, and 5 years later the level of mistletoe infestation remained low. On the afternoon of 7 February 2009, tens of thousands of elm leaf beetles, which heavily graze the mature elms of Melbourne (*Ulmus procera* and *U.* × *hollandica*), were found dead under the canopies of street trees, and numbers remained low for at least 5 years thereafter. Similarly, psyllids, *Mycopsylla fici*, and infestations of *Ficus macrophylla*, which can seriously defoliate trees, fell from high to undetectable levels in the month following the heat wave. The effects of heat waves and very high temperature days have significant implications for those managing pests in urban forests. Pest control programs were unnecessary in the immediate aftermath of the heat wave and hot days and for up to 5 subsequent years. This has positive implications for tight tree management budgets, but could also lead to a discontinuation of pest monitoring and control programs. Such an approach could see a return to high levels of infestation.

Keywords. *Amyema miquelii*; Elm Leaf Beetle; *Eucalyptus camaldulensis*; *Ficus macrophylla*; High Temperatures; Mistletoe; *Mycopsylla fici*; *Ulmus*.

INTRODUCTION

There is a paucity of information on the effect of extreme weather events, such as heat waves and very hot days, on urban tree populations (Jentsch et al. 2007). Burrows defined a "hot wave" as a spell of three or more days on each of which the maximum shade temperature reached or exceeded 90 °F (32.2 °C)(Glickman 2000), but the Australian Bureau of Meteorology defines a heat wave as three or more days of unusually high maximum and minimum temperatures in any area (Bureau of Meteorology 2016). Under climate change, the frequency and magnitude of heat waves and hot days is predicted to rise in Melbourne, with the number of hot days (> 35 °C) and very hot days (> 40 °C) predicted to double by 2050 and almost triple by 2070 (Commissioner for Environmental Sustainability 2012). Tree managers will have to plan for a warmer, drier climate and consider the impact of extreme weather events on tree health and pest and disease management.

The urban heat island (UHI) effect causes higher temperatures in large cities than in the surrounding countryside, and could favor the development of ectotherms such as insects (Meineke et al. 2013). However, pest insect abundance varies with the patchiness of the UHIs, which adds greater uncertainty for urban tree managers already dealing with climatic uncertainty (Bennett and Gratton 2012; Meineke et al. 2013). Climate change will affect urban forests and street trees and while there will be adverse effects, there will also be benefits (Grace et al. 2002; Salzer et al. 2009; Yang 2009; Nathan et al. 2011; Kendal and McDonnell 2014; Kendal et al. 2014; Brandt et al. 2016; Pretzsch et al. 2017). The challenge for those managing urban forests is to reduce the negative impacts of uncertainty on effective management (Kendal et al. 2014; McPherson et al. 2018).

There are 91 Australian hemi-parasitic mistletoes (mostly Loranthaceae). Many have evolved host mimicry (crypsis) where their foliage resembles the host's (Watson 2011), so they often go unnoticed by those managing trees. They are water and nutrient parasites (Calder and Bernhardt 1983; Davidson et al. 1989; Watson 2011), and in large numbers can compromise the host tree's vigor when branches beyond the point of mistletoe attachment die back, particularly on older trees and in drier seasons (Knutson 1983). When there are greater than 20 mistletoes per tree, both the growth rate and flowering of the host are reduced (Watson 2011). *Eucalyptus camaldulensis* Dehnh. (river red gum) is a single-trunked eucalypt between 12 and 40 m tall and is widely distributed across Australia (Boland et al. 1984; Nicolle 2006). The period 1999 to 2010 was a period of below average rainfall for southeastern Australia (Bureau of Meteorology 2011) and many remnant river red gums heavily infested with native mistletoes (40 to 50 parasites) died. The mistletoes (*Amyema miquelii* Lehm. ex Miq. Tiegh. and *A. pendula* Sieber ex Spreng. Tiegh.) are native species important in the ecology of plant communities and to native bird and insect species (Calder and Bernhardt 1983; Watson 2011; Moore 2018).

Large English (*Ulmus. procera* Salisb.) and Dutch (*U.* × *hollandica* Mill) elms make a significant contribution to the landscapes of Melbourne, where the avenues are among the finest in the world, as Australia is Dutch Elm Disease free (Moore 1990; Dunn 2000). *U. procera* and *U* × *hollandica* are heavily grazed by the elm leaf beetle (ELB), *Xanthogaleruca* (=*Pyrrhalta*) *luteola* (Muller)(Kwong and Lefoe 1998; Miller 2000; Lefoe et al. 2014). There is usually one life cycle of ELB per season in Melbourne, but there may be two. Infestations are sublethal, but trees suffer major foliage damage by the end of summer, which impacts on their appearance. The life cycle of the ELB is influenced by temperature and grazing occurs earlier and to a higher level under warmer conditions. Peak egg laying occurs at 289 degree-days (DD), peak first instar at 400 DD, and third instar larvae at 551 DD (Dreistadt et al. 1991; Dahlsten et al. 1993; Lawson and Dahlsten 2003; Lefoe et al. 2014). The late instar larvae begin their trunk assent at 500 DD. In Melbourne, egg laying occurs in mid-November, first instar peaks in very late November/early December, and the third instar larvae peak from mid-December to Christmas day (Lefoe et al. 2014). When the value of accumulated DD exceeded 380, effective chemical control with imidacloprid (0.125 g/L) was undertaken (Kwong and Lefoe 1998).

The City of Melbourne manages 568 Moreton Bay fig trees, *Ficus macrophylla* Desf. ex Pers. A native in the states of New South Wales and Queensland up to 50 m tall, with a large flanged and buttressed trunk, it is widely planted in other Australian states and has been planted in Hawaii and New Zealand (Boland et al. 1984). The figs are threatened by the psyllid, *Mycopsylla fici* (Tryon 1895), which defoliates trees, impacting on their health and amenity value by depleting nutrients, potentially vectoring pathogens, and causing early leaf fall. The psyllids form a protective shell-like structure from crystallized honeydew called a lerp. Some trees suffer complete defoliation but damage to that extent is rare in Melbourne (Fromont et al. 2015). Higher temperatures are drivers of higher psyllid numbers (Hall et al. 2015). The pattern of fig psyllid infestation in Melbourne sees a rapid rise in adult numbers from less than 10 to 50 to 90 per leaf in one or two weeks with a peak in late-December or January. Infestation levels on Melbourne's Moreton Bay figs have been determined by randomly sampling a proportion of trees within sites since 2004, and control with imidacloprid (0.125 g/L) effectively targeted sites with unacceptable damage (Honan and McArthur 1998).

The occurrence of heat waves and record daily high temperature days in Melbourne, Australia, in January and early February 2009 afforded an opportunity to investigate their impact on urban trees and pests in Melbourne. During this period, a heat wave culminating on 7 February with a record temperature of 46.4 °C (115.5 °F) in Melbourne (Figure 1) resulted in the infamous Black Saturday bushfires that killed 173 people and in another 374 heat wave-related deaths. The impact of these heat waves and very high temperature days on the infestations of native mistletoes on a eucalypt species, the grazing of elm leaf beetle (ELB) on elms, and psyllid infestations of Moreton Bay figs have significance for the management of the urban forest in Melbourne. An article in *Arborist News* reported on some aspects of these impacts using smaller and different data sets (Moore 2018), but this paper reports greater detail of these impacts that were detected through observation by arborists and by structured sampling, which detected changes in pest populations that had not been

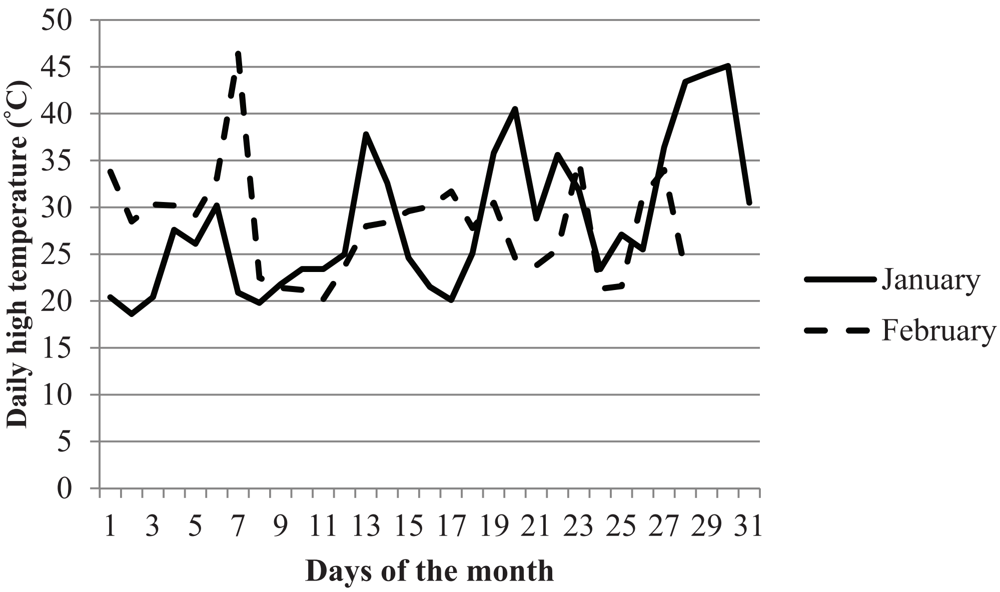

Figure 1. Maximum daily temperatures in Melbourne, Australia, during the heat waves of 2009 that culminated in the hottest day on record (Bureau of Meteorology 2016).

anticipated prior to the extreme weather. There were significant financial consequences of these events for urban tree managers, which may be long-lasting.

MATERIALS AND METHODS

Mistletoe and River Red Gums

In 2008, it had been noticed that mistletoe numbers on some of the older *Eucalyptus camaldulensis* trees were increasing as the long dry period that had commenced in 1999 continued. Forty-six specimens growing along the Maribyrnong River, Brimbank Park, west of the City of Melbourne in Victoria, Australia, chosen at random from three age classes were surveyed in what was intended to be a long-term study of mistletoe numbers. Mature, older trees were defined as large trees > 20 m height with a diameter at breast height (dbh) > 40 cm, semi-mature trees were defined as those < 15 m height and with 20 cm < dbh < 40 cm, and young trees were defined as trees < 10 m in height and with dbh < 20 cm. Twenty-five young trees, ten semi-mature trees, and eleven mature specimens were surveyed in the spring (October) of 2008. All mistletoe counts were taken from ground level.

In the week following the very hot day, 7 February 2009, it was observed that the color of the foliage of many mistletoes had changed as the leaves dried and started to die. Consequently, the same 46 trees were surveyed for living and dead mistletoes on 9 March 2009. Given the significant number of dead mistletoes that were recorded, another survey was undertaken on 9 September 2011 and a final survey was undertaken on 12 February 2014, five years after the record hot day and heat wave.

As data from these surveys were collected, it became clear that the extreme weather had affected mistletoe numbers and so a further survey was undertaken in other parts of Melbourne and of other host species. Some 300 trees from 6 different locations and 20 species were surveyed in the spring (September) of 2011, but only six species had mistletoes present. The 129 trees that possessed mistletoes belonged to both native and exotic species. A number still had dead mistletoes present in their canopies, which were consistent with a killing date in 2009. Again, counts were taken from ground level, and given the growth rate and the size of mistletoes, it could be determined that any living mistletoes had been in the canopy on 7 February 2009.

Elms and ELB

Agriculture Victoria Services Pty. Ltd had been collecting field data relating to ELB grazing of elms since 1999–2000. These data showed that ELB grazing normally continued until defoliation of the elms began in mid-autumn (early April). When thousands of dead ELBs were discovered below the canopies of street tree elms after 4 pm on 7 February, data were sought on the levels of ELB damage to leaves, which are indicative of ELB numbers, recorded in surveys before and after the heat event and on the subsequent level of ELB control measures undertaken in the years after the heat wave and record hot day. Data were available from the Department of Environment and Primary Industry (DEPI) and the Urban Forest Group of the Melbourne City Council for ten targeted locations: Epsom and Flemington Roads, Powlett, George and Clowes Streets, Fitzroy and Carlton Gardens, Alexandra Avenue, Royal Parade, and Fawkner Park.

At each location, ELB damage was determined using a point rating scale of the percentage of leaf damage where damage up to 10% of the leaf area removed was rated as 1, up to 20% as 2, up to 30% as 3, up to 100%, which was scored as 10. The sites were surveyed fortnightly in December 2008, and then from January until March 2009, and again from November to March in 2009/2010, 2010/2011, 2012/2013, and 2013/2014. The best estimate of the full extent of ELB grazing on tree species is made when the leaves of trees are assessed for damage after the ELBs have completed their grazing late in the growing season. For this reason, only data for late-season grazing levels are presented in this paper, as these best represent seasonal damage to trees and reflect beetle numbers that allow annual comparisons to be made. Control measures for ELBs were undertaken when a rating of 1 or more was recorded for high-profile sites and when scores exceeded 2 for less prominent sites.

Figs and Psyllids

Psyllid egg-laying in Melbourne usually occurs from late-October to early-February, with adult emergence ceasing in mid-autumn (early April)(Honan and McArthur 1998). The City of Melbourne with Agriculture Victoria Services Pty. Ltd had monitored fig psyllid infestation using protocols and sample sizes recommended by Honan and McArthur (1998). Leaf samples were examined from figs growing at 12 sites across Melbourne from 19 November 2008 through 6 March 2009. Trees within each site were selected randomly and, for each sample, branch terminals (approximately 40 cm long) were examined from the ground or by cutting with pole pruners. They were examined from varying heights (to 4 m) and distances from the trunk, and from each direction (north, south, east, and west) around the tree until 50 leaves were available for examination. The number of lerps with living nymphs beneath them on each leaf was recorded and then doubled to obtain an average number of living psyllids per 100 leaves (Honan and McArthur 1998). Control measures were recommended when an infestation level above 25 psyllids/100 leaves was recorded. Similar sampling was done in 2005 and data are presented for comparison with 2008 and 2009. Yellow sticky traps were placed in trees in Princes and Fawkner Parks to trap flying adult psyllids. Traps were checked and replaced weekly from 19 November 2008 through 6 March 2009, when they were discontinued, as no living psyllids were recorded for three successive sampling periods. The psyllid monitoring was funded to inform the Melbourne City Council's pest management program, but there was so little psyllid activity that surveys were not funded from 2010 through 2013.

The data comparing mistletoe, ELB, and psyllid infestation levels before and after 7 February 2009 did not conform to the assumption of a normal distribution and so the Mann-Whitney test was applied (White and White 1996).

RESULTS

River Red Gum and Mistletoes

The survey data on mistletoe occurrence on river red gum, *E. camaldulensis*, show that mistletoe numbers were significantly reduced after the extreme weather and subsequent occurrence rates have remained low (Table 1). Living mistletoe numbers were significantly lower 1 month and 30 months after the hot day when compared to the numbers prior to 7 February ($P < 0.01$ for both comparisons). None of the 46 surveyed eucalypts died during or after the hot day, and in the two years that followed, above average rainfall resulted in the trees refoliating and having higher density canopies. Of the 237 mistletoes present on the *E. camaldulensis* before 7 February 2009, 210 (88.6%) were killed.

The data also reveal that mistletoe numbers have continued to remain low for a period of five years ($P < 0.01$) after 7 February (Table 1) and that there was a low incidence of new mistletoe establishment, with only nine new mistletoes establishing on the trees over that period. No new mistletoes established on the young or semi-mature trees surveyed, but mature trees were susceptible to infestation (Figure 2).

Table 1. Number of mistletoes (*Amyema miquelii* and *A. pendula*) growing on *Eucalyptus camaldulensis* trees prior to, one month, 30 months, and 5 years after the heat wave and the 46.4 °C day of 7 February 2009.

Tree type	Number of trees	Number of living mistletoes prior to 7 Feb 2009	Number of living mistletoes 1 month after 7 Feb 2009	Number of new mistletoes established after 7 Feb 2009	Number of living mistletoes 30 months after 7 Feb 2009	Number of living mistletoes 5 years after 7 Feb 2009
Young trees (< 10 m height with dbh < 20 cm)	25	45	0	0	0	0
Semi-mature trees (< 15 m height with 20 < dbh < 40 cm)	10	54	0	5	5	6
Mature trees (> 20 m height with dbh > 40 cm)	11	138	27	4	26	26
Total	46	237	27	9	31	32

Mann-Whitney test results	*U*-value	*P*-value
Comparing mistletoe numbers before and one month after 7 February 2009	7.5	< 0.01
Comparing mistletoe numbers before and 30 months after 7 February 2009	6.5	< 0.01
Comparing mistletoe numbers before and 60 months after 7 February 2009	7.0	< 0.01

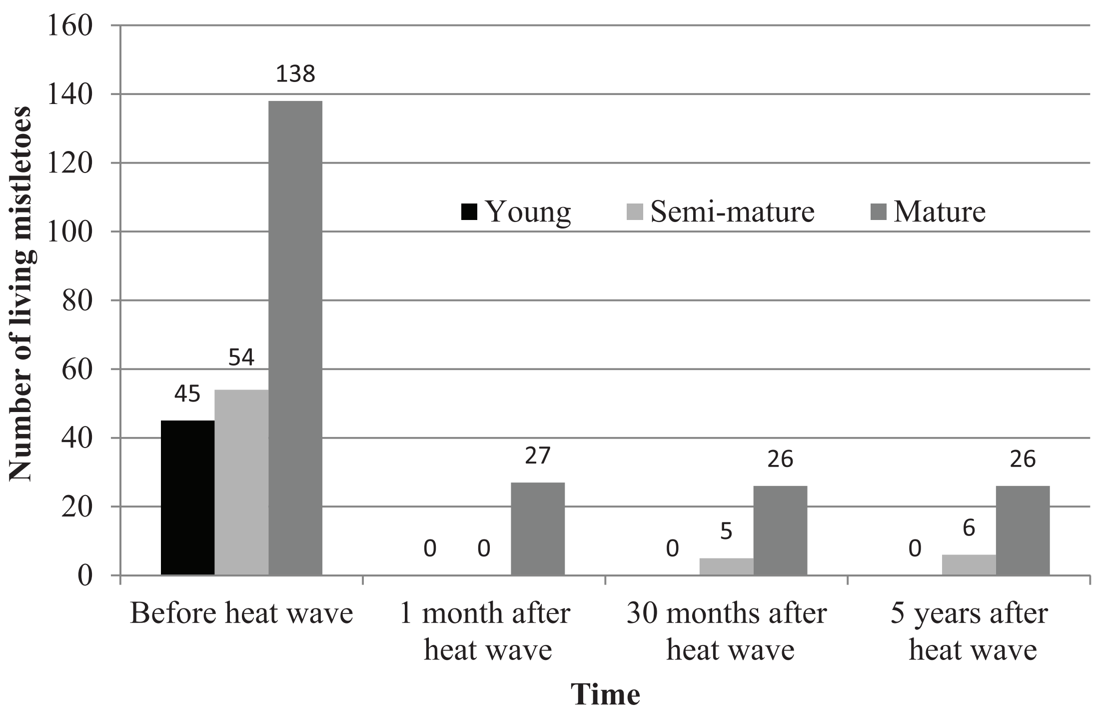

Figure 2. Living mistletoes on young, semi-mature, and mature *E. camaldulensis* trees after 7 February 2009. Standard error (SE) before 7 February for young trees (SE = 1.29) and for semi-mature trees (SE = 0.97) and after for both (SE = 0). For mature trees, before (SE = 16.45) and after (SE = 2.77).

For one mature *E. camaldulensis* specimen, 50 of the 60 mistletoes growing on it before 7 February were dead one month later. Fifty mistletoes had died after two years, fifty-five after thirty months, and after five years, the tree hosted only five mistletoes. For young specimens of *E. camaldulensis*, all mistletoes present before 7 February were killed and five years after the event, all trees remained mistletoe free. Mistletoe numbers on both native and exotic species were reduced significantly (Table 2) with 88 of 130 mistletoes (67.7%) killed ($P < 0.01$). Many specimens that had previously hosted mistletoes had lower rates of infestation or remained mistletoe free after 30 months. Only two new mistletoe plants were evident.

Elms and ELB

While the data for damage done to trees for December 2008 and January, February, and March 2009 suggest that there was some decline in leaf damage after 7 February 2009, most trees had already been grazed and suffered leaf damage and so ratings were not expected to change (Figure 3). A better comparison is to compare data from late-season damage in 2008/2009 with late-season damage in the following years. The surveys of the damage done to trees at ten different locations across Melbourne for 2008/2009, 2009/2010, 2011/2012, 2012/2013, and 2013/2014 (Figure 4) showed that ELB damage in 2009 before 7 February was significantly greater ($P < 0.01$) than at the same time of year in 2009/2010, 2010/2011, and 2012/2013. ELB damage remained so low for these three survey seasons that control measures were considered to be unnecessary, as damage ratings did not exceed 1. There was a significant rise in ELB grazing in 2013/2014 when compared with 2012/2013 ($P < 0.01$), and that grazing with this rise in 2013/2014 was not significantly different from grazing recorded in 2008/2009 ($P > 0.05$)(Figure 4).

Figs and Psyllids

The program of monitoring fig psyllids undertaken between November 2008 and March 2009 identified only two sites with high living psyllid infestation levels above 20 lerps/100 leaves and nine sites with psyllid infestation levels above 10 psyllids/100 leaves. Data for the Princes and Fawkner Park sites (Figure 5) showed that psyllid numbers fluctuated over the summer, peaking in late December and early January as expected for Melbourne but then unexpectedly plummeted to 0 after 7 February 2009. There were no living adult psyllids for either park after February 2009, which was significantly lower than numbers prior to that day ($P < 0.05$ for each park).

Table 2. Dead and living mistletoes (*Amyema miquelii* and *A. pendula*) on different hosts from four different Melbourne locations (67.7% of mistletoes were killed).

Species	Number of trees of each species	Number of living mistletoes prior to 7 Feb 2009	Number of new mistletoe plants established after 7 Feb 2009	Number of living mistletoes 30 months after 7 Feb 2009
Ulmus procera	65	49	1	19
Platanus × acerifolia	45	42	1	13
Pyrus calleryana	2	3	0	0
Allocasuarina littoralis	10	8	0	4
Quercus palustris	2	16	0	4
Eucalyptus melliodora	3	4	0	1
Eucalyptus camaldulensis	2	18	0	3
Total	129	130	2	44

Mann-Whitney test results	*U*-value	*P*-value
Comparing mistletoe numbers before and 30 months after 7 Feb 2009	22.5	< 0.01

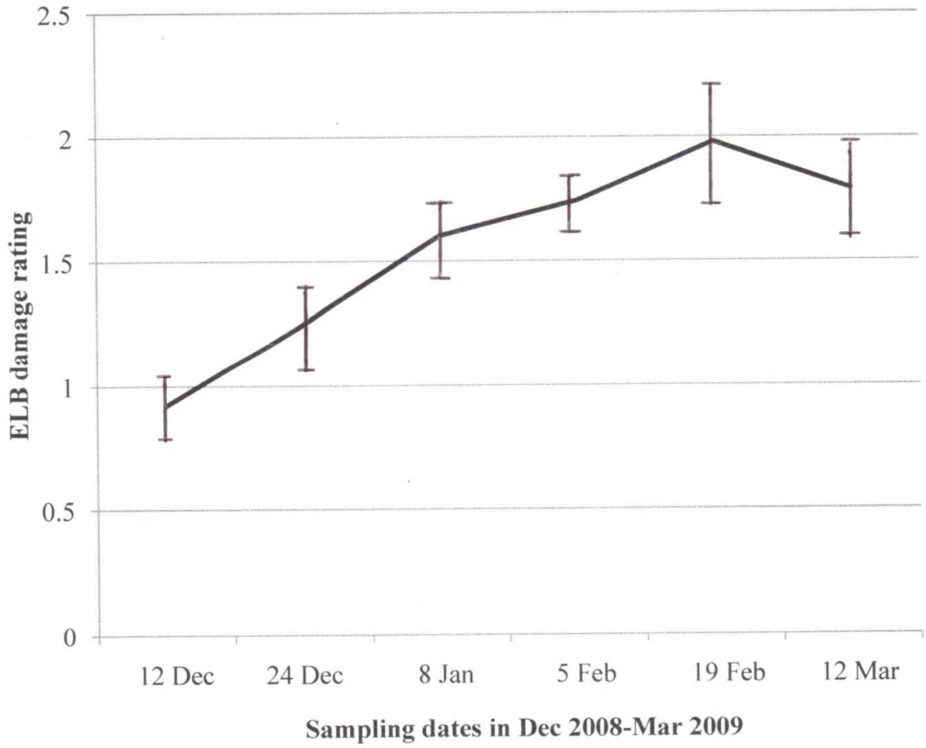

Figure 3. Average ELB damage ratings at ten sites in Melbourne, Australia, from December 2008 to March 2009. The bars show SE.

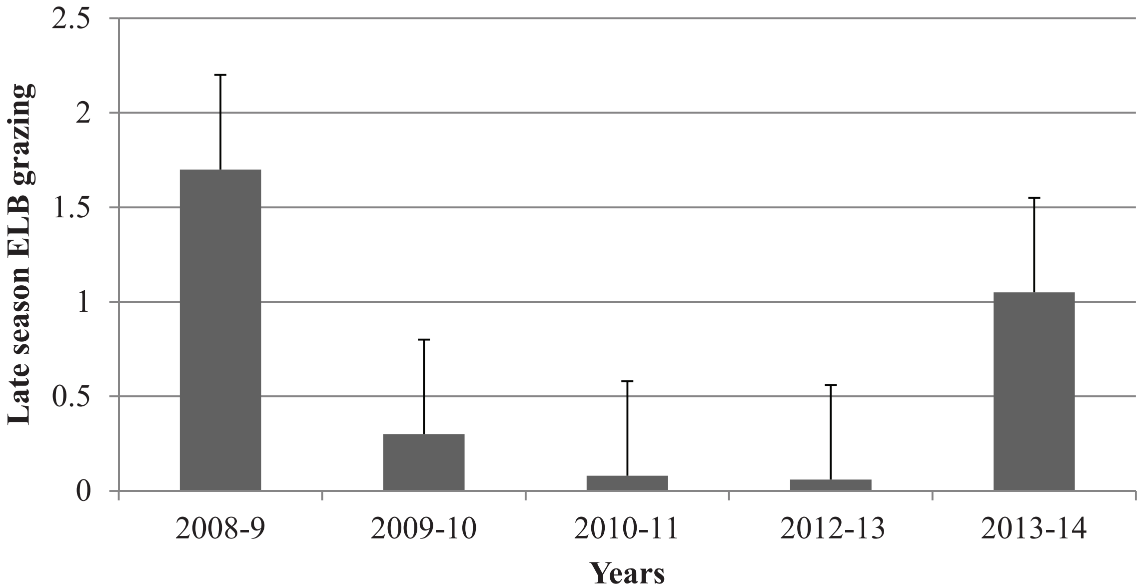

Figure 4. A comparison of average late-season (March) elm leaf beetle (ELB) damage at ten Melbourne sites from 2008/2009 to 2013/2014. The bars on columns show SE.

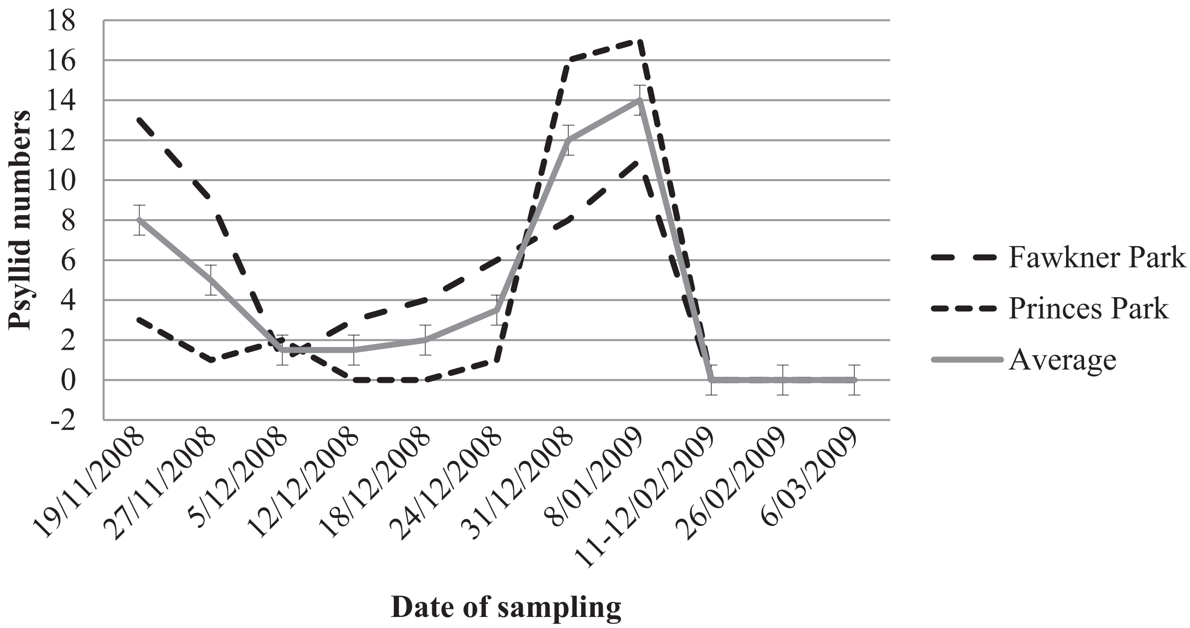

Figure 5. Comparison of adult psyllid numbers trapped on sticky traps for the period November 2008 to March 2009. A Mann-Whitney test of the number of psyllids trapped before and after 11/12 February 2009 showed a significant decrease with a *U*-value of 6.0 and $P < 0.01$. The bars on the average line show SE.

In previous seasons, such as 2004/2005, when trapping was undertaken, the number of adults recorded per trap rose quickly within 7 to 14 days, from less than 10 to a peak in late December or January of between 50 and 90 (Honan and McArthur 1998). The average number of living adult psyllids for 12 sites across Melbourne in 2008–2009 was 11.18 (SE = 1.53), compared to the 2004–2005 average of 20.90 (SE = 2.17) for the same sites. Furthermore, in contrast to earlier psyllid surveys such as in 1996/1997, 1997/1998, and 2004/2005 when adult emergence continued until surveying ceased at the end of March, during the 2008/2009 season, no large peak in adult emergence occurred. By the middle of February 2009, the absence of psyllids meant that no control measures were necessary in that year or in subsequent years to 2015 (Figure 5).

DISCUSSION

The impacts of pest species on urban trees during climate change will depend on the pest organism and may vary spatially and temporally, with some species disadvantaged while others thrive (Broadmeadow et al. 2005; Rouault et al. 2006; Danby and Hick 2007; Deutsch et al. 2008; Harsch et al. 2009; Clark et al. 2011; Kendal et al. 2012; McPherson et al. 2018). The impacts of warming on insect pest species are largely influenced by the timing of vulnerable insect life stages (Nathan et al. 2011), while in eucalypt woodlands the extent of insect herbivory depends on leaf phenology and rainfall-induced production of young leaves, which insects preferentially graze (Gherlenda et al. 2016). This paper reveals some of the impacts of heat waves and very high temperatures on pest species of urban forest tree species.

Mistletoe and River Red Gums

There is a direct xylem to xylem contact between mistletoes and their hosts that forms a continuous apoplastic connection. The parasite's transpiration rate is usually higher than the host's, but varies less with soil moisture and is primarily influenced by evaporative demand and parasite host vascular connection (Davidson et al. 1989). During periods of water stress, mistletoes show no reduction in water use and their stomatal response to water deficits is slower than that of the host (Fisher 1983). During the heat waves and the day of record high temperature, the evaporative demand would have been very high and it seemed that the mistletoe plants reached permanent wilting before host trees, which resulted in their deaths, while none of the host trees died.

There is a hormonal involvement in the response of *Amyema miquelii* and *A. pendula* and hosts, such as *E. camaldulensis*, to hot dry conditions. The host trees produce abscisic acid (ABA) in response to lowered soil moisture levels, which induces stomatal closure. It is part of a more general involvement of ABA in stress responses (Moore 1998). Mistletoes lack ABA and so their stomata remain open, which leads to wilting (Fisher 1983). The main damage caused by mistletoes to mature host trees is through their excessive transpirational water loss. The hypothesis that mistletoes wilted before their hosts is supported by the observation that nearly all of the mistletoe on the extremities of the canopy died while those that survived seemed to be on older, larger branches within the canopy, closer to the trunk.

Changes to fire regimes and the clearing of native vegetation are considered causes of increased mistletoe infestation (Liddy 1983; Jurskis et al. 2005; Bowen et al. 2009; Start 2011; Watson 2011). Heat waves and very hot days may play a role similar to fire in limiting mistletoe numbers, which could prove useful especially in urban and peri-urban areas where the occurrence of fire is rare or the risks of fire are too great to allow naturally occurring fires to burn. The surveys undertaken after Saturday, 7 February 2009 indicated that the mistletoe numbers remained low for a period of 5 years after the heat events and that establishment of new mistletoes was very low.

Elms and ELB

Warm weather, as experienced in November 2009, usually favors the growth and development of ELB larvae, increasing the potential for significant elm leaf beetle damage (Clair 1986). However, average elm leaf beetle damage remained low throughout the 2009/2010 season, despite the potential for increased damage. The large number of ELBs killed by the high temperatures on the hottest day on record in the previous summer appeared to significantly affect ELB numbers and grazing in the following year. The temperature of 46.4 °C is consistent with the general range of lethal temperatures for insects, where temperatures of 44 to 47 °C for durations ranging from a few minutes to several hours killed insects in hot air (Richcigl and Richcigl 2000). The duration over which the heat is experienced is critical to the effect that high temperatures have on insects. Insect death occurs in minutes at temperatures of 55 °C, but can take hours at temperatures of about 45 °C (Mech et al. 2018).

Grazing of elms was observed to be lower for five years following 7 February 2009. It is difficult to establish a causal relationship between the killing of ELBs and the heat waves and high temperature, as there may have been confounding effects. However, there is little doubt that the large number of ELBs killed during the heat wave and on the record hot day contributed to reduced grazing in the following spring and summer and so eliminated the need for ELB control measures for a period of about five years.

Figs and Psyllids

Given that adult psyllid emergence usually ceases in early autumn (April)(Honan and McArthur 1998), there are three likely explanations for the absence of psyllids in surveys across Melbourne after mid-February 2009: host plant condition, parasitoid survival, and high temperature. Host plant condition involves drought stress favoring psyllid outbreaks (White 1969; Morgan 1984), but more recent work concluded that sap feeders exhibited enhanced performance when plants were intermittently but not continuously water stressed (Huberty and Denno 2004), which is supported by data showing reduced herbivory if drought curtailed new leaf production in eucalypts (Gherlenda et al. 2016). Under the weather conditions experienced in Melbourne during 2008 and 2009, this would suggest that a rise in psyllid number might have been expected. Parasitoid survival depended on accurate targeting of sprays against psyllids favoring parasitoid build-up (Honan and McArthur 1998). However, Victoria had been subjected to prolonged drought for ten years prior to 2008 and 2009, when psyllid numbers remained high and improved spraying had been in place for over a decade with no evidence of impact. Furthermore, Meineke et al. (2013) found that temperature did not differentially affect parasitoids, which is supported by the finding that parasitoids had little impact on psyllid outbreaks in a eucalypt woodland (Hall et al. 2015).

High temperature remains the most likely cause of psyllid decline, as adult longevity can be reduced by high temperatures; from 8 days at 30 °C, to 2 or 3 days at 35 °C. Moreton Bay fig psyllid emergence usually peaks in December or January in Melbourne, which coincided with Victoria's periods of extreme heat in 2009. There were four days in January on which temperatures exceeded 40 °C and another eight days over 35 °C before the heat wave in February culminating on the 7 February (Figure 1). Longevity of psyllids emerging in Melbourne during this period appears to have been greatly reduced.

The optimal time for psyllid control by foliar treatment is during the peak adult emergence period, when emerged adult psyllids are vulnerable to contact insecticides. Based on the low number of adults counted on traps, it was considered unnecessary and an unjustifiable expense to implement planned spraying during 2008/2009 because without a clearly defined peak, it was not possible to identify the optimal timing of treatment, and low adult numbers indicated that treatment was unnecessary.

CONCLUSION

In Victoria, in February 2009 when temperatures rose to 46.4 °C following a heat wave, an unexpected consequence of the high temperatures was the killing of many of the mistletoes affecting older eucalypts. Mistletoe deaths were also observed in non-eucalypt species, including *Platanus* × *acerifolia*, *U. procera*, and *Pyrus calleryana*. The effect of high temperatures, compounded by high winds driving excess water use, in killing mistletoes may have a broader impact on the health and management of urban tree species. Similarly, the reductions in ELB and psyllid infestations of elms and Moreton Bay fig trees after the heat wave and record high temperature day were so great that control measures were not required for several subsequent years. Ongoing monitoring, however, alerted urban tree managers to the rise in ELB numbers in the summer of 2014 and control measures were implemented in the summer of 2015/2016. Monitoring identifies pest infestation hot spots and allows the appropriate allocation of limited resources.

In the areas surveyed, there was no need to undertake mistletoe, psyllid, or ELB control measures for at least five years after the heat wave and high temperature day, which impacted upon the work schedules of municipal arborists and tree-related expenditures. There is a strategic opportunity for urban tree managers to integrate climatic events with urban pest control measures. Routine and costly pest control programs could be deferred until surveys indicate that they are needed. While there is a danger that this could lead to complacency where surveys are abandoned, in situations where arboricultural budgets are tight, funds freed from pest control could be allocated to other important arboricultural priorities.

Climate change will have a diverse range of effects on the urban forest, making decisions related to planning and management more complex. However, by better understanding tree and pest biology, those responsible for urban forests may be able to use some of the influences wrought by climate change to manage urban trees and forests more efficiently and proactively.

LITERATURE CITED

Bennett AB, Gratton C. 2012. Local and landscape scale variables impact parasitoid assemblages across an urbanization gradient. *Landscape and Urban Planning*. 104:26-33.

Boland DJ, Brooker MIH, Chippendale GM, Hall N, Hyland BPM, Johnston RD, Kleinig DA, Turner JD. 1984. *Forest trees of Australia*. Melbourne (Australia): Nelson-CSIRO.

Bowen ME, McAlpine CA, House APN, Smith, GC. 2009. Agricultural landscape modification increases the abundance of an important food source: mistletoes birds and brigalow. *Biological Conservation*. 142:122-133.

Brandt L, Lewis AD, Fahey R, Scott L, Darling L, Swanston C. 2016. A framework for adapting urban forests to climate change. *Environmental Science and Policy*. 66:393-402.

Broadmeadow MSJ, Ray D, Samuel CJA. 2005. Climate change and the future of broadleaved tree species in Britain. *Forestry*. 78:145-161.

Bureau of Meteorology. 2011. Monthly rainfall, Melbourne airport, 1971-2010. Melbourne (Australia): Australian Government.

Bureau of Meteorology. 2016. Heatwave service for Australia. Australian Government. [Accessed 24 June 2016]. http://www.bom.gov.au/australia/heatwave

Calder DM, Bernhardt P. 1983. *The biology of mistletoes*. Sydney (Australia): Academic Press.

Clair DJ. 1986. Bionomics of the elm leaf beetle, *Xanthogaleruca luteola* (Muller), in north eastern California [PhD thesis]. Berkeley (CA, USA): University of California.

Clark JS, Bell DM, Hersh MH, Nichols L. 2011. Climate change vulnerability of forest biodiversity: climate and competition tracking of demographic rates. *Global Change Biology*. 17:1834-1849.

Commissioner for Environmental Sustainability. 2012. Foundation paper one: climate change Victoria. The State of Victoria: Commissioner for Environmental Sustainability.

Dahlsten DL, Tait SM, Rowney DL, Gingg BJ. 1993. A monitoring system and developing ecologically sound treatments for elm leaf beetle. *Journal of Arboriculture*. 19:181-186.

Danby RK, Hik DS. 2007. Variability, contingency and rapid change in recent subarctic alpine treeline dynamics. *Journal of Ecology.* 95:352-363.

Davidson NJ, True KC, Pate JS. 1989. Water relations of the parasite: host relationship between the mistletoe *Amyema linophyllum* (Fenzl) Tieghem and *Casuarina obesa* Miq. *Oecologia*. 80:321-330.

Deutsch CA, Tewksbury JJ, Huey RB, Sheldon KS, Ghalambor CK, Haak DC, Martin PR. 2008. Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings National Academy of Sciences*. 105:6668-6672.

Dreistadt SH, Dahlsten DL, Rowney DL, Tait SM, Yokota GY, Copper WA. 1991. Treatment of destructive elm leaf beetle should be timed by temperature. *California Agriculture*. 45:23-25.

Dunn CP. 2000. *The elms: breeding, conservation and disease management*. Boston (MA, USA): Kluwer Academic Publishing.

Fisher JT. 1983. Water relations of mistletoes and their hosts. In: Calder M, Bernhardt P, editors. *The biology of mistletoes*. Sydney (Australia): Academic Press. p. 161-183.

Fromont C, Riegler M, Cook JM. 2015. Characterisation of 14 microsatellite markers for the Australian fig psylloid, *Mycopsylla fici*. *Australian Journal of Zoology*. 63:233-235.

Gherlenda AN, Haigh AM, Moore BD, Johnson SN, Riegler M. 2016. Insect herbivory in a mature Eucalyptus woodland canopy depends on leaf phenology but not CO_2 enrichment. *BMC Ecology.* 16:47.

Glickman TS. 2000. *Glossary of meteorology*. Boston (MA): American Meteorological Society.

Grace J, Berninger F, Nagy L. 2002. Impacts of climate change on the tree line. *Annals of Botany*. 90:537-544.

Hall AAG, Gherlenda AN, Hasegawa S, Johnson SN, Cook JM, Riegler M. 2015. Anatomy of an outbreak: the biology and population dynamics of a *Cardiaspina* psyllid species in an endangered woodland ecosystem. *Agricultural and Forest Entomology*. 17: 292-301.

Harsch MA, Hulme P, McGlone MS, Duncan RP. 2009. Are treelines advancing? A global analysis on treeline response to climate change. *Ecology Letters*. 12:1040-1049.

Honan P, McArthur K. 1998. Fig psyllids in the City of Melbourne. Report to Melbourne City Council. Frankston (Victoria, Australia): Department of Natural Resources and Environment.

Huberty AF, Denno RF. 2004. Plant water stress and its consequences for herbivorous insects: a new synthesis. *Ecology*. 85:1383-1398.

Jentsch A, Kreyling J, Beierkuhnlein C. 2007. A new generation of climate-change experiments: events not trends. *Frontiers in Ecology and the Environment*. 5:365-374.

Jurskis V, Turner RJ, Jurskis D. 2005. Mistletoe increasing in undisturbed forest: a symptom of forest decline caused by unnatural exclusion of fire. *Australian Forestry*. 68:221-226.

Kendal D, Dobbs C, Lohr VI. 2014. Risks to global patterns of diversity in the urban forest: Is there evidence to support the 10/29/30 rule? *Urban Forestry & Urban Greening*. 13:411-417.

Kendal D, McDonnell MJ. 2014. Adapting urban forests to climate change. *CityGreen*. 8:130-137.

Kendal D, Williams NSG, Williams KJH. 2012. A cultivated environment: exploring the global distribution of plants in gardens, parks and streetscapes. *Urban Ecosystems*. 15:637-652.

Knutson DM. 1983. Physiology of mistletoe parasitism and disease responses in the host. In: Calder M, Bernhardt P, editors. *The biology of mistletoes*. Sydney (Australia): Academic Press. p. 295-316.

Kwong RM, Lefoe G. 1998. A guide to elm leaf beetle management in Victoria. Report to Melbourne City Council. Frankston (Victoria, Australia): Department of Natural Resources and Environment.

Lawson AB, Dahlsten DL. 2003. Implementation of a citywide monitoring program to base treatment decisions on elm leaf beetle abundance. *Journal of Arboriculture*. 29:34-41.

Lefoe G, Dominiak B, Worsley P, Davies J. 2014. Elm leaf beetle *Xanther galeruca* (Miller) dispersal across south eastern Australia (1989-2011). *Plant Protection Quarterly*. 29:61-65.

Liddy J. 1983. Dispersal of Australian mistletoes: the Cowiebank study. In: Calder M, Bernhardt P, editors. *The biology of mistletoes.* Sydney (Australia): Academic Press. p. 101-116.

McPherson EG, Berry AM, van Doorn NS. 2018. Performance testing to identify climate-ready trees. *Urban Forestry & Urban Greening*. 29:28-39.

Mech AM, Tobin PC, Teskey RO, Rhea JR, Gandhi KJK. 2018. Increases in summer temperatures decrease the survival of an invasive forest insect. *Biological Invasion*. 20:365-374.

Meineke EK, Dunn RR, Sexton JO, Frank SD. 2013. Urban warming drives insect pest abundance on street trees. *Plos One*. 8:1-7, e59687.

Miller F. 2000. Insect resistance of elm genotypes. In: Dunn CP, editor. *The elms: breeding, conservation and disease management.* Boston (MA, USA): Kluwer Academic Publishing.

Moore GM. 1990. The elm in Australia: threats and opportunities. In: Hitchmough JD, Arthur TE, editors. *Does the elm have a future in Australia?* Melbourne (Australia): Victorian College of Agriculture and Horticulture. p. 1-3.

Moore GM. 1998. Tree growth regulators: issues of control, matters of management. *Journal of Arboriculture*. 24:10-18.

Moore GM. 2018. Do heatwaves give us a glimpse of the future under climate change? *Arborist News*. 27(6):24-28.

Morgan D. 1984. *Psylloidea of South Australia*. Adelaide (South Australia): Government Printer, South Australian Government. 136 p. (Series: *Handbook of the flora and fauna of South Australia*).

Nathan R, Horvitz N, He Y, Kuparinen A, Schurr F, Katul GG. 2011. Spread of North American wind-dispersed trees in future environments. *Ecology Letters*. 14:211-219.

Nicolle D. 2006. *Eucalypts of Victoria and Tasmania*. Melbourne (Australia): Blooming Books.

Pretzsch H, Biber P, Uhl E, Dahlhausen J, Schütze G, Perkins D, Rötzer T, Caldentey J, Koike T, van Con T, Chavanne A, du Toit B, Foster K, Lefer B. 2017. Climate change accelerates growth of urban trees in metropolises worldwide. *Scientific Reports*. 7: Article number: 15403.

Richcigl JE, Richcigl NA, editors. 2000. *Insect pest management: techniques for environment protection*. Boca Raton (FL, USA): CRC Lewis Press.

Rouault G, Candau JN, Lieutier F, Nageleisen LM, Martin JC, Warzée N. 2006. Effects of drought and heat on forest insect populations in relation to the 2003 drought in Western Europe. *Annals of Forest Science*. 63:613-624.

Salzer MW, Hughes MK, Bunn AG, Kipfmueller KF. 2009. Recent unprecedented tree-ring growth in bristlecone pine at the highest elevations and possible causes. *Proceedings of the National Academy of Science*. 106:20348-20353.
Start AN. 2011. Fire responses and survival strategies of mistletoes (Loranthaceae) in an arid environment in Western Australia. *Australian Journal of Botany*. 59:533-542.
Watson DM. 2011. Mistletoes of southern Australia. Collingwood (Australia): CSIRO Publishing.
White RS, White JS. 1996. *Statistics*. 5th Edition. Fort Worth (TX, USA): Harcourt Brace Publishers.
White TCR. 1969. An index to measure induced stress of trees associated with outbreaks of psyllids in Australia. *Ecology*. 50:905-909.
Yang J. 2009. Assessing the impact of climate change on urban tree species selection: a case study in Philadelphia. *Journal of Forestry*. 107:364-372.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Department of Environment and Primary Industry (DEPI) and Tania McLeod from the Urban Forest group of the Melbourne City Council (MCC) for providing data on ELB and Psyllid numbers. Ms. Ying Zhao, Master of Urban Horticulture student at the Burnley campus of the University of Melbourne, is acknowledged for her data collected in 2011 as part of her project work. The assistance of Dr. E. Moore, linguist, for her helpful comments on the manuscript and with figures is acknowledged. Dr. D. Johnstone and Dr. D. Moore are thanked for assistance with figures.

G.M. Moore (corresponding author)
School of Ecosystem and Forest Sciences, Burnley College
University of Melbourne
500 Yarra Boulevard
Richmond, Australia
gmmoore@unimelb.edu.au

G. Lefoe
Department of Environment, Land, Water and Planning
AgriBio
5 Ring Road
Bundoora, Australia

Conflicts of Interest:
The authors reported no conflicts of interest.

Résumé. Les changements climatiques auront des conséquences profondes et nuisibles pour de nombreux arbres en milieux urbains; cependant, comme dans toute transition d'un système biologique en cours, il y aura des bénéfices. Le 7 février 2009, la ville australienne de Melbourne a vécu sa plus chaude journée selon les annales, soit 46.4 °C (115.5 °F) suite à une vague de chaleur. Dans les jours qui suivirent, il fut observé que le feuillage de guis indigènes australiens, *Amyema miquelii* et *A. pendula*, croissant sur *Eucalyptus camaldulensis* perdirent leur couleur verte et devinrent gris. Lorsque présents en quantité, les guis peuvent générer du stress significatif pouvant mener à la mort de l'arbre qu'elles colonisent. À la suite de cette température record, de grandes quantités de guis moururent et cinq ans plus tard, le niveau d'infestation du gui est demeuré bas. Dans l'après-midi du 7 février 2009, des dizaines de milliers de galéruques de l'orme, qui se nourrissaient sur les ormes matures de Melbourne (*Ulmus procera* et *U.* × *hollandica*), furent découvertes mortes sous la canopée de ces arbres d'alignement et les populations de ces insectes demeurèrent basses durant au moins les cinq années suivantes. De manière similaire, les populations de psylles, *Mycopsylla fici*, et leurs infestations de *Ficus macrophylla*, lesquelles peuvent sévèrement défolier les arbres, chutèrent d'un niveau élevé à un niveau non détectable dans le mois suivant la vague de chaleur. L'impact des vagues de chaleur et des journées accablantes eurent des implications significatives pour les gestionnaires de ravageurs dans les forêts urbaines. Certains programmes de contrôle de ravageurs se révélèrent inutiles suite aux vagues de chaleur et aux journées accablantes et ce, pour jusqu'aux cinq années suivantes. Il en résulta des implications positives pour la gestion rigoureuse des budgets destinés aux arbres mais cela pouvait également mener à l'interruption de programmes de dépistage et de contrôle de ravageurs. Une telle approche est susceptible de générer le retour de taux élevés d'infestation.

Zusammenfassung. Der Klimawechsel wird profunde und schädliche Auswirkungen auf viele Bäume in urbanen Bereichen haben; dennoch, so wie in vielen biologischen Systemen, die einen Wechsel erleben, werden auch hier Vorteile liegen. Am 9. Februar 2009 erlebte die australische Stadt Melbourne nach einer Hitzewelle den heißesten Tag seit der Aufzeichnung (46.4 °C[115.5 °F]). An den folgenden Tagen wurde beobachtet, daß das Laub von australischen Misteln, *Amyema miquelii* und *A. pendula*, die auf *Eucalyptus camaldulensis* wachsen, seine grüne Farbe verlor und grau wurde. In großer Anzahl können die Misteln signifikanten Stress verursachen, und zum Absterben von Bäumen führen. Als Nachwirkungen dieses Hitzerekordtages starben große Anzahlen von Misteln und auch fünf Jahre später blieb die Mistelinfektionsrate niedrig. Am Nachmittag des 7. Februar 2009 fand man Zehntausende von Ulmenblattkäfern, welche sich von den ausgewachsenen Ulmen (*Ulmus procera* und *U.* × *hollandica*) von Melbourne ernähren, tot unter den Kronen der Straßenbäume liegen und die Anzahl blieb für die nächsten fünf Jahre weiterhin gering. Gleichzeitig fielen die Populationen von Blattläusen, *Mycopsylla fici*, und der Befall von *Ficus macrophylla*, welche die Bäume ernsthaft entlauben können, in dem Monat nach der Hitzewelle von einem hohen auf einen nicht nachweisbaren Grad herunter. Die Effekte der Hitzewellen und des Tages mit den extrem hohen Temperaturen haben signifikante Auswirkungen auf jene, die den Schädlingsbefall in urbanen Grünflächen verwalten. Schädlingbekämfungsprogramme waren in der unmittelbaren Folgezeit nach der Hitzewelle und dem heißen Tag und bis zu fünf Jahren danach unnötig. Das hatte positive Auswirkungen auf die engen Baumpflegebudgets, aber es könnte auch zu einer Unterbrechung der Überwachung von Schädlingen und Bekämpfungsprogrammen führen. So ein Ansatz könnte zu einer Rückkehr von hohem Infektionsdruck führen.

Resumen. El cambio climático tendrá efectos profundos y perjudiciales en muchos árboles en entornos urbanos; sin embargo, como en cualquier sistema biológico que experimente cambios, habrá beneficios. El 7 de febrero de 2009, la ciudad australiana de Melbourne experimentó su día más caluroso registrado (46.4 °C [115.5 °F]) después de una ola de calor. En los días que siguieron, se observó que el follaje de los muérdagos australianos nativos, *Amyema miquelii* y *A. pendula*, que crecían en *Eucalyptus camaldulensis*, perdía su color verde y se volvía gris. En grandes cantidades, los muérdagos pueden causar un estrés significativo, lo que lleva a la muerte del árbol. Después del día caluroso récord, grandes cantidades de muérdagos murieron y por 5 años el nivel de infestación de muérdago se mantuvo bajo. En la tarde del 7 de febrero de 2009, decenas de miles de escarabajos de hojas de olmo, que infestan fuertemente los olmos maduros de Melbourne (*Ulmus procera* y *U. × hollandica*), fueron encontrados muertos bajo las copas de los árboles de la calle y esa cantidad permaneció baja durante al menos 5 años. Del mismo modo, las poblaciones de psílidos, *Mycopsylla fici* e infestaciones de *Ficus macrophylla*, que pueden defoliar gravemente los árboles, cayeron de niveles altos a indetectables en el mes siguiente a la ola de calor. Los efectos de las olas de calor y los días de temperaturas muy altas tienen implicaciones significativas para quienes manejan las plagas en los bosques urbanos. Los programas de control de plagas fueron innecesarios inmediatamente después de la ola de calor y el día caluroso y hasta por 5 años posteriores. Esto tiene implicaciones positivas para los presupuestos ajustados de manejo de árboles, pero también podría llevar a la interrupción de los programas de monitoreo y control de plagas. Tal enfoque podría ver un retorno a altos niveles de infestación.