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# Managing and Monitoring Tree Health and Soil Water Status During Extreme Drought in Melbourne, Victoria

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**Abstract.** Drought can lead to mortality in urban tree populations. The City of Melbourne, Victoria, Australia, manages a large population of trees that provide important ecosystem services and cultural heritage values. Between 1997 and 2009 Melbourne was affected by a serious drought resulting in significant tree health decline. Elms and planes in particular, were badly affected. This paper presents data from a survey of tree health status, and of studies of retrofitted buried drip line irrigation. A study of soil wetting in autumn of 2009 found that the use of drip irrigation had, in most cases, little or no effect on soil moisture levels and a modeled study of tree water use showed that water delivered by drip irrigation provided only a fraction of the water required by a mature tree. By contrast, drip irrigation in late winter was able to recharge soil moisture levels. Mechanisms responsible for the decline in tree health seen during the drought are discussed. While the drought has temporarily been alleviated, climate change scenarios for southern Australia suggest that increased rainfall variability and drought events will be more common. The experiences gained during the recent drought event provide useful information for urban tree managers planning for the future.

**Key Words.** Australia; Climate Change Strategy; Drip Irrigation; Drought; Melbourne; *Platanus* × *acerifolia*; Retrofitted Irrigation; Soil Moisture; Tree Health, Tree Water Use; *Ulmus procera*.

Climate change is seen as posing serious risks to the health of forest trees (Allen et al. 2010), and increased frequency of tree deaths is being seen in response to more frequent and severe droughts and extreme temperatures. While urban forests may have been insulated from these effects by access to irrigation water, increasing water scarcity issues in many cities suggests that climate change-induced drought will threaten urban tree populations in the future. Kjelgren et al. (2011) have investigated some of these issues in tropical urban tree species, but in general there seems little literature on the impacts of climate change on urban tree populations. Despite the lack of literature on the subject, urban forest managers should consider the impacts of climate change on their current tree populations and develop strategies for the monitoring and management of tree stress as well as strategies for future plant selection. In the period 1997–2009, much of eastern Australia was affected by a prolonged period of below-average rainfall (this will be referred to as the drought in the remainder of this paper). Drought conditions are defined as a period of time greater than three months when recorded rainfall falls into the lowest tenth percentile of all comparable rainfall records (lowest 10% of records) (Bureau of Meteorology 2011). In response, a series of increasingly severe water restrictions were instigated upon private and public water users (Table 1), and such a response can be expected to be repeated under future drought events. Many urban trees were deleteriously affected by the 1997–2009 drought and imposed water restrictions and urban tree managers had a range of responses to these stresses. Since events of this type have the potential to inform us about the likely impacts of future climate change scenarios, an evaluation of data collected during this period may be useful for tree managers in Australia and other parts of the world. This paper is a case study of information collected by the City of Melbourne (Victoria, Australia) during the drought period. Council staff, consultants, and researchers collected the data presented. The paper aims to:

1. Improve understanding of the nature and extent of tree water stress through qualitative soil moisture monitoring and tree canopy health survey.
2. Assess the efficacy of retrofitted drip irrigation system through excavated wetted profiles (summer and winter) and the use of a simple tree water balance model.

Several case studies of environmental conditions and management interventions are presented:

- soil moisture monitoring network
- tree health surveys
- soil moisture profiles under retrofitted drip irrigation (summer supply and winter recharge)
- drip irrigation water supply against modeled tree water demand

These are discussed with regards to the two aims and in the context of possible drought response, or climate change adaptation strategies, for future management of urban tree populations.

**Table 1. Timeline of significant events related to the 1997–2009 drought in the City of Melbourne.**

| Date | Event |
|---|---|
| 1993 | First appearance of elm leaf beetle in Melbourne tree population. |
| 1997/98 summer | First year of extended drought period. |
| 1999 | First applications of imidacloprid (Confidor®) to treat elm leaf beetle. |
| 2004 | Evidence of crown death beginning in older elm trees. |
| 2006 November | Application of Stage 2 Water Restrictions – irrigation of lawns banned. |
| 2007 January | Application of Stage 3 Water Restrictions – first installations of drip irrigation. |
| 2010 autumn | Drought "ends" with good autumn rain. |
| 2010/11 summer | Wet summer. |

## BACKGROUND TO THE STUDY

Melbourne is the oldest municipality in Greater Melbourne, a large urban area managed by approximately 40 independent local government bodies (Frank et al. 2006). The city manages a population of approximately 58,000 trees that are located primarily in parkland and streetscapes (Shears 2011). The street and park landscapes of Melbourne are of great importance to the entire metropolitan area and contain a number of precincts that have heritage status. The tree population of Melbourne includes an important population of approximately 6,500 European elms (*Ulmus procera*, *U.* × *hollandica*, *U. glabra*, and *U. minor*) that have never been affected by Dutch elm disease (*Ophiostoma* spp.). The oldest of these trees date to the period 1850–1860 (Spencer 1997). These elms, with London plane tree (*Platanus* × *acerifolia*) account for many of the large street trees in Melbourne and contribute character to many parks. London plane trees account for more than 75% of the trees in the Melbourne CBD (City of Melbourne 2011).

The long-term average rainfall of inner Melbourne is 640 mm $y^{-1}$ (1908–2011; Bureau of Meteorology 2011) with approximately 50 mm falling each month throughout the year. Higher summer temperatures (January mean maximum 25.9°C, January mean minimum 14.3°C) and elevated evaporation during summer months result in a moderate level of summer water deficit. While the original tree plantings in Melbourne would have been established without fixed irrigation systems, technological improvements from the 1950s meant that most parks and streets had irrigation systems installed to maintain green grass cover over summer and to assist trees to withstand dry periods.

In Australia, year-to-year rainfall variability is a characteristic of the climate and recurring droughts are common (Gentilli 1971). Since records have been kept in Melbourne (from 1855), there have been a number of drought events, usually lasting for one or two years. However, between 1997 and 2009, an extended serious drought affected much of Australia, including the Melbourne area. Figure 1 shows annual rainfall for the period 1855–2011, with drought events evident, as is the protracted nature of the drought of concern in this paper. The drought period of 1997 to 2009 is the most severe on record for the Melbourne metropolitan area. During the period covered by this paper the average annual rainfall was 515 mm (a reduction of 20% from the long-term average) and during the final four years of the drought, the average annual rainfall was only 450 mm, a reduction of 30%. In the previous severe drought of 1982–1983, the City of Melbourne responded with radial trench cutting and flooding in an attempt to provide relief to water stress being experienced by 'valued' trees in iconic parks. This practice met with variable success and has not been repeated.

The recent drought (1997–2009) depleted the water storage reservoirs in the hills to the north and east of Melbourne, resulting in increasingly severe water-use restrictions, such that in late 2006, irrigation of parkland was banned (Table 1). Water restrictions have been used in Melbourne in the past, in the summers of 1967–1968, 1972–1973, and 1982–1983 (I. Watson, Melbourne Water, pers. comm.), but the most recent restrictions have been exceptionally long. Parkland trees are normally irrigated with turf sprinklers, but these irrigation restrictions and the severity of the drought resulted in significant damage to the health of many trees, particularly poplars (*Populus* spp.), elms (*Ulmus* spp.), and plane trees (*Platanus* spp.). In the case of the elms, a concomitant infestation of elm leaf beetle (*Pyrrhalta luteola*) may have contributed to the decline in tree health. The City of Melbourne was able to negotiate a partial exemption from these irrigation restrictions but was only permitted to use potable water if drip irrigation was used. Accordingly, a program to retrofit drip irrigation into a number of parks and streetscapes began in 2007 (Table 1). The drip line used was primarily Techline™ (Netafim™, Laverton North, Victoria, Australia), buried approximately 50 mm below the soil surface.

In addition to the ongoing drought, the summer of 2008–2009 had some of the highest temperatures ever recorded in Melbourne, which further increased tree stress. Plane trees were severely affected with significant defoliation in late January 2009 after three consecutive days of maximum air temperatures >43°C, followed by one day >48°C one week later.

Cooler temperatures, and higher than average rainfall, during the summer of 2010–2011 alleviated some of the effects of the drought and water restrictions were eased during 2011.

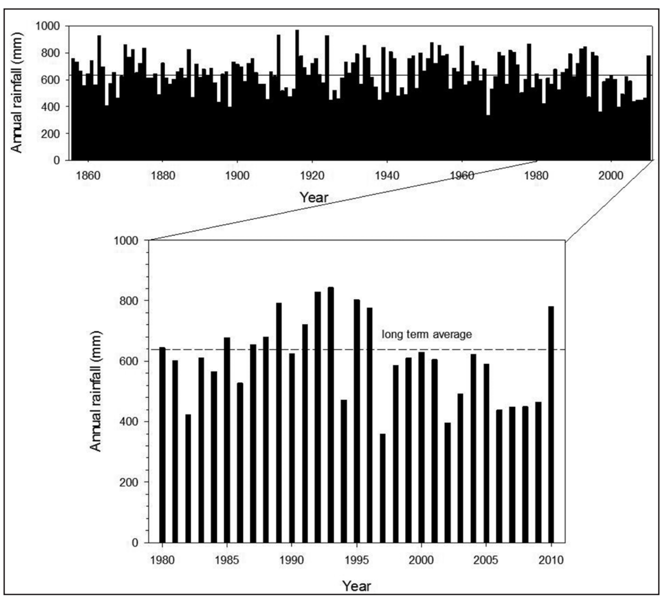


**Figure 1. Annual rainfall (mm) for Melbourne CBD 1855–2010 (Bureau of Meteorology, Australia, www.bom.gov.au).**

Regardless, the predicted future climate change scenarios for southern Australia suggest increased rainfall variability and increased frequency and intensity of drought events. The conditions experienced during the 13 years of the drought between 1997 and 2010 may provide a foretaste of what Melbourne's climate could be like under future climate change conditions.

## METHODS AND RESULTS

### Soil Moisture Monitoring

In 2009, Melbourne started to monitor soil moisture content change at a number of locations around the city. At potential monitoring sites, ground-penetrating radar was used to ensure that there were no buried services in a zone of approximately 1 $m^2$ at each site. Ten precincts were monitored at a total of 127 sampling points. At each sampling date a soil gouge auger (Spurr Dig Stick™, Adelaide, South Australia, Australia) provided an intact 0 to 600 mm deep soil core sample at each point. Soil moisture content was assessed using visual and tactile indicators (Handreck and Black 2010). This approach does not generate quantified soil moisture content but rather estimates the proportion of the soil's available moisture remaining in the sample. As an example of the data collected, Figure 2 shows soil moisture (expressed as % available water remaining) between October 2009 and March 2011, averaged across 14 sampling points in The Domain Park, an area of parkland just outside the Melbourne central business district. Soil drying in late spring 2009 (November) and early summer 2010 (January) is evident, as is the improvement in soil moisture conditions from autumn 2010 (April) onwards. These soil monitoring data were used to negotiate continuation of the irrigation exemptions allowed by the local water supply authority and were also used as triggers for the start of each summer's irrigation program. The data was not used to schedule irrigations.

### Tree Health Surveys

Tree responses to the drought included the following symptoms: reduced shoot extension, reduced leaf size, pale foliage, premature autumn leaf drop, death of fine branches in the canopy, canopy thinning, growth of epicormic shoots, death of large branches, and whole tree death. To collect data on the extent of these responses, a series of surveys of tree health were undertaken, beginning in 2009. The canopy condition of each tree was rated as either 1-Healthy, 2-At Risk, 3-Declining, or 4-Dying, based on assessment indicators of i) foliage color, ii) canopy density, iii) presence of epicormic growth, and iv) canopy death. The categories were based on the mortality spiral published by Clark and Matheny (1991). Figure 3 shows photographs of trees that exemplify each canopy condition. A total 25,000 trees were surveyed. From these surveys,

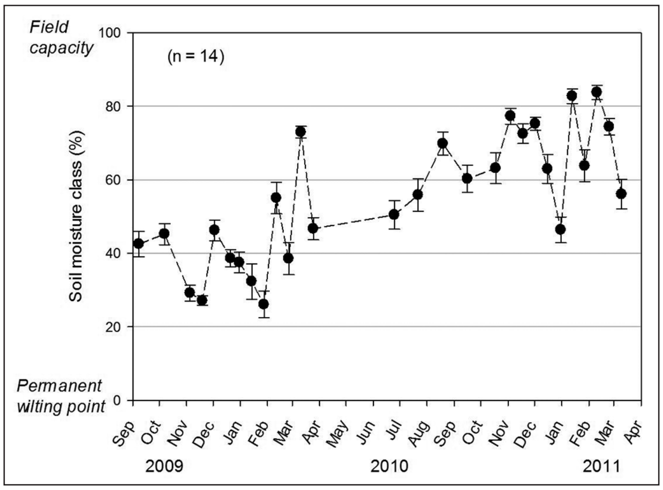


**Figure 2. Available soil moisture (%) in The Domain Park from September 2009 to March 2011 in relation to monthly rainfall (mm).**

**Table 2. Tree health data from The Domain Park, February 2010.**

| Scientific name | Common name | (n) | Dying (%) | In decline (%) | At risk (%) | Healthy (%) |
|---|---|---|---|---|---|---|
| *Acmena smithii*[z] | lilly pilly | 35 | 6 | 0 | 6 | 89 |
| *Agathis robusta*[z] | Queensland kauri | 28 | 0 | 4 | 4 | 93 |
| *Angophora floribunda*[z] | flowering apple | 15 | 0 | 0 | 0 | 100 |
| *Araucaria* spp.[z] | southern pines | 52 | 0 | 0 | 4 | 96 |
| *Cedrus deodara* | deodar cedar | 55 | 2 | 2 | 4 | 93 |
| *Cinnamomum camphora* | Camphor laurel | 33 | 3 | 6 | 6 | 85 |
| *Corymbia citriodora*[z] | lemon-scented gum | 38 | 3 | 0 | 0 | 97 |
| *Corymbia ficifolia*[z] | red-flowering gum | 70 | 1 | 3 | 16 | 80 |
| *Corymbia maculata*[z] | spotted gum | 52 | 0 | 0 | 2 | 98 |
| *Eucalyptus botryoides*[z] | southern mahogany gum | 17 | 0 | 0 | 6 | 94 |
| *Eucalyptus camaldulensis*[z] | river red gum | 38 | 0 | 0 | 0 | 100 |
| *Ficus macrophylla*[z] | Moreton Bay fig | 64 | 3 | 2 | 47 | 48 |
| *Lophostemon confertus*[z] | Queensland brush box | 47 | 0 | 0 | 9 | 91 |
| *Phoenix canariensis* | Canary Island palm | 83 | 0 | 0 | 1 | 99 |
| *Pinus radiata* | Monterrey pine | 21 | 5 | 0 | 10 | 86 |
| *Pittosporum undulatum*[z] | sweet pittosporum | 26 | 0 | 12 | 8 | 81 |
| *Platanus × acerifolia* | London plane | 158 | 17 | 18 | 46 | 18 |
| *Populus* spp. | poplars | 86 | 28 | 6 | 16 | 50 |
| *Quercus canariensis* | Canary Island oak | 35 | 3 | 3 | 40 | 54 |
| *Quercus palustris* | pin oak | 37 | 5 | 8 | 11 | 76 |
| *Quercus robur* | English oak | 88 | 10 | 19 | 30 | 41 |
| *Tilia cordata* | linden | 46 | 4 | 11 | 24 | 61 |
| *Ulmus* spp. | European elms | 209 | 14 | 25 | 42 | 20 |
| *Total* | | *2252* | *7* | *8* | *22* | *64* |

[z] Trees native to Australia.

| Stage | Drawing guide | Tree health characteristics | Photo guide |
|---|---|---|---|
| Healthy (green) |  | Normal growth characteristics<br>Tree contribution to landscape is not compromised |  |
| At Risk (blue) |  | Stress evident, including:<br>• Leaf yellowing / defoliation<br>• Minor epicormic growth<br>• Minor die back<br>• Minor pest / disease damage |  |
| Declining (orange) |  | Stress evident, including:<br>• Epicormic growth<br>• Die back<br>• Evidence of dead branches<br>• Severe pest/disease infestation or damage |  |
| Dying (red) |  | Stress evident, including:<br>• Extensive epicormic growth<br>• Extensive die back<br>• Large dead branches |  |

**Figure 3. Tree canopy health stages used in condition surveys by the City of Melbourne [after Clark and Matheny (1991)]. Photographs courtesy of the City of Melbourne.**

maps of Melbourne's tree population were prepared to identify patterns of stress and priority areas for intervention. For example, in The Domain, a total 2,252 trees were assessed (Table 2; Figure 4). Of these, 22% were regarded as being at risk and 15% were assessed as being in serious decline or dying. The highest proportions of trees in serious decline or dying were in the genera *Platanus*, *Populus*, *Quercus*, and *Ulmus*.

## Soil Moisture Profiles Under Retrofitted Drip Irrigation

Retrofitting of drip irrigation lines adjacent to park and street trees began in January 2006. The response of trees to this mode of irrigation varied between species and locations, with some trees showing no improvement in health. In March 2009 (late summer), trenches were dug at six parkland locations to determine what impact, if any, drip irrigation was having on soil moisture content at depth and distance from the dripper line. Surface soils at these sites varied from sandy loams to clay loams, depending on site history and local geology. Trenches were dug with a backhoe, at right angles to the drip line, at approximately the canopy edge. The depth of the trench was determined by site conditions and direct observation of the limits of soil wetting but was typically between 400 and 600 mm. Soil moisture status was immediately assessed in the field using a combination of volumetric soil moisture content measured using a handheld impedance dielectric sensor (Theta™ Probe, Delta-T, Cambridge, UK) and gravimetric soil moisture content was measured through mass loss of oven dried (105°C) soil samples (Handreck and Black 2010) from samples collected into sealed containers and transported to the laboratory. The extent of the wetted zone was assessed by eye using soil color as an indicator. Figure 5 presents one cross section of the soil moisture profile under a drip irrigation line 4 m from a sweetgum (*Liquidambar styraciflua*) tree in The Domain parkland. The Domain has an area of trees planted in turf. Soil type varies with surface geology and topsoils range from silt loams to sandy loams. At this location, the surface soil was a silt loam (bulk density 1.1 Mg $m^{-3}$, field capacity 43% by volume, wilting point 16% by volume). The irrigated zone was found to have extended to a depth of 300 mm and a distance of approximately 500 mm either side of the

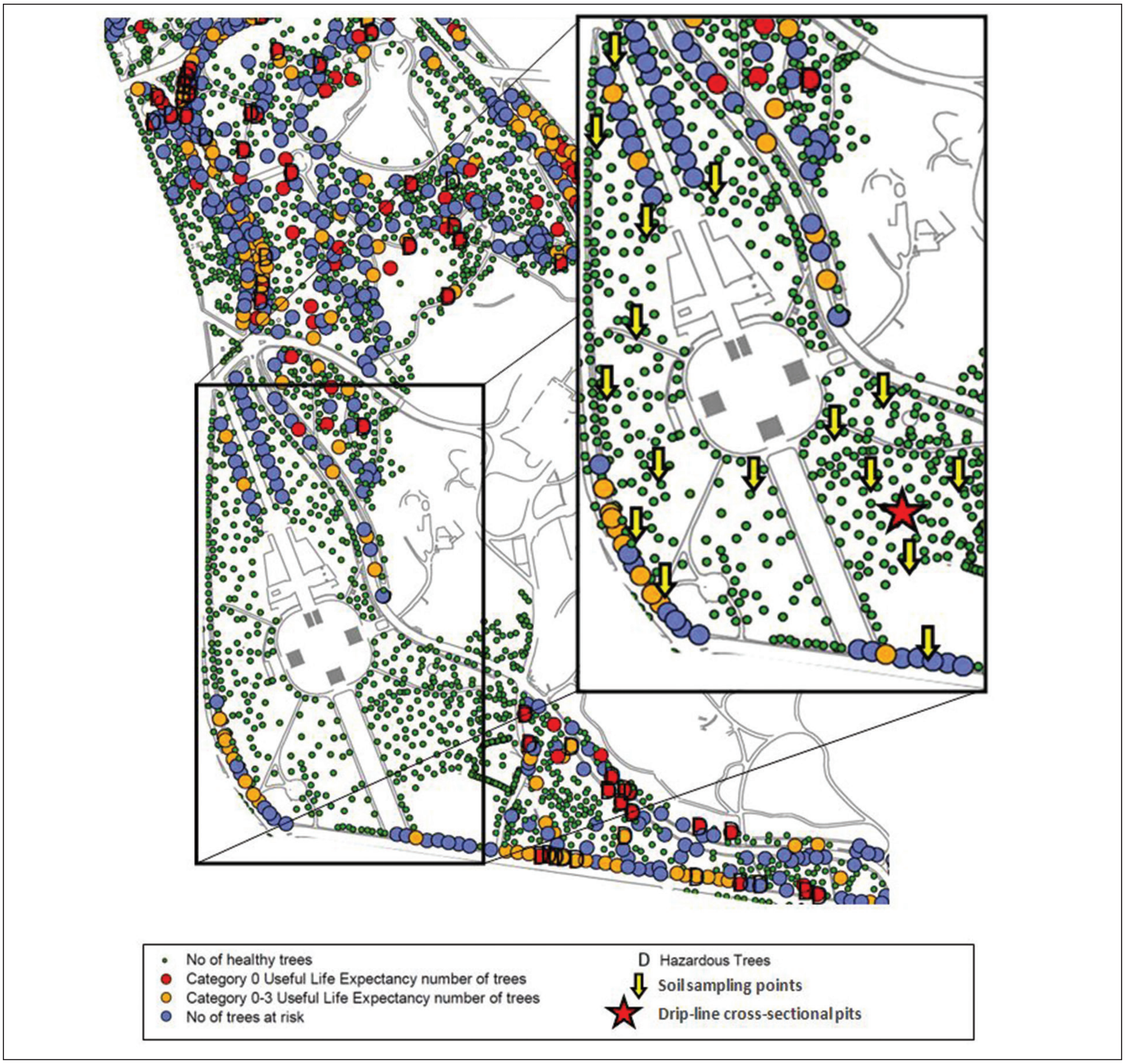


**Figure 4. Map of The Domain Park, Melbourne, showing assessed tree canopy health stages, soil moisture monitoring locations, and sites of trench dug investigations of drip irrigation.**

drip line, but soil moisture content was close to wilting point. At three other parkland locations, the zones of drip line irrigation were similarly dry, whereas at two parkland locations the soil under the drip line was approaching field capacity. These differences in soil moisture content probably relate to differences in the irrigation schedules at these different locations. The surface soil textures and dimensions of the wetted zones at the other parkland locations were: Domain West (loam) 1200 mm wide, 250 mm deep; Domain South (sandy loam) 800 mm wide, >600 mm deep; Macarthur Square Gardens (clay loam) 1000 mm wide, 450 mm deep; and Princes Park (loam) 600 mm wide, 200 mm deep. At Carlton Gardens (loam), the soil was so dry that no wetted zone could be distinguished.

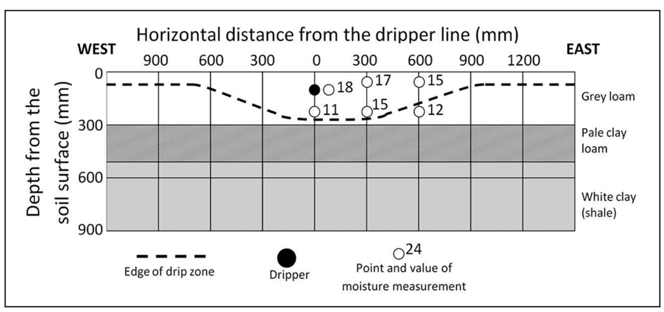


**Figure 5. Soil moisture data (% soil water v/v) at the Polo Lawn, Domain Park (north) in March 2009 (early autumn).**

## Tree Water Demand and Supply Balance

To provide some insight into the adequacy of the drip irrigation water supply to meet tree water demand, a tree water balance model was developed for European elms growing in Macarthur Square, Carlton (a small park north of the central business district with a double row of mature elms planted in turf), for the month of January 2009. This modeling exercise was conducted to elucidate why elm tree canopy health had remained poor despite the operation of retrofitted drip line irrigation over the summer period. In Macarthur Square, each elm tree possesses an approximately rectangular canopy of dimensions 15 m E-W and 16 m N-S (240 $m^2$). Water was supplied to each tree by two drip lines running parallel E-W, at an irrigation rate of 1.6 L $h^{-1}$ per dripper and one dripper every 0.3 m, which delivered approximately 160 L $h^{-1}$ $tree^{-1}$. In January 2009 the system was delivering 450 L $tree^{-1}$ $day^{-1}$.

Using January 2009 climate data from the Melbourne Regional Office weather station (1 km from the study site) (Bureau of Meteorology 2011), daily and cumulative water use by a single elm tree was estimated using the following relationship:

$$ET_L = ET_O \bullet K_L$$

where $ET_L$ is landscape evapotranspiration, $ET_O$ is the reference evaporation value, and $K_L$ is the landscape coefficient for the planting in question (Pannkuk et al. 2010). Less than 1 mm of rain fell during January 2009, and by this stage of the extended drought elm tree canopy density had thinned, reflecting probable water stress. A $K_L$ value of 0.60 was used to model water use in the park, this value reflecting a mid-season value for trees under-planted with turf (Pannkuk et al. 2010). Daily $ET_O$ during January ranged from 3.8 mm $d^{-1}$ to 8.7 mm $d^{-1}$ resulting in daily potential water use for each tree ranging from 550 L $d^{-1}$ to 2,190 L $d^{-1}$. Cumulative modeled tree water use for the month was 32,640 L $tree^{-1}$.

In January 2009, the daily irrigation volume of 450 L for each tree would not have met potential tree water demand on any day in that month. Overall the irrigation met 43% of potential demand. As the soils in Macarthur Square would have been dry leading into spring, these trees would have been subject to continued and increasing water stress, regardless of the retrofitted drip irrigation measures put in place in response to the tree health survey data and extended drought conditions.

## Drip Irrigation for Winter Soil Water Recharge

As the retrofitted drip irrigation lines had been shown to produce a limited zone of wetting in summer (500 mm deep and approximately 500 mm from drip line) and had been shown to not meet summer water use demand, the potential of these retrofitted drip irrigation lines to help recharge soil water contents in late winter, before the onset of summer, was investigated. By recharging soil water profiles in winter, these drip irrigation lines may provide drought-affected trees with respite from continued physiological stress and may encourage fine root growth in springtime in areas to be supplementary irrigated through summer.

Eight sites in parklands across Melbourne were chosen, with a range of soil types and conditions. At each parkland location, the drip irrigation system was operated for an estimated 14-day period in August 2009 (late winter). As in March 2009, trenches were dug with a backhoe, at right angles to the drip line, at approximately the canopy edge. The depth of the trench was determined by site conditions and direct observations and soil moisture conditions were assessed by i) visual assessment of the extent of the wetting pattern, ii) volumetric soil moisture content using a Theta Probe, and iii) the use of a metal spike to test soil softness (which is directly related to soil moisture content). Figure 6 shows soil moisture profiles at two locations in The Domain, one under a retrofitted drip line and the other an adjacent un-irrigated area.

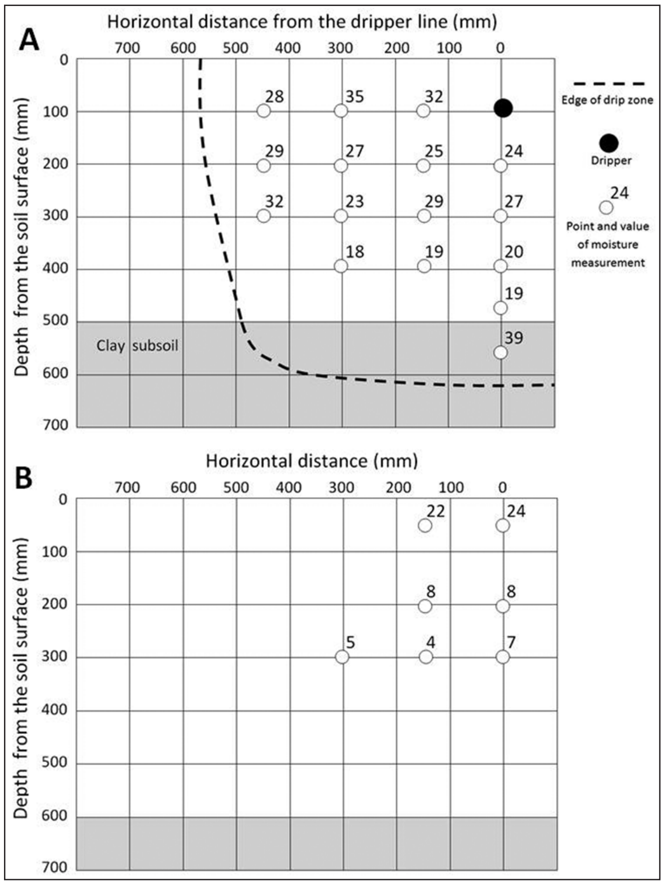


**Figure 6. Soil moisture data (% soil water v/v) after winter irrigation in Domain Park (south) in August (winter) 2009 (A is the irrigated site, B is a neighboring site without irrigation).**

At this location in The Domain, the soil has a deep sandy loam A horizon (bulk density 1.1 Mg $m^{-3}$, field capacity 27% by volume, wilting point 9% by volume), with a clay B horizon at 500 mm. The soil in the trench was wet directly below the drip line, and this irrigated wet zone extended into the clay subsoil to a total depth of 630 mm (Figure 6A). In the upper, coarse sandy loam, the irrigated wet zone extended approximately 500 mm on either side of the drip line and was at, or above, field capacity.

A comparative trench dug a few meters from the drip line exposed soil that was very dry to the touch except for a layer at the surface wetted by recent rainfall (Figure 6B). At depths of 300 mm the soil was dryer than wilting point, indicating the deficiency of winter recharge rainfall that season. These differences show clearly that the late winter irrigation was responsible for the elevated soil moisture content below and around the drip line. Across all eight study sites, the operation of drip irrigation for two weeks in August 2009 wetted the soil to at least the depth of the subsoil, and in most cases some way into the subsoil. The volume of wetted soil varied from site to site but ranged between 0.5 and 1.4 $m^3$ soil $m^{-1}$ drip line. The irrigated zone extended to depths of up to 800 mm and distances of up to 1 m on either side of the drip line. Between 30% and 90% of the water irrigated during the two-week period could be accounted for as stored in the wetted soil volume. By contrast, un-irrigated soils at most parkland sites had no available water within their topsoil, except for a shallow (0–25 mm) surface layer wetted by recent rainfall.

This study showed that drip lines typically wetted a horizontal column of soil along the line and suggested that winter drip irrigation can be used in dry, or below-average rainfall winters to help recharge soils to alleviate tree water stress, encourage appropriate fine root development and provide a resource for tree water use in the coming spring. The volume of soil that can be effectively wetted through this approach is as yet unknown, but longer run times or staggered run time schedules may be able to wet larger volumes of the tree root zone. Obviously, installing multiple drip lines would also enable wetting of a larger soil volume.

## DISCUSSION

During the drought period from 1997 to 2010, many trees in the streets and parks of Melbourne suffered health declines and in some cases death. The health and survival of European elms and London planes within the City of Melbourne are of particular interest because they are such an important element of the city landscape. The causes of tree health decline are not completely understood and may vary with species; however, the extended period of drought and associated restrictions on tree irrigation are undoubtedly major contributors. Extended tree water stress is recognized as one of the most common contributors to tree mortality, but tree mortality is often multi-factorial in nature (McDowell et al. 2008). The effects of an elm leaf beetle infestation during this period of drought undoubtedly added another level of stress to elms and contributed to mortality levels (Kuhlman 1971).

There is a commonly held view that the years of sprinkler irrigating parkland has led to the development of trees with shallow root systems that are subsequently more vulnerable to water stress when irrigation is reduced or restricted. However, not all parkland tree species in Melbourne experienced a decline in health during the drought or in response to irrigation restrictions. Figure 4 and Table 2 show the health status of trees surveyed in The Domain. The trees shown in the table are those species where there were more than 15 specimens present. This data clearly shows that many of the temperate zone species are in poorer health than most of the Australian native trees or trees from other drier regions. In fact, it may rather be the case that years of lawn sprinkler irrigation allowed the continued growth and survival of species that have become, or always were, marginal under a Melbourne climate.

The process of tree health decline, where trees gradually lose canopy volume (leaf thinning followed by branch death and eventually tree death), has been described many times. Various contributory factors can include drought, acid rain, disease, insect pests, changed soil physical conditions, and root loss. An assessment of the stages of a tree decline provided by Heatwole and Lowman (1986) state that if a tree's energy resources are exhausted by epicormic shoot growth in an unsuccessful attempt to replace crown loss, epicormic growth then ceases and the tree eventually dies. Melbourne canopy health surveys employed in this study use a similar series of stages to categorize tree condition. Surprisingly, the mechanisms of drought-induced tree health decline are not universally accepted and debate continues as to the dominant mechanisms involved. McDowell et al. (2008), in a review of drought and plant death, stated that drought-induced tree injury or mortality had two possible mechanisms. In one mechanism, trees ultimately perish as a result of "hydraulic failure" and desiccation, and in the other they perish through sustained "carbon starvation," whereby carbohydrate reserves are exhausted by ongoing metabolism and respiration demands that are not adequately replenished by photosynthesis because of stomatal closure from associated water stress (Waring 1987; McDowell et al. 2008). Regardless, it is apparent that tree water stress plays a role in both scenarios as tree health declines towards mortality, and the dominant mechanism probably varies according to the species, plant functional group, and their suite of stress adaptation strategies. For example, more drought tolerant species, able to maintain low levels of carbon assimilation, may be more likely to suffer "hydraulic failure" where soil moisture availability (or atmospheric vapor pressure deficit) drops so low that the continuum of water between the soil, roots, stem, and canopy is broken, resulting in the death of crown tissues. However, as summarized by McDowell et al. (2008), "our current understanding of the causes of tree mortality is surprisingly limited, even though a rich literature exists on plant responses to stress. Essentially, we cannot address questions such as: how severe must a drought be to kill a tree; and during drought, which trees will die and which will survive?"

In the 1997–2010 drought, the soil moisture conditions presented in this paper and the heat wave temperatures experienced in January 2009 can be considered as a foretaste of future climate change conditions. The environmental conditions that the trees in Melbourne experienced, as a result of drought and water restrictions, and the efficacy of subsequent management interventions, need to be assessed, considered, and discussed to inform future urban greenspace management. The development of tree and green space management strategies for drought preparation and response should be central to any city's overall climate change adaptation strategy and should consider some of the following issues and management options.

### Plant Selection

The recent drought in Melbourne resulted in several consecutive years where rainfall was reduced to two-thirds of the long-term average, which adversely affected some species more than others, with temperate deciduous species in particular being badly affected. Tree managers should be considering the species composition of their tree population renewal programs to accommodate the possibility that extreme and extended drought events become more common in the future. While tree population diversity is regarded as desirable (Muller and Bornstein 2010), diversity reflecting increased tolerance of environmental stresses is rarely specifically addressed.

Trees that are most likely to be successful under the environmental conditions forecast under climate change will possess physiological attributes that endow both tolerance of water stress and heat stress (Moore 2011). Potentially useful species may be found in examination of published tree lists from other regions, wider ranges of provenance for species with extensive ranges (Santamour et al. 1980), or from homoclime studies (matching against likely future climates rather than current conditions). The effects of the drought (see Table 2) have been considered by Melbourne city planners. In late 2011, a draft urban forest strategy was published (City of Melbourne 2011). One of the goals of the strategy is to increase tree species diversity, with a stated goal of having no more than 5% of the tree population represented by a single species. At present, three species [elms, London plane trees, and river red gums (*Eucalyptus camaldulensis*)] make up 35% of the city's tree population.

## Irrigation

If water deficit due to drought was the major cause of the health decline in Melbourne's tree population, irrigation is the most logical solution, as no other soil or tree treatment is capable of overcoming sustained drought stress of mature trees. To improve the efficiency with which irrigation water is delivered, various approaches can be taken. These include improved soil moisture monitoring, use of alternative water sources, and high-efficiency delivery systems.

## Soil Moisture Monitoring

To improve the quality of data provided by the soil moisture monitoring program described in this study, Melbourne has established a further network of 100 sampling sites for capacitance dielectric soil moisture measurement to a depth of 1 m (Diviner 2000™, Sentek Pty. Ltd., Stepney, South Australia, Australia) in both irrigated and un-irrigated parks throughout Melbourne. While this technology can provide useful soil moisture information for tree managers, it is recognized that the installation of the permanent access tubes for this technology is complex and quite expensive, which may limit its wider use.

## Alternative Irrigation Water Supplies

It is unlikely that there will be a return to unrestricted irrigation of trees and greenspace with potable-quality water, although access to recycled sewage wastewater and/or desalinized water in the future may provide greater flexibility and improved tree health. These alternative water sources will require the monitoring of soil health indicators to detect potential salinization effects of these higher-salt water sources (e.g., Tanji et al. *undated*). Another promising alternative water source is the use of on-site (or near site) captured storm water for tree irrigation. This builds upon the water sensitive urban design concept with localized storage and distribution (passive or pumped) networks. Melbourne is beginning to install these facilities at a number of locations around the city.

## Point Source Irrigation Systems

Because of their high efficiency, the continued adoption of drip irrigation, and similar point source systems, seems probable, but their efficacy for irrigation of parkland trees requires a clear understanding of water supply and demand. The tree water balance model reported in this paper indicated that potential tree use of drip-applied water can be greater than the rate of supply, making it difficult to wet large volumes of soil or alleviate tree water stress. However, a study in California (Hickman 1993) showed that using drippers in mid-summer to irrigate drought-stressed oak trees led to improved growth that was evident up to four years after the irrigation event. In that California study, the drippers were run for 30 hours at 2.5 mm $h^{-1}$, delivering the equivalent of 75 mm of irrigation, which wetted the soil to field capacity to a depth of at least 350 mm. This is a much heavier application rate than that used by the City of Melbourne and it is worth investigating whether this level of irrigation is feasible with the infrastructure available within an urban context. The California study did not present information that allowed the irrigation application to be converted to L $tree^{-1}$ for comparison.

## Irrigation for Root Growth

Cockroft and Olsen (1972) and Richards and Cockroft (1975) found that in irrigated deciduous trees, fine root growth occurred in spring and was dependent on soil moisture content at that time. While irrigation could offset tree moisture deficit during summer, it had little effect on new root growth over summer unless soil was kept constantly wet. These findings suggest that apart from the obvious water deficit effects on tree canopy processes, many of Melbourne's trees may not have been able to produce new fine roots in spring or sustain them for water resource acquisition through the summer months, possibly for several years. This may have resulted in a concurrent decline in root system health, in addition to the observed poor canopy health. It may be possible to address this issue through the timely operation of point source irrigation systems, to support and promote fine root growth in early spring, prior to the commencement of normal summer irrigation.

Winter and spring irrigation with drip systems is one way of recharging larger soil volumes to field capacity at a time when evapotranspirative demand is low, and this will have great value in years when winter rainfall is below average and therefore soil water recharge is poor. The August 2009 study showed that in winter, soil could be brought to field capacity quite quickly with drip irrigation, but that most wetting occurred close to the emitter. Wetting to a depth of 1 m was possible but this would only be of benefit if there were roots at that depth to exploit the water. Urban tree root systems are often shallow (Gilman 1990), but deep roots can occur close to the trunk of many species (Stone and Kalisz 1991; Canadell et al. 1996). As such, it may be more effective to place drip irrigation lines close to the trunk for this reason and for the fact that potential evaporation will be less under the canopy of the tree. Heavy irrigation at the base of the trunk may also simulate the effects of stem flow (water captured in the canopy and directed down the branches and trunk to the ground, where it is redirected along major roots) (Johnson and Lehman 2006). If access to tree irrigation water is limited in the future, drip irrigation and mulch are demonstrated to improve the efficiency of delivering that water. Further work is needed to investigate whether there is strategic value in being selective about where that water is placed.

# CONCLUSION

The period of below-average rainfall that affected much of southern and eastern Australia between 1997 and 2009, and the changes in tree irrigation practices as a result of tighter restrictions in urban water use in response to this drought, led to a decline in tree heath in the parks and streets of Melbourne, Victoria, Australia, especially in temperate climate species. The City of Melbourne retrofitted drip line irrigation systems in many park areas in an attempt to comply with tighter water restrictions while ameliorating soil moisture conditions experienced by valued tree populations. A study of soil wetting patterns under drip lines in late summer 2009 found that at most sites the soil under the drip lines remained relatively dry. A model of tree water consumption demonstrated that drip line irrigation flow rates were less than potential tree water demand, and as such were insufficient to alleviate tree drought stress. However, a study of drip line irrigation in late winter showed that to be an effective way of recharging a large proportion of the soil profile to compensate for failed or below-average winter rains. Tree decline and crown death is likely due to hydraulic failure, rather than carbohydrate starvation, and was more evident in vulnerable tree species experiencing drought conditions beyond their tolerances. In the light of this, it is recommended that urban tree managers review their tree population management and renewal schedules with regard to forecast climate change scenarios, and that further research is performed to investigate how point source irrigations systems, because of their water efficiency, can be used more effectively to manage trees under drought conditions.

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**Zusammenfassung.** Trockenheit kann zur Sterblichkeit von urbanen Baumpopulationen führen. Die Stadt Melbourne, Viktoria, Australien, verwaltet eine große Population von Bäumen, die einen wichtigen Beitrag zum Ökosystem leisten und ein wertvoller Teil des kulturellen Erbes sind. Zwischen 1997 und 2009 wurde Melbourne von einer ernsten Trockenheit bedroht, die zu einem signifikanten Rückgang der Baumgesundheit führte. Besonders Ulmen und Platanen waren schwer betroffen. Diese Studie präsentiert die Daten aus einer Umfrage zum Baumgesundheitsstatus und aus Studien zur nachgerüsteten Tropfenbewässerung. Eine Studie zur Bodenbefeuchtung im Sommer 2009 fand heraus, dass die Tropfenbewässerung in den meisten Fällen keinen oder nur wenig Einfluss auf den Bodenfeuchtigkeitsgehalt hatte und eine modellierte Studie über den Baumwasserverbrauch zeigte, dass Wasser aus einer Tropfenbewässerung nur einen Bruchteil des Wasserbedarfs eines ausgewachsenen Baumes liefern kann. Im Gegensatz dazu kann Tropfenbewässerung im Winter die Bodenfeuchtigkeitsgehalte wieder auffüllen. Der verantwortliche Mechanismus für den Rückgang von Baumgesundheit während der Trockenheit wird hier diskutiert. Während die Trockenheit zeitweise abgeschwächt war, suggerieren die Klimawechselszenarien für Südaustralien, das zunehmende Variabilität des Regenfalls und Trockenheitsperioden auftreten werden. Die aus den kürzlich auftretenden Trockenheitsperioden gewonnenen Erfahrungen liefern nützliche Informationen an den urbanen Forstplaner bei künftigen Projekten.

**Resumen.** La sequía puede llevar a la mortalidad de poblaciones de árboles urbanos. La ciudad de Melbourne, Victoria, Australia, maneja una gran población de árboles que proporcionan importantes servicios a los ecosistemas y de valores culturales patrimoniales. Entre 1997 y 2009 Melbourne se vio afectada por una sequía grave que ha causado una disminución significativa en la salud de los árboles. Los olmos y los plátanos en particular se vieron seriamente afectados. Este artículo presenta los datos de una encuesta del estado de salud del árbol, y de los sistemas de riego en la línea de goteo. Un estudio de la humedad del suelo en el otoño de 2009 encontró que el uso de riego por goteo tenía, en la mayoría de los casos, poco o ningún efecto sobre los niveles de humedad del suelo y un estudio de modelado de uso del agua por el árbol mostró que el agua suministrada por riego por goteo proporcionó sólo una fracción del agua requerida por un árbol maduro. En contraste, el riego por goteo en el último invierno fue capaz de recargar los niveles de humedad del suelo. Se discuten los mecanismos responsables de la disminución de la salud de los árboles durante la sequía. Mientras que la sequía ha sido aliviada temporalmente, los escenarios de cambio climático para el sur de Australia sugieren que la variabilidad en el aumento de las precipitaciones y las sequías serán más comunes. Las experiencias adquiridas durante la reciente sequía proporcionan información útil para los administradores de los árboles urbanos en la planificación para el futuro.