ARBORICULTURE & URBAN FORESTRY

ISA

Scientific Journal of the International Society of Arboriculture Volume 39, No. 3, May 2013

ARBORICULTURE & URBAN FORESTRY
Volume 39, Issue 3, May 2013
Formerly the Journal of Arboriculture, 1975 – 2005 (Volumes 1 – 31)

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Key Words. Adelaide; Australia; Stormwater; Urban Forest Management; Water Policy.

Abstract. Water is a valuable resource, but its preferred use by society for other, higher priorities has resulted in a scarcity for the urban forest. However, the value of the urban forest in providing environmental and ecological services that have significant benefits for human health, well-being, and the liveability of cities demands the reconsideration of the priority of water use by the urban forest. Health authorities are advocating the value of urban greenspace that may require the use of water, especially storm water, as climate change threatens more severe heatwaves.

Trees have an important and long-term role in water-sensitive urban design that efficiently uses and reduces pollution from storm water. Knowledge of tree root systems and their interaction with soils means that irrigation can be targeted in a way that maximizes the efficient and effective use of water. Understanding stomatal behavior also allows optimal timing of irrigation for photosynthetic efficiency while capturing the benefits of transpirational cooling, which may reduce extra deaths during heat waves. The economic, social, and health benefits justify the efficient and effective use of valuable water.
Key Words. Australia; Drought; Foliage; Root Adaptation; Urban Water Use.

Abstract. The maintenance and expansion of urban forests is a major challenge in periods of low rainfall and restricted availability of appropriate-quality water sources for trees. The recent drought in eastern Australia has highlighted the need for innovation and new approaches to ensure tree health is preserved. Responses adopted by the Royal Botanic Gardens Melbourne and others have involved investigations into species more suited to changing climate conditions, assessment of tree and landscape water demand, understanding the hydrology of the site, effective irrigation delivery, management of the soil reservoir to optimize harvested stormwater, and provide soil water reserves for future high demand summer periods.
Key Words. Australia; Crop Coefficients; Drought; Royal Botanic Gardens Melbourne; Tree Watering; Soil Moisture Sensors; Urban Forest.

 | ISSN:1935-5297

Abstract. Understanding native habitats of species successful as subtropical and tropical urban trees yield insights into how to minimize urban tree water deficit stress experienced during monsoonal dry periods. Equatorial and montane wet forest species rarely subject to drought are generally absent in subtropical and tropical cities with pronounced monsoonal dry seasons. Species native to monsoonal dry forests appear to have wide environmental tolerances, and are successful as urban trees in many tropical cities. Monsoonal dry forest species have a tendency to be deep rooted to avoid drought, with leaf habits falling along an avoidance to tolerance spectrum. Dry deciduous species, typically found on more fertile soils, maximize growth during the monsoonal wet season with high photosynthesis and transpiration rates, then defoliate to avoid stress during the dry season. Evergreen tree species, typically found on less fertile soils, have a higher carbon investment in leaves that photosynthesize and transpire less year-round than do dry deciduous species. Dry deciduous tree species are more common urban trees than dry evergreen species explicitly due to more ornamental floral displays, but also implicitly due to their ability to adjust timing and duration of defoliation in response to drought. An empirical study of three tropical species exhibiting a range of leaf habits showed isohydric behavior that moderates transpiration and conserves soil water during drying. However, dry evergreen species may be less adaptable to tropical urban conditions of pronounced drought, intense heat, and limited rooting volumes than dry deciduous species with malleable leaf habit.

Key Words. Climate Change; Drought Deciduous; Drought Physiology; Dry Evergreen; *Lagerstroemia loudonii*; *Pterocarpus indicus*, *Swietenia macrophylla*; Urban Forestry; Water Stress; Wet Evergreen.

Abstract. A review of the literature concerning water needs and water loss from landscape plants is presented. Studies conducted in the field, using lysimeters, and in containers are summarized and discussed. In some studies, crop coefficients or water use coefficients are included. A discussion of the variability found in research methods and the need for a standardized protocol for tree water needs studies is presented.

Key Words. Crop Coefficients; Irrigation; Lysimeter; Plant Water Loss; Reference Evapotranspiration; Tree Water Needs; Urban Trees; Water Conservation.

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*.

 ISSN:1935-5297

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CONVERSION CHART (METRIC TO IMPERIAL)

Metric unit	Multiply by	To obtain English unit
Length		
millimeters (mm)	0.04	inches (in)
centimeters (cm)	0.4	inches (in)
meters (m)	3.3	feet (ft)
meters (m)	1.1	yards (yd)
kilometers (km)	0.6	miles (mi)
Area		
square centimeters (cm^2)	0.16	square inches (in^2)
square meters (m^2)	1.2	square yards (yd^2)
square meters (m^2)	10.8	square feet (ft^2)
square kilometers (km^2)	0.4	square miles (mi^2)
hectares (ha)	2.5	acres (ac)
Mass (weight)		
grams (g)	0.035	ounces (oz)
kilograms (kg)	2.2	pounds (lb)
metric tonnes (t)	1.1	short tons
Volume		
milliliters (mL)	0.03	fluid ounces (fl oz)
milliliters (mL)	0.06	cubic inches (in^3)
liters (L)	2.1	pints (pt)
liters (L)	1.06	quarts (qt)
liters (L)	0.26	gallons (gal)
cubic meters (m^3)	35	cubic feet (ft^3)
cubic meters (m^3)	1.3	cubic yards (yd^3)
Temperature (exact)		
degrees Celsius (°C)	multiply by 9/5, then add 32	degrees Fahrenheit (°F)

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Water Scarcity and Urban Forests: Science and Public Policy Lessons from a Decade of Drought in Adelaide, Australia

Mark Brindal and Randy Stringer

Abstract. Drawing on the experience of greater metropolitan Adelaide, South Australia, Australia, the paper points to the links and gaps between science and public policy. The paper explores urban stormwater management lessons emerging from a ten-year, prolonged dry period that impacted the integrity of urban forests in the City of Adelaide. Among the questions addressed: will stormwater remain, as its historic and institutional settings suggest, a liability or can it become an asset? Who owns stormwater resources and to whom is its management vested? The paper examines these issues with consideration to the dangers of continuing to use urban forestry management practices that are not informed by science. The study concludes that a more integrated approach to urban water management can maintain the integrity of urban forests in ways that potentially enhance social amenities and economic efficiency.

Key Words. Adelaide; Australia; Stormwater; Urban Forest Management; Water Policy.

In the urban environment, trees are forced to compete for their water with the conflicting demands of the urban built form: vast areas of impermeable surface and drainage infrastructure designed, traditionally, to ensure that precipitation run-off is expeditiously and efficiently removed. Where they exist, the narrow verges through which street trees are supposed to obtain their water are too often inadequate for that purpose (Connellan 2008; May 2009). A number of studies present valuable evidence as to why this occurs (Whitlow et al. 1992; Wagar and Franklin 1994; Morgenroth and Buchan 2009).

In Adelaide, South Australia, Australia, with an average annual precipitation of less than 600 mm, the urban forest, and in particular street trees, prosper. In recent years, Adelaide's urban forests have faced significant challenges from a ten-year, prolonged dry period (PDP), spanning November 2001 until March 2010. Several key developments during the PDP suggest that the urban forest and street trees are unlikely to maintain their health. First, natural underground water resources provide sustenance for some of the city's street trees, leaky potable water, and sewerage infrastructure for many others. For the most part, it is the proximity to the city's well-watered greenspaces (most of which are privately owned) that contribute to the health of the street tree component of Adelaide's urban forest. However, during the PDP all households were subjected to water restrictions, greatly reducing the amount of water applied to gardens (Government of South Australia 2011).

Second, two recently released government program initiatives require changes to how street trees are managed. The '30 Year Plan for Greater Adelaide' (Government of South Australia 2010) and 'Water for Good' (Government of South Australia 2009) programs aim to integrate policy for stormwater and urban forest management. The private and public incentives created by each program impact the viability of urban greenspaces. For example, the 30 Year Plan controls urban sprawl by pursuing urban infill, with potential negative consequences for how impermeable surface areas impact the ability of the urban forest to receive its water requirement through natural absorption.

The Water for Good program enshrines a target for the harvesting of 60 GL of stormwater a year by 2050 to ensure the ongoing viability of the city's potable water supplies. One recent study estimates that urbanized areas in the region produce about 86 GL of stormwater run-off per annum (Government of South Australia 2009). At present, most stormwater flows into the gulf to the west. The volume targeted for collection represents approximately two-thirds of the total estimated urban run-off (Government of South Australia 2004a).

The third development impacting street trees is proposals to reduce leakage in both the potable water and sewerage systems, further depriving the urban forest of water. Because of the water restrictions implemented during the PDP, the suburbs of Adelaide present many examples of abandoned gardens. Some households installed water-wise plants or subsurface irrigation, while others increased areas of impermeable paved surface. Some of these actions may deprive plants of moisture.

Drawing on the experience of greater metropolitan Adelaide during the PDP, this paper aims to highlight the links and gaps between science and public policy that inhibit the capacity to organize more effective institutional structures to manage water for trees. In Adelaide's case, urban stormwater management is the core issue. The paper examines whether the recent experience with stormwater events reveal the city's current institutional arrangements as more of an asset or liability. Why are the tradeoffs of how storm water is managed and used not considered? Who owns storm water, in whom is its management vested and does its management impact the urban forest? This paper seeks to explore these questions, examining the risks for Adelaide's urban forest. It concludes that through a more holistic approach to urban water management the integrity of urban greenspaces can not only be maintained, but can be enhanced in a manner that improves social amenity and economic efficiency.

OVERVIEW OF ADELAIDE

Adelaide, the capital city of South Australia, and its metropolitan environs, is the 80 km long, 30 km wide urban capital of the driest state on Earth's driest inhabited continent. Despite low rainfall levels and high summer temperatures, Adelaide maintains a higher density of urban trees than many of its Australian capital city counterparts (Kirkpatrick et al. 2011). During most of the last decade, the entire southeastern region of Australia was subjected to a PDP, the result of which included severe water restrictions for Adelaide's private and public gardens. Emerging from this experience are first-hand lessons about the costs associated with stressed landscapes, dead tree removal and the loss of environmental services from the urban forest. The drought also highlights how policy reductionism and cost-center accounting create greater potential for institutional conflicts.

Empirical evidence has long demonstrated that urban forests provide multiple benefits that go far beyond adding aesthetic beauty to neighborhoods. Trees in parks, streets, and yards conserve energy in buildings, improve air quality, reduce storm run-off, and enhance the beauty of communities by adding color, texture, and form to community landscapes (e.g., Dwyer et al. 1992; McPherson et al. 1998; McPherson et al. 1999; Brack 2002; Killicoat et. al. 2002; McPherson and Simpson 2002; Nowak and Dwyer 2007). Additionally, Tarran (2009a) summarizes numerous studies that document the beneficial human health outcomes attributed to urban forests.

Policy failures and the complexities of managing urban forests are also well recognized, if not yet well understood, addressed, and resolved. Developing effective urban forestry strategies and policies involves an array of difficult choices. Some choices result in inefficient resource use because many essential benefits and services of urban trees, such as aesthetic values, watershed protection, and climate regulation, are not priced. These benefits and services are valued differently by different households within the same neighborhoods and across different communities. These values and interests in the urban forest and the resources they provide may differ greatly and have a tendency to shift over time, for example, during a PDP.

As policy interests shift and community expectations conflict, difficult management challenges are created that require innovative, science-informed strategies to better integrate urban trees into community development efforts and balance economic, social, and environmental needs with local interests. The emerging views of what urban trees are and what they contribute requires local governments to search for pragmatic management strategies that deal coherently with the contributions of trees to urban development. Additionally, governments must search for organizational structures that better use of these contributions.

These issues are especially relevant for Adelaide because the city's history and identity are associated with its public space, parks, and gardens. The 'parkland town' is a distinctive feature of the urban scene throughout Australia. Its main elements are a central core of town-lands for business and commerce with a surrounding belt of parklands reserved for public use and a peripheral zone of suburban lands. Williams (1966) described the parkland concept with these three elements, explaining "the whole served by a pattern of roads radiating from the center. This threefold division had its first and greatest expression in Adelaide."

Over time, Adelaide's provision of public open space, streets, and generous-sized housing allotments resulted in household blocks with a mix of fruit trees, native plants, and exotic ornamentals, providing canopies that filled in the linear matrix provided by street trees. Today, viewed from an elevated vantage point, the suburban sprawl is lost beneath a canopy, high-rise buildings appearing to be dotted throughout a forest.

Climate and Trees in Adelaide

Adelaide is situated on the St. Vincent Gulf in central, southern Australia and has a hot Mediterranean climate (Koppen climate classification Csa; Peel et al. 2007), meaning mild, wet winters and hot, dry summers. Of all the Australian capital cities, Adelaide is the driest. Rainfall is unreliable, light, and infrequent throughout summer. The average monthly rainfall in January and February, according to data collected for more than 150 years, is around 20 mm, but completely rainless months are not uncommon. In contrast, the winter has fairly reliable rainfall with June being the wettest month of the year, averaging around 80 mm. The annual estimated average rainfall for Adelaide is 585 mm. Annual rainfall totals have ranged from a high of 882.4 mm to 257 mm. In the summer, the average maximum temperature is 29°C, with around three days a year when the daytime temperature is 40°C or warmer (National Climate Centre 2009; Australian Government 2011).

Awareness of the climatological conditions experienced on the Adelaide plains during the PDP is essential to the scientific understanding of the response of the urban forest. The Government declaration that the city was experiencing drought is of interest since evidence suggests it was declared because of a water supply shortfall (Gómez-Muñoz et al. 2010) rather than a lack of precipitation (Australian Government 2011).

While a consistent lack of precipitation throughout the water catchments over the time under discussion led to the drought declaration, precipitation on the city and its metropolitan environs was either average or above average for three of the ten years, and during the summer period (i.e., the time of greatest stress for the urban forest) of two others, there was higher than average summer rainfall. From March 3, 2008, Adelaide recorded 15 consecutive days of temperatures more than 35°C, again a record for an Australian capital.

In November 2009, another heat wave occurred. Daily maximum temperatures during the heat wave were roughly 10°C above average in many locations. From late October until mid-November, the city experienced 10 consecutive days with maximum temperatures greater than 30°C, six consecutive days over 38°C, and the highest November temperature ever recorded, 43°C, on November 19, 2009.

Both heat waves were unusual since the highest temperatures are usually recorded in January and February. Since, locally, these heat waves generally correspond to periods of no precipitation, substantial stress was placed upon the city's urban flora. The combination of high temperatures with the lack of available moisture in the soil profile highlights the stresses to which the urban forest was subjected during prolonged dry periods (Correy 1992; McPherson et. al. 1999; McPherson and Simpson 2003; Gómez-Muñoz et al. 2010).

INSTITUTIONAL FRAMEWORK FOR TREES AND WATER MANAGEMENT

The institutional framework within which urban forestry and stormwater are managed in South Australia is complex. The Government is currently working toward integrating all acts related to water into a single piece of legislation. At a legislative level, trees are mentioned in forty different Acts of Parliament or their attendant regulations. These include, but are not limited to:

- The Sewerage Act of 1929
- The Waterworks Act of 1932
- Water Conservation Act of 1936, and various drainage acts

The principal acts governing urban forestry are:

- The Crown Land Management Act of 2009
- The Residential Parks Act of 2007
- The Native Vegetation Act of 1991
- The Environment Protection Act of 1993
- The Natural Resources Management Act of 2004b
- The Development Act of 1993 and the Development Regulations of 2008

Except in the case of designated National Parks (which fall within the jurisdiction of the Department of Environment and Heritage) and on private lands, management and development of the urban forest falls within the jurisdiction of Local Government Authorities, of which nineteen separate authorities constitute the City and its suburban environs. Three other rural councils have jurisdiction over much of the watershed and drainage in the hills to the east.

The institutional settings in respect to water management and ownership are of critical importance since these will have a direct bearing on the future of Adelaide's urban forest. The kernel of the dilemma surrounding the better use and management of South Australia's stormwater for its urban forest is property rights. The Natural Resources Management Act of 2004 vests ownership of the resource in the State Government; each and every right of any individual to take water within the State falls within the jurisdiction of the Government (sec. 124). All rights at common law—that is, those rights that have been previously adopted into the law through usage, custom, and judicial precedent—are abolished (sec. 124.8).

Administrative arrangements are further complicated since they effectively involve three tiers of government. The Water Act of 2007 and the National Water Commission Act of 2004, of the Commonwealth of Australia, confer shared jurisdiction on the Federal Government. The Government only asserts its rights over water or stormwater in stressed areas. At the present time, Adelaide and most of its suburban areas are not 'prescribed.' Prescription is the method by which the government formally asserts its ownership claim, thereby establishing its jurisdiction.

Because government ownership rights can be asserted at any time, local governments seeking to harvest stormwater, or to utilize it in the watering of its urban forest, cannot operate with certainty, since they are utilizing a resource that is not theirs to claim. This ownership uncertainty acts as an impediment to the speedy evolution of the best management practices for the city's urban forest.

The debate about what constitutes 'best practice' in water resource management continues to be hampered by favoring a technical conceptualization of water. In line with this view, water resources management is seen as controlling and governing direct water use and related waste flows, not as managing water's various functions in the landscape (Falkenmark 2003). One key stormwater function is its role in maintaining the health of urban forests.

Evidence suggests stormwater run-off from impervious surfaces can contribute to the collapse of healthy freshwater ecosystems in urban environments (Ladson et al. 2006; Roy et. al. 2008). In the Australian context, research emphasizes an *ad hoc* approach to stormwater management characterized by partial remedies overly focused on engineering solutions and a lack economic analysis and attempts to integrate policies (Tisdell and Ward 2003; Grafton and Ward 2008; Ward et al. 2008). A recent study focusing specifically on evidence from the United States and Australia identifies seven major impediments to sustainable urban stormwater management (Roy et. al. 2008): 1) uncertainties in performance and cost, 2) insufficient engineering standards and guidelines, 3) fragmented responsibilities, 4) lack of institutional capacity, 5) lack of legislative mandate, 6) lack of funding and effective market incentives, and 7) resistance to change.

In South Australia, the fragmented responsibilities impediment is a significant concern as water is not treated as a single resource with multiple functions, nor are the watersheds considered on a system-wide scale. Water is compartmentalized into three discrete business units: potable water supplies, sewerage water disposal, and stormwater disposal. Unlike many cities where effluent and stormwater disposal are served by common infrastructure, in South Australia, both infrastructures

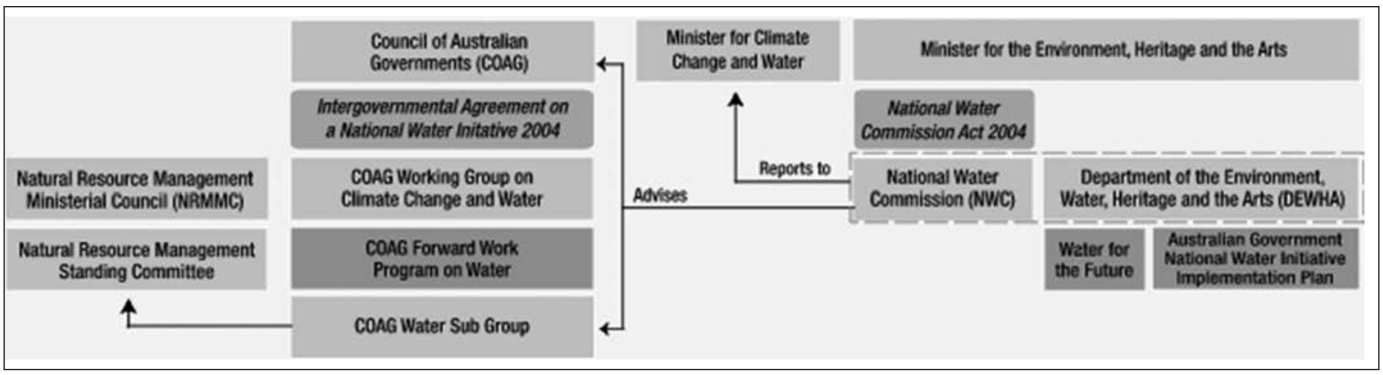

Figure 1. Natural arrangements for water governance (2010). Diagram courtesy of the National Water Commission Archive.

are discrete: it is unlawful to drain stormwater into the effluent disposal system (Government of South Australia 1929).

While some local council innovations treat the resource in a more holistic manner, urban-wide and watershed-wide integrated management is in its early development stages. Most solutions to date center around demand management through regulation and pricing, the installation of rain water tanks plumbed directly into the household grey-water system, and the watering of parks and gardens using treated effluent rather than potable water (Laurenson et al, 2010).

Figure 1 illustrates national arrangements for water governance. At the state level, three tiers of governance are involved (Figure 2).

The convoluted nature of these interfaces generates haphazard institutional arrangements. Many of the organizational structures result in a silo approach to their perceived areas of responsibility, engendering uncertainty and greatly complicating resource management.

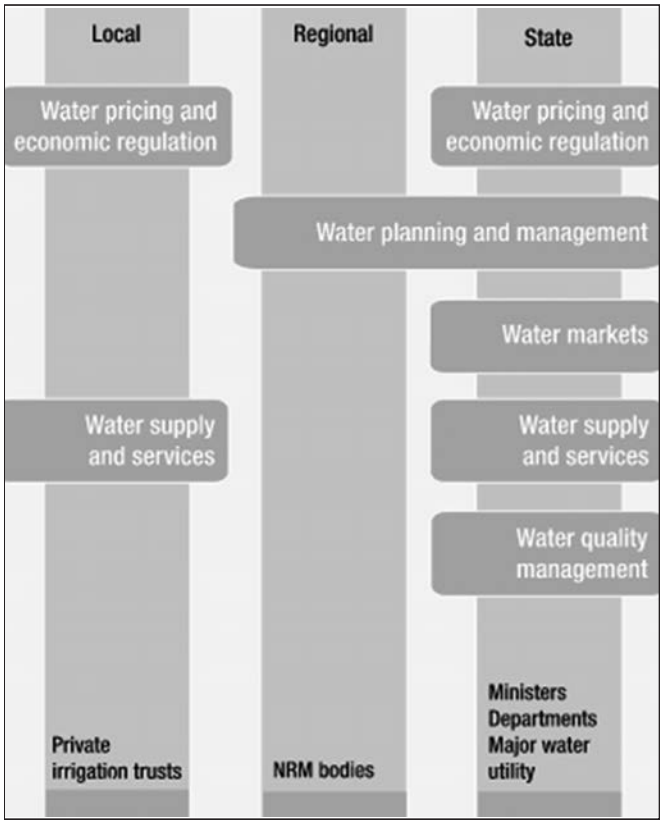

Figure 2. South Australian (state) arrangements for water governance (2010). Diagram courtesy of the National Water Commission Archive.

Seeking and Implementing Science Based Information

While the relationship between science and public policy is symbiotic, in Adelaide, when necessity dictates, such as with the introduction of policies that which might prove unpopular to constituents (e.g., water restrictions), science is invoked selectively to justify the policy and to seek solutions that lessen negative public reaction. Short-term political expediency too often ignores good science.

For example, substituting treated effluent for the potable water previously used to irrigate the city's parks and gardens, especially within the constraints of what was seen as a drought situation, has public appeal. Adelaide has three main sewerage treatment plants. The northern plant's effluent is used for irrigated agriculture, the southern plant provides grey water for some of the State's premier vineyards, and the central effluent treatment plant discharges the majority of its treated output directly into Gulf St. Vincent. With water restrictions, the Federal and State governments constructed a pipeline to convey treated effluent to the city's parks and gardens. The project proceeded despite warnings by scientists and arborists concerning the long-term viability of the project: the treated effluent has elevated sodium levels and many of the soil profiles to which it will be applied are sodic (Meyer 2008).

To better integrate urban greenspaces with the environment in which the city is situated, some research argues for planting species indigenous to the area (Mibus and Shepherd 2004). In making their arguments, the authors of these studies often ignore the built forms as a major and inescapable factor of the urban environment. Especially in periods such as the recent PDP, calls are made for plantings of water efficient, indigenous, desert region tree species. The aggressive nature of their root systems, with the consequent threat to pavements, road surfaces, and adjacent buildings, is often not considered. Indeed, in some cases, urban environments may be so anthropogenically affected that native plants may be inappropriate as urban habitat.

Most Australian native flora are non-deciduous. Consequently, understory litter problems are continual, and especially where such trees are planted adjacent to roads and walkways, management demands in respect to understory maintenance are higher than for deciduous species. Additionally, many writers suggest that the most beneficial remediation of the urban heat island effect can be most efficiently achieved through the planting of deciduous species, allowing maximum solar warming of buildings in the winter while shielding them from summer radiation (Correy 1992; Brindal and Stringer 2009; Fisher 2009; Gómez-Muñoz et al. 2010).

Lost opportunities notwithstanding, a number of scientific innovations with potential importance to urban foresters have been validated by the climatic conditions of the last decade. An example are projects to collect stormwater runoff directly from buildings or adjacent paved areas, channeling it either into aquifer storage for subsequent irrigation use or dispersing it directly into soil profiles, thus making it available to local trees. The system in one of these projects, Brompton Parfitt Square, is illustrated in Figure 3. Mortality of trees that have access to these projects was, during the decade under examination, zero.

Interestingly, as urban run-off increases, existing infrastructure constraints can provide an unexpected opportunity for innovative urban greenspace design. One residential suburb (Northgate) was recently developed on land that had previously been used for agricultural research purposes. However, because the stormwater infrastructure that carried the water westward to the gulf could not carry the additional capacity, the suburb had to incorporate a series of greenspaces and wetlands to retain the stormwater run-off on site, thus making it available to the urban forest in the vicinity.

Other scientific research with empirical evaluation includes a stormwater harvesting trial by a local non-government organization (TREENET). The trial includes the installation, monitoring, and evaluation of stormwater diversion devices (Wark 2003). Each device diverts stormwater from the water table into a soakage trench, then into a soil medium within the verge. The aim is to increase the moisture available to street trees, remove pollutants from stormwater, and reduce the need for tanker watering of street trees.

The proposed TREENET system can be engineered to collect given volumes of water during any rainfall event. It has the advantage of capturing first flush run-off. Importantly, this initial run-off contains all of the environmental 'bads.' Because these pollutants can be captured either by the soakage trench or captured and processed in the root zone of trees, the ecosystem advantages and the smaller amount of remediation required to purify the remaining water in wetlands is axiomatic (Brindal and Stringer 2009). A cost-effective adaptation includes a curbside topographical modification to enable the *in situ* construction of curbside swales (Kazemi et al. 2011). The emergence of NGOs like TREENET demonstrate how urban forests are gradually becoming topics of discussion among articulate groups of tree specialists, city dwellers, scientists, and educators.

DISCUSSION

The climatological conditions in southeastern Australia during the last decade have provided unique opportunities for policy makers and scientists alike to better understand the impacts of stormwater on urban forests and opportunities for urban forests to ameliorate drought impacts. The opportunity still exists to improve understanding of these impacts and opportunities both scientifically and in the development of public policy. However, the Australian experience has been characterized more by individuals choosing the science to justify particular policy initiatives than by individuals using the science to uncover optimal solutions.

This paper highlights the issues, links, and gaps between science and public policy that inhibit capacity to organize more effective institutional structures. These gaps are closely aligned with the seven major impediments to sustainable urban stormwater management presented in the findings of Roy et al. (2008). These impediments include:

- inadequate property rights surrounding the ownership and management of stormwater for trees;
- a long tradition of choosing engineering solutions to justify policy decisions;
- no process in place to encourage, seek, or implement science-based information;

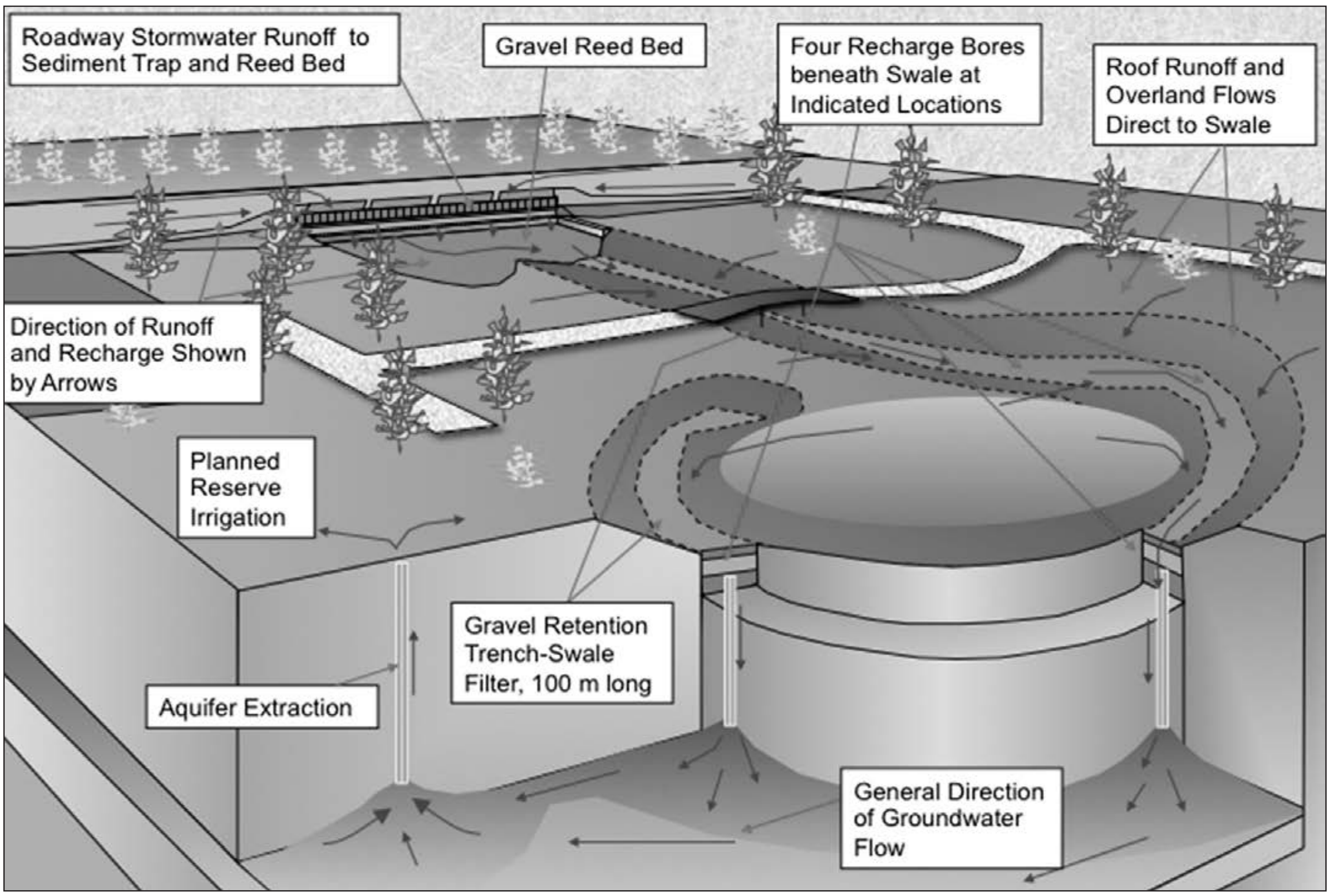

Figure 3. Stormwater Harvesting, Brompton Parfitt Square, South Australia. Diagram courtesy of Brompton Parfitt Square Stormwater Management System, Centre for Water Management and Reuse, University of South Australia.

- a lack of knowledge and interest in economic incentives and cost–benefit analyses;
- complex administrative arrangements, involving three tiers of government; and
- the city's watersheds and drainages that not considered on a system-wide scale, resulting in fragmented responsibilities.

This paper attempts to demonstrate that these links and gaps impinge negatively on the management of the urban forest. The arguments presented here suggest the need for a much more integrated policy and management approach to address the water needs of Adelaide. Urban foresters are uniquely positioned to lead and to support these initiatives. Developing more effective, integrated urban forestry policies involves an array of difficult choices. Some policy choices result in inefficient resource use because many essential benefits and services of urban trees are not priced. As policy interests shift and community expectations conflict, difficult management challenges are created, requiring innovative, science-informed strategies that better integrate urban trees into community development efforts and balance economic, social, and environmental needs among local interests.

Tarran (2009b) presents a compelling case in that by drawing on theory and methods of natural and social sciences in an integrated manner, the emerging urban ecology discipline will lead to better ways of managing settlements where people live, work, and play. Part of this new management regime includes greater attention to supporting ecosystem functions that influence the quality of life. In Adelaide, the PDP emphasized to public policy managers how and where water flows across the landscape. However, the policy community pays less attention to understanding how capturing and changing stormwater flow impacts the benefits provided by urban forests, or how urban forests could substitute for this infrastructure.

Making use of urban forest benefits requires local governments to search for practical management strategies that deal coherently with the contributions of trees to urban development. In addition, there is a need to search for organizational structures that make better use of these contributions. The science, policy roles, and management of urban forestry (i.e., the knowledge, concepts, institutions, and practices through which multiple and competing demands for trees are managed), is changing as well. The changes are emerging as awareness grows of how local communities control and depend on trees and urban forests, prompting efforts to strengthen local stakes in urban forestry and street tree management, programs, and activities (Killicoat et. al. 2002).

An important message of this paper is that Adelaide's forests need to be better recognized as an integral part of the urban economy. Urban development strategies, from stormwater management to urban infill strategies, need to include the capital values of forests in policy design and program evaluations to understand the consequences of modifying tree stocks, qualities, and distributions. Urban trees need to be more widely acknowledged as both productive capital stocks and as components of public infrastructural systems.

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Zusammenfasung. Unter Berücksichtigung der Erfahrungen der größeren Metropole Adelaide, Südaustralien verweist diese Studie auf die Verbindungen und die Lücken zwischen der Wissenschaft und der öffentlichen Politik. Die Studie erforscht die Lektionen aus dem Management des urbanen Sturmwassers aus einer zehnjährigen, verlängerten Trockenperiode, die einen Einfluss auf die Integrität der urbanen Forstflächen in der Stadt Adelaide hatte. Unter der Fragestellung war: wird das Sturmwasser, wie die historischen und institutionellen Begebenheiten suggerieren, eine Belastung bleiben oder könnte es ein Vorzug werden? Wem gehören die Sturmwasserressourcen und an wen ist das Management zu übertragen? Diese Studie untersucht diese Fragen mit der Berücksichtigung der Gefahr des andauernden Gebrauchs urbaner Forstmanagementpraxis, die nicht von der Wissenschaft informiert war. Die Studie ergab, dass ein mehr integraler Ansatz zum urbanen Wasser-Management die Integrität urbaner Forste in Bezug darauf erhalten kann, dass soziale Vorteile und ökonomische Effizienz potentiell verbessert werden kann.

Resumen. Basándose en la experiencia metropolitana de Adelaida, South Australia, Australia, el trabajo se refiere a los vínculos y los abismos entre la ciencia y la política pública. El documento explora las lecciones de la gestión de aguas pluviales urbanas resultantes del prolongado período de sequía de diez años que afectó la integridad de los bosques urbanos en la ciudad de Adelaida. Entre las preguntas abordadas: ¿seguirán las tormentas como lo sugieren las configuraciones históricas e institucionales o se convertirán en una preocupación actual? ¿Quién posee los recursos de aguas pluviales y a quién corresponde su gestión? El documento examina estos temas con consideración a los peligros de continuar con el uso de prácticas de manejo forestal urbano que no han sido informadas por la ciencia. El estudio concluye que un enfoque más integrado de la gestión del agua urbana puede mantener la integridad de los bosques urbanos en formas que potencialmente mejoren los servicios sociales y la eficiencia económica.

Arboriculture & Urban Forestry 2013. 39(3): 109-115

Adaptations of Australian Tree Species Relevant to Water Scarcity in the Urban Forest

G.M. Moore

Abstract. Water is a valuable resource, but its preferred use by society for other, higher priorities has resulted in a scarcity for the urban forest. However, the value of the urban forest in providing environmental and ecological services that have significant benefits for human health, well-being, and the liveability of cities demands the reconsideration of the priority of water use by the urban forest. Health authorities are advocating the value of urban greenspace that may require the use of water, especially storm water, as climate change threatens more severe heatwaves.

Trees have an important and long-term role in water-sensitive urban design that efficiently uses and reduces pollution from storm water. Knowledge of tree root systems and their interaction with soils means that irrigation can be targeted in a way that maximizes the efficient and effective use of water. Understanding stomatal behavior also allows optimal timing of irrigation for photosynthetic efficiency while capturing the benefits of transpirational cooling, which may reduce extra deaths during heat waves. The economic, social, and health benefits justify the efficient and effective use of valuable water.

Key Words. Australia; Drought; Foliage; Root Adaptation; Urban Water Use.

Recently, much of the east coast of Australia was gripped with a prolonged period of lower than average rainfall. The State of Victoria had entered its fourteenth consecutive year of below-average rainfall (Bureau of Meteorology 2011). Since then, there has been record rainfall and flooding in much of the region, and the media have reported the general relief that the drought had finally broken.

The dry period may have been a drought and part of natural cycles of perhaps five hundred years or more, but current meteorological data are too recent to reveal such patterns. However, the dry period, recent major storm events, changes in rainfall patterns, and summer flooding are consistent with predictions made over the past two decades in relation to climate change. It is too early to trumpet the end of the dry period—one season of above-average rainfall should not obliterate the trend of the previous fourteen years.

So the focus on water scarcity, availability, and the efficiency of water use in the urban forest is timely and of great urgency in the context of the Australian environment and climate change more generally. However, is there really a scarcity of water for the urban forest? In cities as diverse as Melbourne, Victoria, and Perth, Western Australia, Australia, only about 8%–9% of the available potable water is used for general open space purposes. This includes both public and private (back and front gardens) open space, and even less water is allocated to trees in the urban forest (Victorian Department of Sustainability and Environment 2006; Victorian Department of Sustainability and Environment 2007).

Furthermore, 10 years ago, gardens, parks, and sporting ovals consumed about 12% of the State of Victoria's water. Now it is less than 9%. This is a 25% reduction, and the Law of Diminishing Returns suggests that having made significant savings in water, no matter how much one tries, they are unlikely to get more significant savings from parks, gardens, and the urban forest (Water Resources Strategy Committee 2002; Victorian Department of Sustainability and Environment 2004; Victorian Department of Sustainability and Environment 2007).

Water is a precious commodity, but it is only scarce because other priorities for its use are seen as being more important than open space and the urban forest. No one would deny that the first priority for potable water is to meet the drinking and health needs of citizens. However, in every State, the greatest users of water by far rest in industry and agriculture (Victorian Department of Sustainability and Environment 2004; Victorian Department of Sustainability and Environment 2007). No one would suggest that the urban forest should be irrigated at the expense of drinking water or at a cost to human health or life. The issue is about using a valuable resource sustainably and effectively to capture maximum benefits, including environmental benefits (Nowak et al. 2010). Research must inform the management practices that are required to maintain the urban forest, using water effectively, efficiently, economically, and sustainably.

THE PRIORITY FOR WATER AND THE URBAN FOREST

While urban forests are beautiful and decorative, these attributes often conceal the many functions and services that they provide to cities to the point where their social, health, economic, and environmental benefits are overlooked (McPherson 2007; Moore 2009; Nowak et al. 2010). What else delivers so many benefits immediately, and benefits that last centuries into the future, prolonging healthy lives and making cities both sustainable and liveable? Urban forests have been silent assets to cities for decades and even centuries. They are major and essential urban infrastructure (Daniels and Tait 2005).

Cities are biodiversity hot spots due to the variety of habitats available in public and private open space, especially the diversity of plantings in domestic front and back yards (Daniels and Tait 2005). The requirement for tree managers is to establish a priority for the urban forest in the allocation of a precious and valuable, rather than scarce, commodity (Connellan 2008). Society will allocate water to items for which there is an economic and political imperative.

For most of its history, the price of water in Australia has been subsidized, however, it does have a real economic value and in most States increasing water prices are moving toward that value (Victorian Department of Sustainability and Environment 2004; Victorian Department of Sustainability and Environment 2006; Victorian Department of Sustainability and Environment 2007). To maintain the urban forest, water must be used effectively and efficiently. There can be no going back to the days of profligate water use and year-round emerald green lawns (Moore 2009). The environment and economy cannot sustain such an approach (Water Resources Strategy Committee 2002). How well informed are the practices governing the use of water in the urban forest and what are the research needs that would enhance best management practices?

ADAPTATIONS RELEVANT TO WATER STRESS

Trees in the urban forest face the dilemma of all terrestrial plants: the need to balance the interaction of carbon and water cycles to allow survival and growth. If water is limited and stomata close, carbon assimilation through photosynthesis is reduced (Cowan 1981; Curran et al. 2009; Martin St. Paul et al. 2012). Thus in the urban environment, restricting water availability to trees in the urban forest may also restrict the benefits that they provide, such as their capacity for carbon sequestration (Jonson and Freudenberger 2011) and transpirational cooling.

The performance of different trees species in minimizing water loss, but at the same time maintaining carbon dioxide gain, is defined as water-use efficiency:

$$\text{Water-use efficiency} = \frac{\text{Carbon gained}}{\text{Water lost}}$$

The value of water use efficiency varies for different species and can be used to select trees that are more productive for use in cities of drier climates (Ladiges et al. 2005).

Australian tree species possess many and varied adaptations to growing in arid environments (Table 1). One of the defining characteristics of many Australian plant genera is sclerophylly. Sclerophyllous trees possess large amounts of sclerenchyma tissue, which maintains cellular volume as conditions dry. It is often assumed that sclerophylls are low water users, but paradoxically many have poor stomatal control and will use whatever water is available until they wilt (Ladiges et al. 2005). Many have the capacity to survive in environments where water is limited, and managers could proactively minimize the supply of water in low-water environments using sclerophyllous trees.

Table 1. Adaptations of Australian tree species to aridity (Ashton 1975; Moore 1981; Pate and McComb 1981; New 1984; Moore 1990; Knox et al. 1994; King 1997; Atwell et al. 1999; Ladiges et al. 2005).

Adaptation	Mechanism	Examples
Sclerophylly	Maintains cellular volume	Many Australian genera, such as *Acacia,* and members of the Proteaceae and Myrtaceae families
Altered leaf anatomy	Reduces leaf surface area	*Hakea* and *Acacia* species with rolled needle like leaves
Phyllodes/cladodes	Reduces surface area; reduces evapotranspiration	Most Australian *Acacia* species
Vertically hanging leaves	Reduces absorption of radiation	Many eucalypt species
Leaf/pinnule movement	Reduces exposed leaf surface area	Bi-pinnate *Acacia* species; *Lophostemon confertus*
Cuticular adornment	Reduces evapotranspiration	Many genera, such as *Eucalyptus*, *Acacia*, and *Casuarina*, with hairy, spiny, or glaucous leaves
Stomatal crypts	Reduces evapotranspiration	*Banksia* species, *Hakea* species
Cuticular ledges	Reduces evapotranspiration	*Eucalyptus preissiana*, *E. obliqua*
Stomatal closure in response to atmospheric vapor deficit	Reduces transpirational water loss	*Eremophila macgillivrayi*, *Myoporum floribundum*, *Myoporum platycarpum*, *Pittosporum phylliraeoides*, *Geijera parviflora*
Facultative deciduousness	Reduces growth but allows survival over tropical dry period	Some Blakella eucalypts, such as *E. clavigera*, *E. grandiflora*, and *E. brachyandra*
Lignotubers/basal burls	Rapid regrowth after foliage loss	Most eucalypts; *Acmena smithii*
Epicormic buds	Rapid regrowth after foliage loss	Most eucalypts
Deep tap root	Allows access to deeper soil water profile	*E. camaldulensis*
High root:shoot ratio	Increases soil volume accessed for water supply	*E. camaldulensis*

The leaves and phyllodes of many Australian species (Table 1) are isobilateral and often hang vertically, thereby reducing the surface area that is exposed to the sun (King 1997). Species such as *Eucalyptus preissiana* (Knox et al. 1994) and *E. obliqua* have prominent cuticular ledges, which overarch their stomata, creating a stomatal antechamber that reduces transpirational water loss (Moore 1981). However, the stomatal anatomy of many common street trees species remains unknown.

In Australian tree species, the number of stomata ranges from about 28 mm^{-2} in *Persoonia* (geebung) to between 100–350 per mm^2 in eucalypts. The number often varies inversely with size with fewer larger stomata contrasting many smaller stomata (Knox et al. 1994). In *Eucalyptus globulus*, there are 300 stomata mm^{-2}, but the leaf area occupied by stomatal apertures is only about 1%. However, with stomata open, the rate of transpirational water loss is the same as for evaporation from an open wet surface; water and gaseous movement through open stomata is remarkably efficient. Thus, knowledge of stomatal rhythms and behavior is essential to understanding tree water use and survival in water-limited environments.

Trees such as *Casuarina littoralis*, *Eucalyptus calophylla*, *Eremophila macgillivrayi*, *Pittosporum phylliraeoides*, and *Myoporum floribundum* show effective stomatal control and so more efficient water use, but if water is limited then their growth rates may be slowed to the point where they are ineffective for planting in the urban forest. Similarly, species such as *Acacia melanoxylon* or *Eucalyptus grandiflora*, which reduce water use through reduction in leaf surface area, may lack the canopy characteristics and density that would make them attractive for urban forest planting.

For most Australian tree species planted in urban environments there are almost no data on basic physiological processes, such as stomatal behavior, let alone whether they are stress avoiders or tolerators in relation to water (Table 2). Which trees have good stomatal control as soil moisture diminishes (Eamus et al. 2001; Prior et al. 2005), which keep their stomata open and so are luxury water-users, and which species can tolerate low internal water potentials are largely unknown (Atwell et al. 1999), except for those few species that are of interest for forestry, timber, or agricultural research (Pate and McComb 1981; Meier and Leuschner 2008). Such basic research would not take large amounts of funding, and simple data gathering using basic porometry would not take long, but this has not attracted the interest of the research funding bodies.

Acacia is Australia's largest indigenous genus with over 900 woody species ranging from shrubs to large trees. They are generally sclerophyllous and Australian species are typically phyllodenous in contrast to the *Acacia* species of Africa and South America (Thukten 2006). Many arid zone *Acacia* species are known for their extreme avoidance of desiccation (New 1984; Broadhurst and Young 2006; Page et al. 2011). While *A. harpophylla* is more drought resistant than *A. aneura*, even the latter has phyllodes that can lose a large proportion of their water content without harm.

Many species maintain cell turgor despite high levels of moisture stress. In some species, phyllode size reduces in drier areas (Thukten 2006; Deines et al. 2011). The size and shape of *A. melanoxylon* phyllodes are affected by both aridity and seasonal rainfall patterns (Farrell and Ashton 1978). Several *Acacia* species have very deep roots that may reach depths of 12 m or more (Table 2). *A. mearnsii* may have roots that penetrate to 6 m, but 75% of the root system is within 600 mm of the soil surface.

The closure of pinnules as soils dry is easily observed in *A. mearnsii*—a bi-pinnate leafed species—growing in the basaltic clays of the western plains near Melbourne. This reduces transpirational water loss. In plantations, *A. mearnsii* could lose 261 kg of water per day compared to *A. decurrens*' 44 kg, but this was largely due to a difference in foliage density with *A. mearnsii* having a foliage mass of 69 kg, while *A. decurrens* had a foliage mass of 9 kg (New 1984). In an urban forest, a choice between these species may come down to a decision about canopy appearance, density and impact versus water use.

There are major research gaps in the use of Australian native species, as well as exotic species, growing under Australian environmental conditions. Few studies are available on water use by

Table 2. Avoidance and Tolerance Mechanisms for coping with low water environments.

Strategy	Mechanism(s)	Growth	Examples
Drought avoidance	Grow where and when water is available	Unaffected until water is limiting	*Eucalyptus regnans*, *E. camaldulensis*, *E. marginata*
Drought tolerance by improved water status	Increased rooting volume	Improved	*Acacia mearnsii*, *E. camaldulensis*, *E. clelandii*, *E. trivalvis*
	Increased root density	Improved	*E. camaldulensis*, *Acacia mearnsii*
	Good stomatal control	Usually reduced	*Casuarina littoralis*, *E. calophylla*, *Eremophila macgillivrayi*, *Pittosporum phylliraeoides*, *Myoporum floribundum*
	Capacity for osmotic adjustment	Usually reduced	*Atriplex nummularia*, *E. viminalis*
	Reduced leaf surface area	Usually reduced	*Acacia melanoxylon*, *Acacia mearnsii*, *E. clavigera*, *E. grandiflora*, *E. brachyandra*
	Larger root:shoot ratio	Usually reduced	*E. camaldulensis*, *E. marginata*, *Acacia mearnsii*
Drought tolerance by maintaining cell volume	More elastic cell walls	Usually reduced	*Acacia aneura*
Dehydration tolerance	Cells and physiology unaffected by reduced water content	Usually reduced or restricted	*E. rossii*, *E. viminalis*, *Acacia aneura*

Note: Columns 1–3 of this table are extended and modified from Atwell et al. 1999. Column 4 is based on the author's experience with these Australian species.

Table 3. Australian Tree species with full or facultative deciduousness, usually in response to a dry period (Australian Plant Study Group 1980; Francis 1981; Boland et al. 1984; Snape 2002).

Species	Common name	Species	Common name
Brachychiton rupestris	bottle tree	*Gmelina leichhardtii*	white beech
Brachychiton discolor	lacebark tree	*Lysiphyllum cunninghamii*	native bauhinia
Brachychiton bidwillii	rusty kurrajong	*Lysiphyllum carroni*	native bauhinia
Brachychiton australis	large leaf bottle tree	*Lysiphyllum hookeri*	white bauhinia
Ehretia acuminata	koda	*Nauclea orientalis*	leichhardt tree
Erythrina vespertilio	bat wing tree	*Peltophorum pterocarpum*	yellow poinciana
Ficus superba	deciduous fig	*Sterculia quadrifida*	peanut tree
Ficus virens	white fig	*Terminalia catappa*	sea almond
Ficus fraseri	sandpaper fig	*Toona australis*	red cedar

urban trees growing within the urban environment (Misra and Sands 1993), despite an urgent need by tree and water resource managers for quantification (Connellan 2008). There are better data on the irrigation required for establishing young trees (May 2004).

Drought avoiders such as *E. camaldulensis*, *E. regnans*, and *E. marginata* are profligate luxury water-users that will grow rapidly and use significant volumes of water if it is available. They may be inappropriate for urban use where water is limited in supply or costly, while proving ideal for places where water is abundant or as part of water-sensitive urban design measures to control local flooding by holding and absorbing water during more intense rainfall events predicted under a changed climate (Killicoat et al. 2002; Moore 2009). The economic value of reducing localized flooding could be substantial (Moore 2009). Research shows trees to be effective in removing pollutants, such as nitrogen and phosphorus, from stormwater run-off (Denman 2006), and may prove to be useful, long-term elements of water-sensitive urban design.

Many tree species also possess physiological, anatomical, and morphological adaptations to growing in arid conditions (Kursar et al. 2009). Many eucalypt species seem to remain physiologically active, using water under conditions of moderate to severe water stress, reflecting their mesophytic evolutionary origins. However, not all eucalypts are equal in their capacity to cope with dry conditions. In Western Australia, *E. calophylla* has better stomatal control than *E. marginata*, which is a luxury water-user. Similarly, in eastern Australia, *E. regnans* is a profligate water-user with little capacity for stomatal control, while *E. obliqua* behaves similarly to *E. calophylla*.

It is interesting to compare a hypothetical scenario where *Pinus radiata* and *Eucalyptus rossii* are planted in the same, low phosphorus Australian soil in an urban streetscape where rainfall is low and there is no irrigation after the first year of establishment. When soil water potential falls, the *P. radiata* closes stomata, reducing photosynthetic assimilation and growth. The *E. rossii* on the other hand keeps stomata open and tolerates a decline in internal water potential. When occasional light rain falls, the *E. rossii* resumes photosynthetic assimilation immediately and commences growth (Florence 1981). The *P. radiata* does not open its stomata and the soil dries, perhaps compounded by the opportunistic uptake of water by *E. rossii*. The *E. rossii* out grows and out competes the *P. radiata* under this scenario.

Winter deciduous Australian native trees are relatively rare, with *Melia azedarach*, *Nothofagus gunnii*, and *Brachychiton acerifolius* being notable examples. Furthermore a few northern species, including some eucalypts, such as *E. clavigera*, *E. grandiflora*, and *E. brachyandra*, are facultatively deciduous during the dry period (Williams et al. 1997). This characteristic is shared with a number of other tree species, some of which are suitable for urban use (Table 3). However, there has been very little breeding and selection of these native species for urban use, and even less research on whether breeding might allow deciduousness to apply to southern winters, expanding the potential use of any of these or related species (Munne-Bosch and Alegre 2004).

Some species have stomata that respond to the vapor pressure of the ambient air (Table 1). Stomata close in response to drier air and leaf moisture content increases as a result, but transpiration reduces accordingly. Species with this characteristic could prove very useful in cities where water is limited, but while the response has been observed in some species with potential for urban use, it is largely unresearched.

Some species of Australian urban trees come from populations that have wide and extensive natural distributions in environments where water availability varies (Wheeler et al. 2003). There are good data to inform provenance selections for many forest species (Hamrick 2004; Broadmeadow et al. 2005; Craft and Ashley 2007; Gouveia and Freitas 2009), but arboricultural data on Australian species of amenity trees are not so easily accessed. Studies on provenances of *Lophostemon confertus* (Williams 1996) and *Tristaniopsis laurina* (Looker 2001), from different climate and soil conditions, have been undertaken and would allow urban selections for drier climates. Even if species' ranges are limited, there may be the option of selecting different species from within a genus. This is the case with the genera *Eucalyptus* and *Acacia* within Australia, where there are large numbers of related species occupying a broad range of habitats.

Often in eucalypt-dominated forests it is common for different species to occupy environments that become increasingly drier (Fensham and Holman 1999). This gives rise to the concept of a displacement series, of often-related species, which replace each other over an ecotone of increasingly arid environments (Pate and McComb 1981; Shepherd et al. 2008; Holman et al. 2011). As this happens, species have a tendency to show characteristics (Table 4) that better adapt them to the drier conditions. These characteristics could be used by urban forest managers as a guide for what species might be successful for urban planting in drier conditions, but very little research has been applied to the urban context.

Good Australian data support the use of irrigation under singular mulches in general, and mixed particle size organic mulches in particular (Connellan et al. 2000; Handreck and Black 2002). Early morning subsurface irrigation regimes that permit trees to open stomata early to maximize photosynthesis before water becomes limiting are based on sound tree physiology. In many species, stomata are often closed by about 2:00 pm, especially if soil water is limiting (Eamus 2006). Furthermore, for many tree species evapotranspiration cools them, reducing the risks of heat damage, especially on hot windy days, the frequency of which is likely to increase under climate change. Such irrigation also captures at least some of the general and environmental benefits that the urban forest provides in terms of transpirational cooling.

Table 4. Characteristics of a eucalypt displacement series from wetter to drier environments (Pate and McComb 1981).

Characteristic altered as environment dries
• Greater root:shoot ratio
• Increasing root:shoot ratio in response to water stress
• Slower stomatal response to decreasing xylem water potential
• Slower decline in leaf turgidity with increased water stress
• Lower rate of transpiration in wetter soils

ROOT ARCHITECTURE AND WATER USE

When a tree seed germinates in natural soils, the radicle emerges and usually develops into a tap root. In Australian native tree species, such as *Eucalyptus* and *Acacia*, it is not uncommon to find a seedling of 20 mm height with a primary root of 150–200 mm in length (Moore 2008). This root then rapidly develops as a tap root, anchoring the young tree, providing necessary water and nutrients and the framework from which lateral roots develop (Awe et al. 1976). In most urban trees, however, the tap root should be considered a juvenile characteristic, which only persists for the early establishment phase of the tree's life cycle (Ashton 1975; Moore 1990).

The root systems of mature trees have a tendency to be spreading and relatively shallow (Watson and Neely 1994). The typical urban forest tree root system consists of a shallow spreading root plate of lateral spreading roots complemented by the presence of descending (or vertical or sinker) roots, which usually occur around the base of the tree or close to the trunk, where oxygen is more readily available and where nutrients and organic matter are being actively recycled (Coile 1937; Perry 1982). While the lateral roots are often within 200–300 mm of the soil surface, descending roots may grow to depths of 1000 mm or more. There are also descending roots farther out along the root plate, which have a tendency to be smaller in diameter and shallower in their descent. These roots may persist for a number of years before they die back and are replaced (Moore 1995; Smith and Moore 1997).

This common pattern of urban tree root architecture has profound implications for the application of water. However, there are few data on the variations in root architecture for native and exotic trees and almost none comparing Australian native species. Many irrigation regimes assume that roots are close to the trunk and under the drip line of canopies. This seems to be the case for species such as elms, but is not necessarily the case for eucalypts and other species where exposure of root systems with an air knife shows the presence of major structural roots within the drip line but very few, if any, fine absorbing roots (Moore 2008). The absorbing roots are often 10 m or more from the trunk and concentrated where moisture levels are higher.

There is an urgent need for data on the root architecture of Australian urban tree species. It is vital to know where roots are, why they develop where they do, and how much water they are capable of removing from soil in their vicinity. It is also essential to know where, and at what depth, water should be supplied for efficient and effective irrigation (Connellan 2008). There is a popular view that trees absorb water from deep in the soil profile and that only "deep soaking" is effective irrigation over summer. Current knowledge of root architecture suggests that this is not the case for urban forest trees, but there is little research to inform the debate. Consequently, water restrictions that limit irrigation of urban trees have been imposed rather than allowing an occasional irrigation of the absorbing root plate near the soil surface. This has resulted in higher levels of stress and the deaths of many mature trees in the urban forest over the past decade.

CONCLUSION

There has been great public interest in efficient and effective water use and conservation. However, the debate has often been fuelled by anecdotal information rather than being informed by data on water use by different plant species. There have been debates about whether trees—native or exotic—should be irrigated over the summer, and suggestions that perhaps nature should take its course and trees left to die. In many parts of southeastern Australia, restrictions to water use have been applied to gardens, parks, and streetscapes without data to support the impositions. Does restricting irrigation actually save water, and what are the consequences of the restrictions on trees and society as a whole? It has been argued that the use of water during days of extreme high temperatures could reduce ambient temperatures by both surface evaporation and transpirational cooling (Nicholls et al. 2008; Loughnan et al. 2010), thereby reducing the number of excess human deaths that occur during heat waves.

Australia's major cities are not only urban forests but biodiversity hot spots (Daniels and Tait 2005). The parks, gardens, streets, and front and backyards constitute an urban forest that is very diverse in its range of species that generate myriad habitats and niches. High-density urban developments and inner city renewal make it virtually impossible to grow trees in places that were once green and leafy. Water scarcity is exacerbating the loss of urban vegetation cover, but there are many alternate planting options available to urban tree managers, if they are prepared to use the data that are available, largely from forestry research, on the root, foliage, and physiological adaptations of many Australian trees species to arid environments. There is an urgent need to obtain similar data for tree species commonly planted in urban environments. The costs of such research would be more than offset by improved water use efficiency and the benefits that effectively managed urban forests provide.

At a time of climate change, it is concerning that trees in the urban forest—in both private and public open spaces—are threatened by a scarcity of water that is not just imposed by rainfall decreases and climate change but by water restrictions as well. Water is a valuable commodity in limited supply, but by using the knowledge and data provided by research on the adaptations that many Australian trees have to water stress, much can be done in selecting and managing tree species for use in the urban forest that will allow amelioration of the heat island effect, reduction in wind speed, provision of shade, and reduction in energy use. Such outcomes should ensure enhanced economic viability, capture the health and social benefits that trees in the urban forest provide, and offer valuable green infrastructure that will contribute to the long-term sustainability of cities.

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Zusammenfassung. Wasser ist eine wertvolle Ressource, aber der bevorzugte Gebrauch durch die Gesellschaft für andere, höhere Prioritäten führte zu einer Verknappung für den urbanen Wald. Dennoch erfordert der Wert urbaner Wälder als Lieferant ökonomischer und ökologischer Dienste, die einen wertvollen Beitrag zur Gesundheit und menschlichen Wohlbefinden und zum Lebenswert der Städte leisten, eine Neuüberlegung der Priorität der Wassernutzung durch urbane Wälder. Die Gesundheitsbehörden unterstützen den Wert von urbanen Grünräumen, die den Verbrauch von Wasser, insbesondere Sturmwasser erfordern, weil Klimawechsel mehr schwere Hitzeperioden verursachen.

Bäume spielen eine wichtige und langfristige Rolle im wasser-sensitiven urbanen Design, welches effizient die Umweltverschmutzung durch Sturmwasser nutzt und reduziert. Die Kenntnis der Wurzelsysteme und ihrer Interaktionen mit dem Boden bedeutet, dass die Bewässerung zielgerichtet werden kann zur Maximierung des effizienten und effektiven Gebrauchs von Wasser. Ein Verständnis des stomatalen Verhaltens erlaubt auch ein optimales timing der Bewässerung für die photosynthetische Effizienz bei gleichzeitiger Gewinnung der Vorteile durch transpirationeller Kühlung, die die zusätzlichen Tode während der Hitzewellen reduzieren können. Die ökonomischen, sozialen und gesundheitlichen Vorteile rechtfertigen einen effizienten und effektiven Gebrauch von wertvollem Wasser.

Resumen. El agua es un recurso valioso, la sociedad da prioridades para su uso, por lo que se ha dado lugar a la escasez para el bosque urbano. Sin embargo, el valor de los bosques urbanos en la prestación de servicios ambientales y ecológicos, que tienen beneficios significativos para la salud humana, el bienestar y la habitabilidad de las ciudades, exige el replanteamiento de la prioridad de uso de agua por el bosque urbano. Las autoridades de salud están defendiendo el valor del espacio verde urbano que puede requerir el uso de agua, especialmente el agua de lluvia, ya que el cambio climático amenaza con olas de calor más severas. Los árboles tienen un papel importante y de largo plazo en el diseño urbano, que utilice eficientemente y reduzca la contaminación de las aguas pluviales. El conocimiento de los sistemas de raíces de los árboles y su interacción con los suelos significa que el riego puede ser más objetivo de manera que maximice el uso eficiente y eficaz del agua. La comprensión del comportamiento estomático también permite la sincronización óptima del riego para la eficiencia fotosintética y la obtención de los beneficios del enfriamiento por transpiración, lo que puede reducir las muertes adicionales durante las olas de calor. Los beneficios económicos, sociales y de salud justifican el uso eficiente y efectivo del valioso recurso hídrico.

Arboriculture & Urban Forestry 2013. 39(3): 116–124

Water Management Strategies for Urban Trees in Dry Environments: Lessons for the Future

Peter Symes and Geoff Connellan

Abstract. The maintenance and expansion of urban forests is a major challenge in periods of low rainfall and restricted availability of appropriate-quality water sources for trees. The recent drought in eastern Australia has highlighted the need for innovation and new approaches to ensure tree health is preserved. Responses adopted by the Royal Botanic Gardens Melbourne and others have involved investigations into species more suited to changing climate conditions, assessment of tree and landscape water demand, understanding the hydrology of the site, effective irrigation delivery, management of the soil reservoir to optimize harvested stormwater, and provide soil water reserves for future high demand summer periods.

Key Words. Australia; Crop Coefficients; Drought; Royal Botanic Gardens Melbourne; Tree Watering; Soil Moisture Sensors; Urban Forest.

Management of tree health in Melbourne is an increasing challenge when confronting unprecedented drought conditions, water restrictions, community expectations to conserve water, and bouts of extremely high temperatures. Climate change projections for the Port Philip catchment (which includes Melbourne, Australia) indicate less than average rainfall and higher temperatures in the long term. The study area is located in the southeastern region of the Australian continent. Complicating water supply issues, increases in annual mean temperatures are anticipated to threaten the health and survival of trees adapted to previously cooler conditions. Careful planning is required to assist the transition from a dominance of over-mature and unsuitable tree populations to a more resilient urban forest under future conditions. The Royal Botanic Gardens Melbourne (RBG) and local governments have a range of obligations, including conservation of cultural heritage and delivery of environmental cooling benefits, to maintain trees and historic landscapes, which often require supplementary watering, at a time of projected climate stress and water scarcity.

In developing management strategies for urban trees experiencing dry conditions it is important to recognize the potential reasons for low soil moisture stress. These include:

- species not climatically suited to site
- restricted root systems—small soil volume and limited opportunity for root extension
- compacted soils—reduced water infiltration and limited gaseous exchange
- poor soil structure and low fertility (e.g., low organic content)
- site physical constraints limit opportunity to utilize rainfall—foliage interception, mulch absorption
- mechanical damage of roots and tree crowns

This paper outlines the strategies that are considered to be required to achieve sustainable urban trees and landscapes. These strategies are:

a. species selection to suit drier, higher demand and lower water availability climates, including increased frequency of extreme temperatures
b. determination of plant water demand using site-specific crop coefficients
c. understanding site hydrology, including effectiveness of precipitation and foliage interception
d. effective delivery of irrigation water using real-time multiple layer soil moisture sensing to aid scheduling
e. management of soil moisture, including deep soil water storage to optimize stormwater

SITE CONDITIONS

Potential Climate Change Impacts

Climate change models are generally following higher emission scenarios or the projected changes are happening more quickly than formerly predicted (Steffen 2009). These changes include the threat of recurring extreme events, such as acute bushfires, droughts, heat waves, floods, and drying trends (CSIRO 2008; Climate Change in Australia 2009). While there are still uncertainties about the extent of the main processes driving serious impacts, most of these ambiguities are still heading towards more rapid and serious climate change (Climate Change in Australia 2009; Steffen 2009).

Among the primary threats to health of urban forests and tree collections are changes to temperature regime and the subsequent physiological stresses on taxa better suited to cooler climates (Kozlowski and Pallardy 1997; Hawkins et al. 2008). Some recent models applying a global temperature increase of 2°–3°C are projecting that over the next century, up to 50% of vascular plant species could be threatened with extinction (Bramwell 2007). This risk should also be contemplated for urban forests.

In Victoria, climate change over the coming decades is anticipated to result in increased temperatures; drier conditions and increased frequency in severe events, such as extreme rainfall, bushfires, and droughts (CSIRO 2008), and most of these events are also common to the rest of southeast Australia (Suppiah et al. 2006; CSIRO 2008; CSIRO 2010). For Melbourne, it is expected that by 2070 under a lower greenhouse gas emission growth scenario, it will be 1.3°C warmer with 6% less rain, while under a higher greenhouse gas emission growth scenario it will be 2.6°C warmer with 11% less rain (out of a range of -6% to -24%) (CSIRO 2008). The greatest increases in temperature are expected during summer, while the greatest rainfall reductions are projected during winter to spring, from -11% to -21% respectively (CSIRO 2008).

The potential impact of reduced rainfall on urban vegetation is well illustrated by considering the cumulative deficiency in rainfall, relative to long-term averages, over extended dry periods (Figure 1).

Melbourne's mean annual average temperature is 15°C. Many trees species grown in Melbourne (e.g., *Acer*, *Betula*, *Platanus*, *Prunus*, *Quercus*, and *Ulmus*) commonly occur in cities around the world, with mean annual temperatures ranging from about 10°C to 13°C (Kendal 2011). It is conceivable that some of these taxa are already experiencing significant heat stress, particularly with summer extreme temperatures. It is likely that an overall increase in annual average temperature by 1°–3°C (notwithstanding temperature extremes compounded by urban heat island effects will place many of these species outside their viable cultivation range.

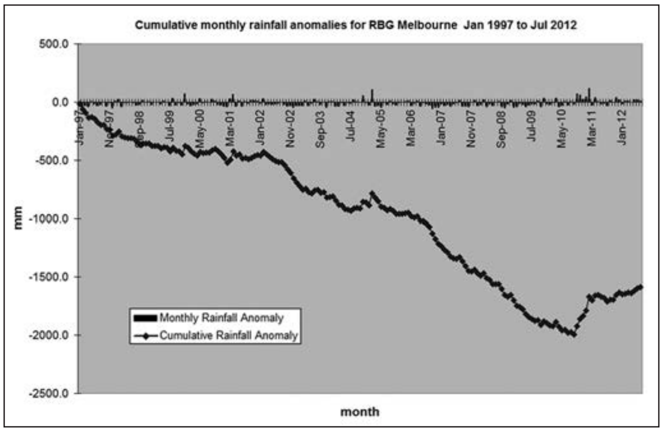

Figure 1. Cumulative monthly rainfall anomalies for RBG Melbourne January 1997 to July 2012. Note: This shows a cumulative trend of monthly rainfall anomalies compared to average monthly values from 1997 to 2012. There was steady decline during what is known as the Millennium Drought in Australia, from 1997 to early 2010. The cessation of the drought followed two La Niña events (often result in above average rainfall for eastern Australia) during 2010–2012, but these were not adequate to return the status to an equilibrium, even though the 2010–2011 La Niña event was unprecedented in its high strength and high amounts of rainfall since records began in Australia.

The impact of climate change and urbanization is likely to expose some plantings, for example street trees, to elevated temperatures. The influence of the urban heat island effect, increased thermal mass and reduced surface permeability of urban sites will contribute to temperature extremes (Coutts et al. 2007).

Rainfall is projected to change, in Melbourne region, by 2070 with average reductions of 11% to 21%, for winter and spring respectively (CSIRO 2008). This can impact on the volume of stormwater harvested for irrigation purposes. There appears to be an amplification relationship between rainfall reductions and runoff of up to 1:3 (Howe et al. 2005). For example a 21% reduction in winter rainfall may translate into a 63% reduction of stormwater flow. Or in another case, the projected 7% reduction in summer rainfall may return a 21% reduction in stormwater harvest at a time of year when it is most needed (CSIRO 2008).

Tree and Landscape Microclimate

Microclimate mapping within the landscape is one approach that can assist with informed tree selection and the development of urban forests. This includes establishing the characteristics of both the edaphic (soil) and atmospheric environments throughout the year. For example, the edaphic environment for a deciduous arboretum will likely contain a higher moisture status during the tree's dormancy. The converse may occur during the tree's active growth period. Microclimate mapping is useful for establishing generic zones within the landscape. Yet, there is still even greater variation involved, even at small units of area. To illustrate, the study of the amount of rain penetrating through overhead tree canopy (throughfall) and corresponding soil moisture levels in the RBG Melbourne has revealed significant variation even at sub-meter spacing. In natural habitats, plants would only typically establish in niches suited to their recruitment and growth.

However, in contrived landscapes, the establishment period and planting site is often chosen to match amenity and functional criteria and this may not be the best match to the environmental conditions. Seasonal soil moisture or the soil water balance is one of the critical factors, and researchers need to develop and improve specific approaches of examining and monitoring point levels of soil moisture in respective landscape zones. This can be achieved in a technologically advanced way by using soil moisture sensors, or by physically examining soil cores or excavating pits, to compare moisture status against standardized methods. While this can be effective, it is usually less practical and more resource intensive, especially when regularly surveying sites across an entire urban forest planting. A simple matrix can be generated using variables—such as sun–shade, dry–moist, or cool–warm—to classify and map areas within the urban forest, to then guide tree selection and planning for the future (Figure 2).

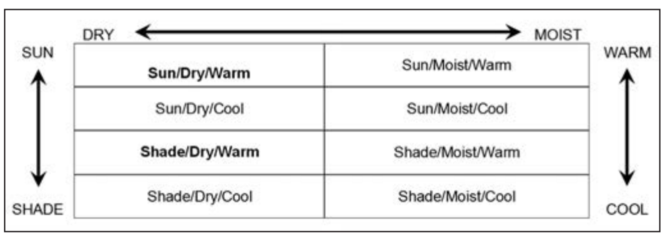

Figure 2. Simple microclimate matrix. Note: Plant selection for the RBG is becoming more focused towards the dry/warm quadrant of the matrix. Some trees from natural habitats in the moist/cool quadrant, such as wet montane forests of southeastern Australia, are already showing signs of stress and some have been removed due to irreversible decline.

Soil Surveys

Comprehensive soil surveys (Van Rees et al. 1993) are also an important part of the landscape planning process. Soils are the foundation of existence for so many life forms, and yet often they are taken for granted, or poorly studied or understood, in the urban landscape. In many landscape projects, the emphasis is on planning the hard landscape structures, services, and infrastructure, but when it comes to soil analysis and design, planning is inadequate or sometimes non-existent. It would not bear contemplation to request a civil engineer to avoid measuring the bearing capacity of a soil for a building, or cutting corners in safety specifications for structural integrity under varying conditions. The same importance must be placed on soils. Performance specifications, structural integrity, and long-term sustainability are also the language of robust landscape soils, and this is best informed by soil surveys.

Soil properties that should be considered primarily in relation to water management of trees include:

a. bulk density and soil strength
b. porosity, total water holding capacity, and plant available water (including soil moisture release curve)
c. particle size analysis (to determine risk of compaction)
d. soil texture and structure
e. infiltration rates and hydraulic conductivities (for both topsoil and subsoil)
f. sodium absorption ratio (to determine risk of soil particle dispersion (poor drainage and aeration) from water supplies containing more sodium.
g. electrical conductivity (to determine risk from the use of more saline water supplies)

Although very challenging, developing a better understanding of the biochemical and physical characteristics of the site soil are crucial for informed tree management.

Tree Selection for Dry Sites

Any assumptions about taxa adapted to periods of aridity need to be reassessed against projected climatic changes. For example, in Australia, there is a strong interest in Mediterranean flora on the assumed basis that these species are drought tolerant due to months of very minimal rainfall, particularly over the summer, in their natural habitat (Dallman 1998; Peel et al. 2007). However, Mediterranean climates are usually characterized by significant winter precipitation (Dallman 1998; Peel et al. 2007), which may also recharge groundwater and subsoil moisture levels. Phreatophytes are plants that either rely on or access ground water for their needs (Sommer and Froend 2011) and can be found in Mediterranean climates both in Australia (Sommer and Froend 2011) and California (Mahall 2009). Californian oaks, such as *Quercus agrifolia* (coast live oak) and *Q. lobata* (valley oak), are considered to be phreatophytes (groundwater-using) that have the capacity to tap groundwater for survival over drought periods (Mahall 2009). Specifically, *Quercus lobata* has been reported to access moisture from depths as great as 24 meters (Howard 1992). In European Mediterranean climates, David et al. (2007) studied *Quercus ilex* ssp. *rotundifolia* (holm oak) and *Q. suber* (cork oak) in southern Portugal and found that more than 70% of the trees' transpiration was sourced from groundwater at 4–5 m depths. Projections of climatic changes for Melbourne indicate a significant reduction in winter-spring rainfall (CSIRO 2008), which can increase the risk of reducing subsoil and groundwater moisture reserves for Mediterranean-climate-adapted trees.

In terms of current water management for trees, it can be useful to use simple graphing techniques to compare the range of trees that are within or outside typical annual precipitation ranges. Graphical summaries of a study of the annual precipitation requirements of some trees growing in the RBG Melbourne showed a significant rainfall deficit between the annual minimum rainfall requirement and the mean rainfall during 1999–2011, of 544 mm, for the site. Figure 3 shows the rainfall deficiency, minimum annual rainfall requirements compared to mean rainfall, for a selection of 34 eucalypts growing at the site. Figure 4 shows the deficiency, graphed in increasing annual rainfall requirement, for more than 80 Australian native species. The difference may be up to 750 mm for some individual species. While some of this deficit is currently being met by artificial precipitation (irrigation), the RBG has set an upper baseline target of 900 mm per year for combined rainfall and irrigation amounts. It is unlikely that this could be sustained into the long term against current climatic projections and resource availability. As a baseline, tree selection should incorporate water requirements that are within the typical annual rainfall requirements for the proposed site including some variation for climatic change and low rainfall years such as decile 1, or lowest 10% events.

LANDSCAPE PLANTING WATER DEMAND

Trees and Landscape Planting Water Demand Estimation

Evolution of irrigation scheduling in urban landscapes has progressed from time-based programming to a more sophisticated application of a greater spread of inputs, such as climatic data, evapotranspiration estimation methodologies, soil moisture sensing, and increasing knowledge of plant performance. However, plant water use in the urban landscape is still considered to be inadequately understood (Symes et al. 2008). Furthermore, a greater emphasis on water use efficiency and the insecurity of water supply presented by greater regulation and restrictions has increased the interest in priority setting of water allocation. This preferential irrigation is usually based on the perceived values or expectations of quality given to different areas or components of the urban forest. The setting of subjective quality standards in urban horticulture has generally been a vexing and contentious dilemma, let alone linking these standards to irrigation scheduling for various landscape performance levels.

There are various methodologies for estimating plant evapotranspiration (ETc). Two terms that are commonly used are Crop Factors (CF) and Crop Coefficients (Kc) (Allen et al 1998; Connellan and Symes 2006).

Plant water demand expressions use a reference evaporation value together with the crop adjustment factor to estimate the water use rate. The following expressions are used:

[1] $ET_c = \text{Crop Coefficient } (K_c) \times \text{Reference Evapotranspiration } (ET_o)$

[2] $ET_c = \text{Crop Factor (CF)} \times \text{Pan Evaporation } (E_{pan})$

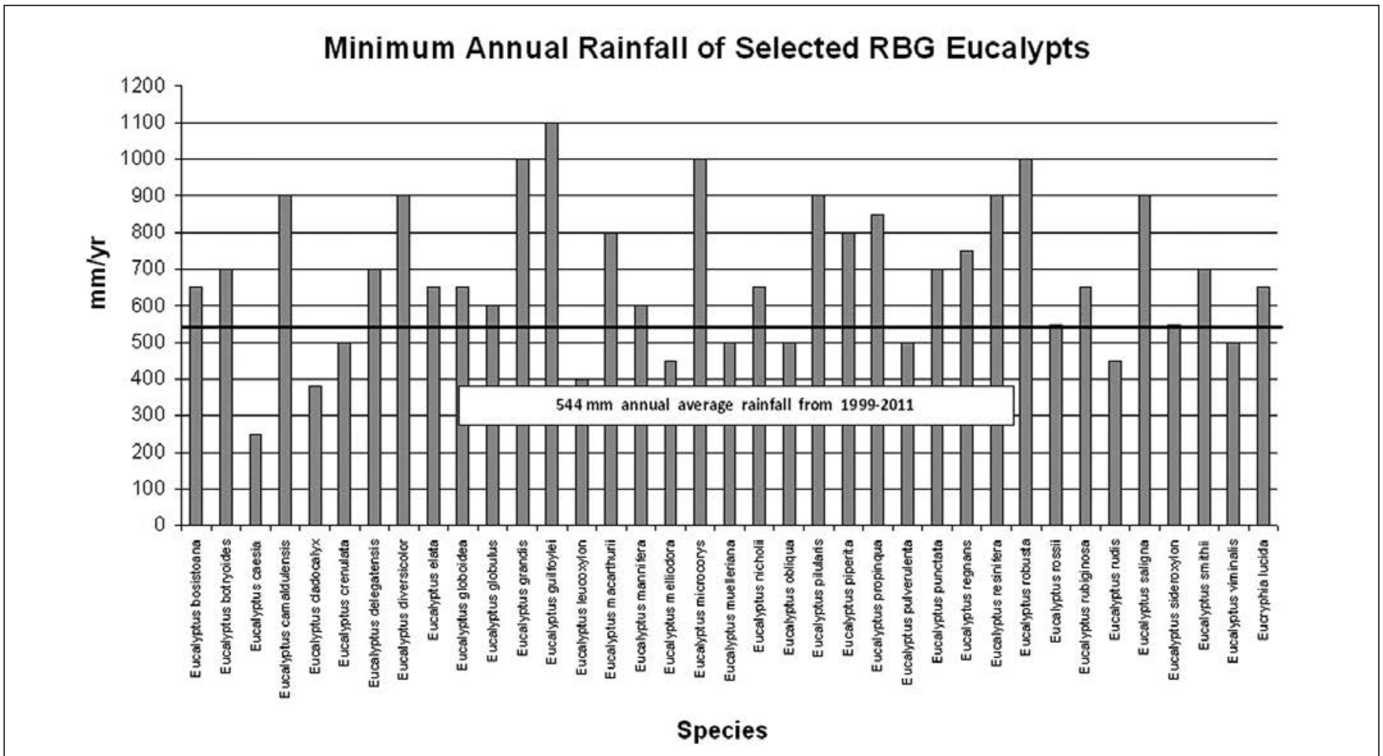

Figure 3. Minimum annual rainfall of selected RBG Melbourne eucalypts. Note: There are misconceptions in Australia that all Eucalypts are drought hardy. It has been the RBG experience that some Eucalypts in this list have exhibited what is considered to be decline from water stress even in areas where supplementary irrigation is applied. Seasonality of rainfall is another factor with some of these species normally experiencing summer maximum rainfall in their natural habitats.

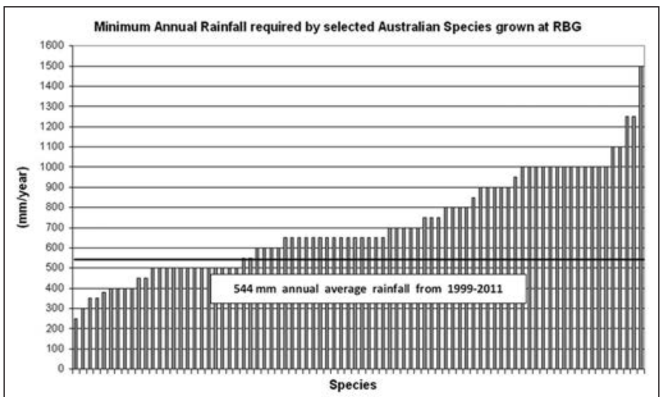

Figure 4. Minimum annual rainfall requirements for selection of Australian native trees at RBG Melbourne compared to mean rainfall for 1999–2011. Note: This chart shows the estimated minimum annual average precipitation requirements (sourced and adapted from Simpfendorfer 1992 and Boland et al. 2006) for a range of trees growing in the RBG. The bolded horizontal line shows the actual average annual rainfall of 544 mm recorded during 1999–2011 for the RBG. Bars that are above this line may demonstrate individual species that are at risk from longer term water deficits.

These are plant specific expressions. However, complex landscapes are characterized by diverse vegetation with multiple root systems and canopy tiers coexisting within the same area. The development of the landscape coefficient methodology of estimating plant water use (Costello and Jones 2000; Connellan and Symes 2006) seems better suited to diverse urban landscapes, and this system is the basis for irrigation scheduling training currently endorsed by Irrigation Australia, a national body representing the irrigation industry. The landscape coefficient methodology (Costello and Jones 2000) incorporates reference evapotranspiration (ET_o), a landscape coefficient (K_L), plant species factor (ks), microclimate factor (km_c), and vegetation density factor (kd) to estimate Landscape Evapotranspiration (ET_L) and is summarized as follows:

[3] $ET_L = K_L\,(ks \times kmc \times kd) \times ET_o$

This methodology does not include prerogatives such as managing water resources in times of scarcity when levels of performance or priorities often have to be determined. Deriving levels of desired landscape performance (Connellan and Symes 2006) has been a water management topic in Australia for over a decade and is described further.

Plant Condition and Water Requirements

Assigning levels of quality or priorities help complete the development of the irrigation schedule. Alternatively, quality ranking in this context can be considered through the amount of water stress that is allowed for particular landscape areas. For instance, areas that were managed in a lush fashion would normally be subjected to only very low levels of water stress (unless waterlogged), while areas not irrigated at all would be subject to very high stress (unless adapted to local climate) (Connellan and Symes 2006). The RBG has developed an

Table 1. RBG Melbourne Landscape Coefficient classification.

	Landscape Coefficient (K_L)				Examples for high scheduling requirement	
		Scheduling requirement			Median January water	Examples of RBG landscape
	Rank	Low	Med	High	requirement (mm)	zones/plant collections
Landscape priority	A	0.4	0.5	0.6	102	Montane, rainforest collections
	B	0.4	0.5	0.5	82	General collections
	C	0.3	0.4	0.4	62	General landscape
	D	0.2	0.3	0.3	41	Low-priority landscape

Note: This shows how the application of landscape coefficients were determined using a combination of landscape priorities and scheduling requirement to derive a value for the summer months. Two examples are provided that follow: The rank of Landscape Priority 'A' combined with a Scheduling Requirement of 'High' results in a landscape coefficient of K_L 0.6 to be applied. This results in a median January water requirement of 102 mm for a Rainforest Plant collection.

A Landscape Priority 'D' site combined with a Scheduling Requirement of 'Low' results in a landscape coefficient of K_L 0.2 to be applied. This results in a median January water requirement of 41 mm for a low-priority landscape area.

irrigation scheduling framework based on the landscape coefficient methodology (Costello and Jones 2000) and included landscape priority levels (Table 1). The implementation of this framework has resulted in improved water distribution to areas of different requirements without increasing overall water consumption. Indeed, the RBG has been able to maintain an overall reduction in potable water use of 40%–50% since 1994–1995 (when improvements to water management were initiated) (Royal Botanic Gardens Melbourne 2011), over 13 years of unprecedented drought conditions for Melbourne.

Determination of Site-specific K_L

Recent studies have been undertaken in the RBG to estimate actual landscape coefficients through the use of capacitance soil moisture sensor technology and a site reference Automatic Weather Station (AWS) (Symes et al. 2008). At one study site comprised of mixed landscape planting, a site-specific calibration of the sensor technology was carried out. Calibration of soil moisture sensors was required to provide greater accuracy of measurement to quantify water movement in the soil volume. The standard method, based on gravimetric sampling, was used in the site calibration. The calibration procedure was carried out according to the Calibration Manual for Sentek Soil Moisture Sensors (Anonymous 2011) procedures. Soil samples were taken immediately adjacent to an installed sensor assembly tube. Soil moisture content and bulk density were determined in a soils laboratory. A calibration polynomial equation was developed for each representative soil layer. The correlation between soil sensor readings and soil moisture was determined to be r^2 0.97 for the sandy organic loam in the 10–20 cm layer and r^2 0.80 for the sandy loam in the 30–50 cm layer.

Average monthly values for landscape coefficient values were calculated for 0–50 cm soil profile depth using soil moisture data from capacitance soil moisture sensors and calculated ETo from the RBG AWS. These values ranged from K_L 0.11 (winter) to K_L 0.41 in late summer/early autumn compared to RBG estimated values of K_L 0.25 for winter to K_L 0.5 for summer that would normally be assigned to this (and similar other garden beds). [See Figure 5 – Measured site specific monthly landscape coefficient (K_L) values for research site RBG5A]. Using the landscape coefficient methodology advocated by Costello and Jones (2000), the summer landscape coefficient was calculated to be K_L 0.65. There are clear opportunities presented to apply data from soil moisture sensing and an AWS to improve irrigation scheduling in matching the seasonal demand and actual water requirement.

RAINFALL EFFECTIVENESS

In the RBG Melbourne, a study of the shifts in the localized trends of rainfall patterns, partitioning of rainfall (fate of rainfall), and rainfall effectiveness is being carried out in conjunction with Monash University, Melbourne. Measurements to date are finding event-based canopy interception rates from 60%–80% of rainfall (Dunkerley 2011).

Changes in the nature of sub-daily precipitation may result in increased precipitation losses via canopy interception and evaporation. Rainfall losses (reduced effectiveness) are more important, as a proportion, in small rainfall events. Understanding rainfall precipitation at higher levels of precision and smaller temporal scales is now recognized as an important part of adaptive management. Further, this research highlights the need to understand precipitation at higher levels of precision and smaller temporal scales in future adaptive management. Rainfall interception by upper tier vegetation canopies and mulch layers was a pertinent factor for all trial sites. Typically, rainfall only appeared effective in increasing soil moisture content if individual rain-

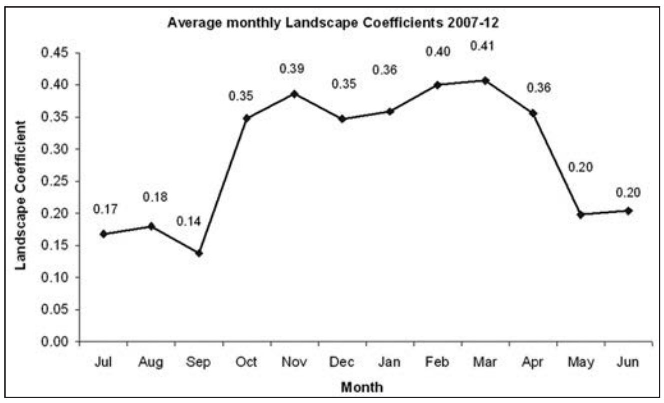

Figure 5. Monthly site specific landscape coefficient (K_L) values for research site RBG5A – Viburnum Bed. Note: RBG5A – Viburnum Bed is study site based in a landscape planting comprising of multi-tiered vegetation strata with perennials, woody shrubs, and deciduous mature trees. The location has a northeasterly aspect (southern hemisphere), exposed to full sun for most of the day and periodic hot northerly winds in summer. This graph shows the range of estimated monthly average landscape coefficient values of this site for the period 2007–2012. These were estimated by comparing plant water use as indicated by calibrated soil moisture sensor readings with Penman-Monteith reference evapotranspiration from the RBG Automatic Weather Station.

fall events were greater than 4–7 mm as measured by the RBG Automatic Weather Station. From July 2009 to June 2011, average canopy interception of total rainfall over the soil moisture sensor sites was 34% compared to AWS data. (Note: to reduce excessive labor in data collection, these measurements did not include daily amounts less that 2 mm, so it is likely this is an underestimation of actual interception values due to the higher proportion of interception for smaller rainfall amounts.) Canopy interception values approaching 67% were measured for some important urban forest sites in the RBG. The variation of rainfall effectiveness for respective events and sites was also readily monitored and observed through soil moisture sensing. This reinforces the importance of applying an 'effective rainfall' factor in irrigation scheduling methodology (Symes et al 2008).

IRRIGATION EFFICIENCY

There are a multitude of techniques employed in irrigating trees, including sprinklers, sprays, bubblers, drip emitters, driplines, wells, and various perforated pipe distribution systems. The key issues are the area of root plate watered, depth of watering, infiltration effectiveness, soil water storage capacity, and total amount of water applied.

In the design and management of tree watering systems there are some key characteristics that should be considered.

Effective Delivery – Deep Watering

Deep watering, for example 200 to 500 mm, is recommended for mature trees as the recharging of deeper soil layers can enhance tree resilience, particularly during periods of drought. This generally requires long run times—hours not minutes—and slow application rates, if drip emitters are being used.

Water will only move down the soil profile under saturated conditions. This requires the wetting of the shallower soil layers prior to the deeper layers being wet. In some situations, the placement of the delivery outlets (e.g., subsurface drip, wells) deep into the soil profile can be used to overcome the need for watering of the top soil layers. This strategy reduces the competition for water between shallow rooted vegetation and the tree.

Dripline Systems

Many dripline systems, as well as sprays, are currently only applying water in the top 100 mm to 150 mm of the soil. Delivery using close emitter spacing interval, for example 300 mm apart, low-flow-rate drippers (e.g., 1.5 L/h), for relatively short periods, is not ideal for trees. The ideal drip delivery would be wide spacing, for example 0.5 m or more, with higher flow rates, providing soil infiltration and percolation capacity is adequate, so that deep soil wetting can be achieved.

Zoning of Irrigation

The ability to control the application of water to areas of vegetation or single large plants (trees) is essential, in terms of achieving effective watering and efficiency. In the design of irrigation systems, the areas containing tree roots should be identified and the water delivery control arranged so that the specific water requirements of that area can be satisfied, without necessarily watering adjacent vegetation or areas. Zoning of tree watering is essential and is sometimes required to comply with water restriction conditions.

Strategies to achieve high water-use efficiency in the irrigation of urban trees are outlined in Connellan (2013).

ROOT ZONE SOIL MOISTURE SENSING

Soil moisture sensing is one complementary technological tool that can be used to provide a greater understanding of plant water use, and assess irrigation and rainfall effectiveness. Knowledge of the soil moisture content, and the response of plants to soil moisture conditions, is essential for precision scheduling of irrigation (Symes et al. 2008). The technology ranges from cost effective but simple equipment to highly sophisticated and expensive systems that are used more for research purposes or large-scale agricultural enterprises (Charlesworth 2000). Nevertheless, the information provides a useful insight into the physical (soil hydrology) and biological (plant water use) patterns under the soil surface and helps close the loop in landscape water management (Symes et al. 2008). It is improved when combined with meteorological measurement and professional judgment to help compensate for the high levels of landscape variability. RBG is currently in a partnership research project to quantify plant water use, including weather data and horticultural expertise (Symes et al. 2008). Apart from the immediate application to improve irrigation management, it is also anticipated that this research will assist in establishing baselines for understanding the influence of the current climate on plant water use, and assessing future trends that may develop.

Soil Moisture Sensor Applications in Scheduling

Knowledge of soil moisture content of plant response to soil moisture conditions is essential for precision scheduling of irrigation. The soil moisture level is typically determined using a predictive technique through ET estimation and conducting a soil water balance. Soil moisture sensing allows the actual value of soil moisture to be an input into the scheduling decision making process. The incorporation of soil moisture sensing in the control process as feedback makes this a true, closed-loop type of control.

Access to soil moisture data significantly expands knowledge of plant and soil water behavior. Identification of the time the soil moisture levels reach a set-point value, to initiate irrigation, is only one application of the technology.

The nature of the soil moisture data that can be obtained determines how it can be used. The number, location, and precision of sensors and frequency of readings are all important. Although a single sensor, positioned within the root zone and monitored on a daily basis, provides valuable information, the installation of multiple sensors greatly expands the knowledge base. The installation of multiple sensors at selected positions down the soil profile allows soil moisture in the different soil zones to be monitored and changes between zones to be analyzed. Continuous monitoring of sensors with access through the internet, in real time, provides the opportunity for enhanced analysis of the plant soil system.

Portable probes provide for assessment of variations in plant water use (ETc) rates across the various hydrozones of the landscape.

Graphical presentation of soil moisture data allows absolute values to be read as well as the changes in soil moisture conditions to be readily interpreted.

Examples of how soil moisture data can be used to provide a better understanding of aspects of the water management of complex landscapes include:

- identification of active root zones in the soil profile
- estimate of the Crop Coefficient (K_c) value
- influence of water logged conditions on plant growth
- effectiveness of irrigation
- effectiveness of rainfall
- drainage characteristics of the soil

Seasonal Adjustment of Site-specific Landscape Coefficients

Based on the information shown by soil moisture sensing, RBG has now included seasonal differentials in its four scheduling regimes for garden areas: landscape coefficients are adjusted for winter, spring, summer, and autumn. This has reduced overwatering in the cooler times of the year, and particularly, the transitional periods from winter-spring-summer. For some areas, it was shown that under-watering occurred in the peak of summer that was difficult to remediate under current water scarcity and restrictions of Melbourne. The availability of soil moisture readings through the internet allows the actual soil moisture conditions to be monitored in real time and direct reference made to the condition of the plants. In periods of high temperatures and high evaporative demand this information allows informed water management decisions to be made. The soil moisture data generated allows key indicators to be used to aid in the water management of the landscape.

SUBSOIL WATER STORAGE

Subsoil Moisture Storage and Recovery is a methodology being developed through a research partnership among the RBG, Sentek Pty, Ltd., and the University of Melbourne to recharge subsoil moisture when the water is freely available as a reserve for trees. The severity of depletion of soil water reserves, over multiple dry years, is illustrated in Figure 4. Soil moisture sensing technology provides the means to study the effectiveness of the irrigation technique and the rate and depth of tree water use. This technique is being considered to optimize the use of stormwater, as this is usually more available in the late autumn-winter months when irrigation is not normally required. The concept is that stormwater is applied via irrigation to soil profiles in winter-spring to 'bank' water when stormwater supplies are more available (Figure 6), thus ensuring subsoil moisture is adequate for the forthcoming summer and to also minimize the use of potable water for irrigation. At study site 57, the graph shows soil moisture traces at each 10 cm layer of soil profile down to one meter depth under a specimen of *Quercus* aff. *alba* (Figure 7). It can be seen that water is not used at most depths during winter when the tree is dormant. However, after precipitation during July to August 2010, all layers of the soil profile including the subsoil have been recharged. The patterns of water extraction by the tree can be more easily seen from mid-December 2010, with most intensive use in January 2011, especially for the deeper soil layers. These findings have led to the consideration of a split irrigation scheduling/water balance regime in the RBG. For example, the landscape coefficient (K_L) for the top 30 cm in December was calculated to be K_L 0.5, but for the full profile it equated to K_L 0.94. This means the turf zone could be managed at lower K_L values while the trees are using subsoil reserves, thus saving potable water during summer. Based on the methodology described by Harris (1998) and Kopinga (1998), modeling of tree water needs in the RBG suggest that if soil moisture was at full capacity and accessible to 1000 mm soil depths, then the average Gardens tree could subsist for about 90 days in summer with no additional precipitation. This potentially extends to 150 days when considering species more adapted to drought conditions. The application of Subsoil Moisture Storage and Recovery has the clear potential to maintain tree health in water-scarce environments, and minimize the use of supplementary potable water.

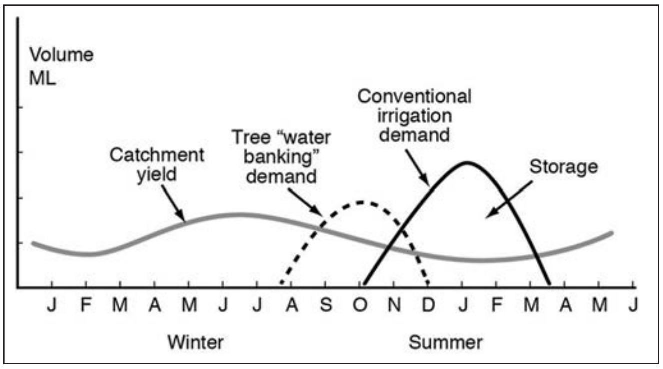

Figure 6. Schematic of typical stormwater availability and irrigation demand.

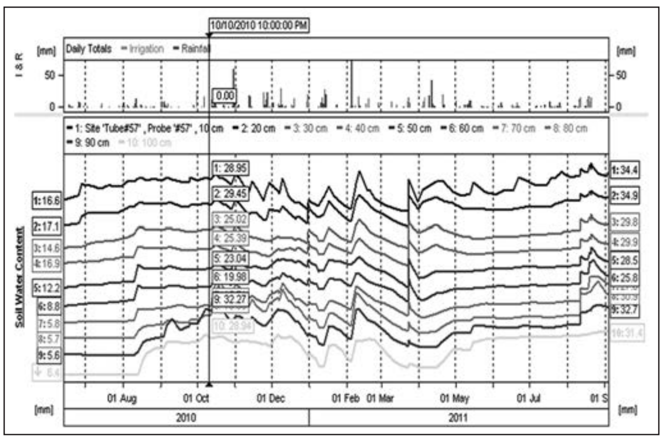

Figure 7. Soil moisture traces for the root-zone of *Quercus* aff. *alba* growing at RBG site 57. Note: Figure 5 shows individual soil moisture traces (mm/10cm) for the root zone of *Quercus* aff. *alba* at 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 cm spacings from top to bottom in the graph. Previous to August 2010, soil moisture contents from 60cm to 100 cm were at or below permanent wilting point. Recharging of soil moisture to 100 cm depth can be seen early on in August 2010. Tree water use is most visible to 100 cm depth from mid-December 2010 until late March 2011. The tree enters dormancy during April 2011 and soil profile begins recharging at this time.

RECOMMENDATIONS FOR HEALTHY AND DROUGHT-RESILIENT TREES

The following are key water management strategies that are essential to achieving sustainable landscapes with trees:

- satisfy water requirements for healthy trees, not just for tree survival
- optimize soil environment to achieve resilient, healthy, and extensive root systems
- ensure site rainfall is fully utilized
- water deep (if required) to achieve wetting of soil profile at depths greater than 200 mm
- water proactively rather than wait for signs or evidence of stress
- adopt "water banking" approach in soil, prior to high water-demand period
- recycled water quality should be checked for potential short- and long-term (accumulation) risks, such as toxicity or degraded soil health
- regularly check what is happening in the soil, sample it or use soil moisture sensors
- evaluate water delivery system hydraulically and in-soil water distribution performance

CONCLUSION

Experiences in the maintenance of urban forests during dry years have shown that a thorough understanding of the tree requirements and site conditions is essential to achieving a sustainable urban forest. The starting point is selecting the right species by taking into account the site's microclimate, special constraints, and the tree's desired functional performance.

Soil moisture sensors have proven to be very powerful tools in providing information about plant water use, soil water behavior, root system activity, and effectiveness of rainfall and irrigation. Measurement of net rainfall reaching the ground, following interception by the tree canopy, has also assisted in building the knowledge base necessary to successfully maintain trees.

A range of techniques have been developed and employed at RBG Melbourne to assist in the scheduling of irrigation and complex landscape plantings. These include site-specific and seasonally adjusted landscape crop coefficients, stress indicators to identify refill points, and soil water banking.

Acknowledgments. The authors wish to express their appreciation for the instrumentation expertise and data collection of Mr. Steven Liu, Curator Assistant, Environmental Horticulture, Royal Botanic Gardens Melbourne.

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Zusammenfassung. Die Erhaltung und die Ausdehnung von urbanen Wäldern ist eine große Herausforderung in Zeiten von geringem Niederschlag und begrenzter Verfügbarkeit von angemessenen, qualitativen Wasserquellen für die Bäume. Die kürzliche Trockenheit in Ostaustralien hat den Bedarf für Innovationen und neue Ansätze zur Erhaltung von Baumgesundheit hervorgehoben. Die gewonnenen Antworten aus dem Königlich Botanischen Gärten in Melbourne und anderswo beinhalteten auch Untersuchungen der Arten, die mehr geeignet sind für Klimaveränderungen, Untersuchung des Baum- und Landschaftswasserbedarfs, Verständnis der Hydrologie des Standortes, effektive Durchführung der Bewässerung, Management der Bodenreserven zur Optimierung von gewonnenem Sturmwasser und erhalten Bodenwasserreserven für kommende Sommerperioden mit hohem Wasserbedarf .

Resumen. El mantenimiento y la expansión de los bosques urbanos son un reto importante en períodos de escasez de precipitaciones y poca disponibilidad de fuentes adecuadas de agua de calidad para los árboles. La reciente sequía en el este de Australia ha puesto de relieve la necesidad de innovación y de nuevos enfoques para asegurar la salud de los árboles. Las respuestas adoptadas por el Royal Botanic Garden de Melbourne, y otros que han participado, ha sido en la investigación de las especies más adaptadas a las condiciones cambiantes del clima, evaluación de los árboles, la demanda de agua para el paisaje, la comprensión de la hidrología del sitio, la entrega efectiva de riego, la gestión del almacenamiento del suelo para optimizar el agua cosechada por tormentas y así proporcionar reservas de agua del suelo para futuros períodos de alta demanda en el verano.

Arboriculture & Urban Forestry 2013. 39(3): 125–131

Subtropical–Tropical Urban Tree Water Relations and Drought Stress Response Strategies

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Abstract. Understanding native habitats of species successful as subtropical and tropical urban trees yield insights into how to minimize urban tree water deficit stress experienced during monsoonal dry periods. Equatorial and montane wet forest species rarely subject to drought are generally absent in subtropical and tropical cities with pronounced monsoonal dry seasons. Species native to monsoonal dry forests appear to have wide environmental tolerances, and are successful as urban trees in many tropical cities. Monsoonal dry forest species have a tendency to be deep rooted to avoid drought, with leaf habits falling along an avoidance to tolerance spectrum. Dry deciduous species, typically found on more fertile soils, maximize growth during the monsoonal wet season with high photosynthesis and transpiration rates, then defoliate to avoid stress during the dry season. Evergreen tree species, typically found on less fertile soils, have a higher carbon investment in leaves that photosynthesize and transpire less year-round than do dry deciduous species. Dry deciduous tree species are more common urban trees than dry evergreen species explicitly due to more ornamental floral displays, but also implicitly due to their ability to adjust timing and duration of defoliation in response to drought. An empirical study of three tropical species exhibiting a range of leaf habits showed isohydric behavior that moderates transpiration and conserves soil water during drying. However, dry evergreen species may be less adaptable to tropical urban conditions of pronounced drought, intense heat, and limited rooting volumes than dry deciduous species with malleable leaf habit.

Key Words. Climate Change; Drought Deciduous; Drought Physiology; Dry Evergreen; *Lagerstroemia loudonii*; *Pterocarpus indicus*, *Swietenia macrophylla*; Urban Forestry; Water Stress; Wet Evergreen.

Urban trees are an increasingly important quality of life issue in tropical cities as economic growth swells their increasingly affluent urban populations (Nilsson 2005). The understanding and management of urban trees in tropical cities (including subtropical cities where cold does not seasonally limit growth), particularly the street tree population, is based on a modest body of scientific knowledge. Temperate (seasonal cold limiting growth) urban tree understanding and management does not necessarily translate well to tropical trees. Tropical trees are adapted to a wide range of rainfall conditions ranging from year-round rainfall to monsoonal climates, where heavy wet seasons vary in duration and periodicity in alternation with often-pronounced dry seasons.

Freestanding urban trees growing along streets, in street medians, or on private properties are a critical foundation for both a healthy human population and a healthy economy (Tzoulas et al. 2007). The UN World Health Organization recommends at least 9 m^2 of urban greenspace per capita to mitigate undesirable environmental effects and to provide aesthetic benefits (Deloya 1993). Urban forests are particularly important to healthy cities in developing countries, which constitute some of the world's largest metropolitan areas. Greenspace and urban tree plantings become imperative where the rate of urbanization is greatest in developing countries, particularly in smaller cities of ~500,000 people in Asia and Africa (UN-ESA 2003).

Tropical cities in developing countries have a diverse pool of potential tree species available from tropical forests (Jim and Liu 2001). The selection of those tree species best suited for tropical urban conditions depends upon matching above and belowground space (Jim 2001) and on matching urban climate to species from an appropriate tropical forest type. Selecting urban trees from an appropriate tropical forest type also depends upon where a tropical city falls along the seasonality gradient of rainfall distribution. This gradient ranges from aseasonal wet, with significant rainfall every month and dry periods rarely longer than a week to a monsoonal climate with alternating dry and wet seasons of varying length and periodicity. Generally, forest tree species in aseasonal wet climates can be described as wet evergreen, while those in monsoonal climates are either deciduous or dry evergreen. While not addressing the many nuances among tropical forest types, this generalization provides a functional conceptual framework for understanding tree adaptations to drought in tropical and subtropical cities.

Cities in equatorial wet climates, such as Singapore in Southeast Asia, logically use many trees from equatorial wet evergreen aseasonal forests. However, cities in wet equatorial climates also use drought-adapted trees from monsoonal climates (Tee and Wee 2001). This is similar in strategy to temperate cities using tree species from colder climates. Tropical monsoonal dry forest species are adapted to forest environments subject to several months of low rainfall (Miles et al. 2006). Tropical dry forest species either avoid drought with a deciduous leaf habit or tolerate drought with evergreen foliage (Santiago et al. 2004). When grown in a wet, aseasonal climate predominated by evergreen species, drought-deciduous species typically retain their leaves most of the year, sometimes shedding foliage briefly during short dry periods (Brodribb and Holbrook 2005).

While monsoonal drought-adapted tree species can be used in an aseasonal wet evergreen climate, the reverse does not appear to be true. Street trees in Bangkok, Thailand, were dominated by deciduous species, mostly native to Southeast Asia but also from Africa and South America (Thaiutsa et al. 2008). This was due largely to deciduous species typically having more ornamental floral displays. Dry evergreen species were more common as large specimen trees, but most were older, often declining specimens found in protected urban locations (Thaiutsa et al. 2008). Similarly, Nagendra and Gopal (2010) reported that deciduous trees dominated the street-side tree population in Bangalore, India. Of the evergreen species, only one was ostensibly from a wet evergreen forest.

Understanding differences in ecological physiology between dry and wet tropical forest species can explain the relative distribution and abundance of deciduous and evergreen species in tropical cities, and inform how they can be managed for drought. Combined with insights into forest change from modeled projections under increased temperature scenarios and paleo-climate reconstructions, urban landscapers in tropical cities can potentially select appropriate deciduous and evergreen tropical species that are best adapted to future hotter and drier conditions. The purpose of this paper is to consider how an appreciation of monsoonal tree species adaptations to variable drought can inform sub/tropical urban tree understanding and management.

TROPICAL FOREST TYPES AND ADAPTATION

Monsoonal Dry Forests

The climate of most subtropical and tropical cities has one or several dry periods long enough that water stress and negative growth effects emerge if not understood and managed properly. Monsoonal dry forests are found within tropical latitudes where the dry season is long enough to cause routine soil water deficits despite episodic rainfall, while the wet season duration is sufficient to support a forest canopy. Because of the extended dry season, monsoonal species appear to be characteristically more deeply rooted than other forest types (Schenck and Jackson 2005), although coarse textured soil can sometimes create dry-deciduous islands in otherwise evergreen forests (Bohlman 2010). Dry forests are a significant ecosystem in the monsoonal tropics whose rich animal and plant biodiversity, particularly in understory environments with greater illumination, is under threat from a range of anthropogenic activities (Miles et al. 2006). The biodiversity of tropical dry forests yields many economically important timber and medicinal species (Johnson and Grivetti 2008) and is also a source of genetic diversity for breeding programs (Purushothaman et al. 2000).

Where soil nutrient levels are low, evergreen species are typically favored, sometimes mixed with deciduous species (Choat et al. 2005; Ishida et al. 2006). Dry evergreen forest species must tolerate intense solar radiation, heat, and drought during the dry season, and low light and high rainfall during the wet season (Graha et al. 2003). The relatively small leaves of dry evergreen forest species relative to deciduous species minimize interception of solar radiation and maximize convective and radiative cooling during the dry season (Pittman 1996). Evergreen species with lower leaf nitrogen concentrations, greater leaf longevity, and greater internal recirculation of nutrients have a lower investment in nitrogen per unit of photosynthetic machinery per year than do deciduous species (Doley 1982; Wright et al. 2002), but they must tolerate low leaf water potentials and survive desiccation (Pittman 1996; Brodribb et al. 2003) during the extended dry season. Dry evergreen forest species typically have lower stomatal conductance and photosynthetic rates than do deciduous species (Choat et al. 2005; Ishida et al. 2006) and a lower hydraulic conductance that limits stomatal conductance and lowers internal water potentials (Brodribb et al. 2003; Ishida et al. 2006).

Deciduous species in monsoonal dry forests have a tendency to occupy more nutrient rich soils, where fire can determine a particular forest subtype (Miles et al. 2006). Dry-deciduous species typically have high transpiration rates and hydraulic conductivities that maximize productivity during wet season foliation. This forest type then enters deciduous leaf senescence to defoliate at some point during the dry season (Choat et al. 2005; Ishida et al. 2006). Deciduous dry forest tree species, in fertile soil where the cost of nutrient loss is not limiting, exhibit a remarkable array of adaptations in response to extreme seasonal wetness and drought. Drought-deciduous species vary with respect to leaf longevity and length of dormancy in response to drought (Elliot et al. 2006) and in hydraulic properties. Some species may undergo xylem cavitation and defoliate in response to modest water stress at relatively less negative internal water potentials and then initiate refoliation with new xylem as rainfall increases the soil water content with onset of the wet monsoon season (Brodribb et al. 2002). Other species under mild water stress avoid cavitation entirely and maintain functional xylem while defoliated. This form of drought sensitivity minimizes soil water depletion, maximizes soil water content, and allows refoliation and sunlight capture before the onset of the wet season and subsequent increased competition for sunlight (Brodribb et al. 2003; Elliot et al. 2006). Some drought-deciduous species have high exchangeable trunk water storage capacity due to their wood anatomy, which facilitates the avoidance of low soil water potential effects by such species (Borchert and Pockman 2005).

Hydraulic signaling appears, however, to be an incomplete explanation for drought-induced dormancy. Changes in hydraulic properties do not correlate to gas exchange reduction prior to senescence in many tropical deciduous species (Brodribb et al. 2002; Brodribb et al. 2003). The speed of signal transfer and the distances over which the signals must be transported in trees would not result in timely stomatal responses to diurnal variations in environmental conditions. Leaf size and heating may provide a possible alternative explanation for drought-induced dormancy in these species. A number of drought-deciduous species have relatively large leaves, such as are rarely found in full sun habitats [e.g., *Tectona grandis* L. f. (teak) and a number of dipterocarp species (Sales-Come and Holscher 2010)]. Large leaves can be maintained only if high transpiration rates facilitate evaporative cooling and maintain photosynthetically optimum leaf temperatures, a characteristic consistent with high stomatal conductance and wide xylem vessels capable of high hydraulic conductance as are found in drought-deciduous species (Choat et al. 2005; Ishida et al. 2006).

High transpiration rates, particularly in species with large leaves, suggest a possible defoliation signal in drought-deciduous species. These species appear to have stomata sensitive to leaf-air vapor pressure difference (LAVPD) (Ishida et al. 2006). Mild, dry season water stress may trigger a rapid and large drop in stomatal conductance in response to a small change in soil water potential, with minimal cavitation and negligible loss of xylem function (Brodribb et al. 2003). A large decrease in stomatal conductance somewhat decoupled from water potential can be explained by a feed-forward process mediated by LAVPD and enhanced by large leaf size, where a small reduction in conductance from soil drying reduces transpirational cooling. Reduced transpirational cooling would increase leaf temperature and LAVPD, which, in turn, would push conductance even lower and LAVPD higher in a feed-forward loop. Buildup of leaf-level abscisic acid (ABA) has been linked to stomatal closure in trees, not only during soil drying (Bauerle et al. 2003), but also in very dry air conditions that causes high LAVPD (Bauerle et al. 2004). Thus, a large-leafed species could reach rapid stomatal closure from small changes in soil drying and decreased internal water potential due to leaf heating that, in turn, triggers ABA buildup to the point of inducing leaf senescence.

Wet Evergreen

Equatorial wet evergreen forests largely, but not exclusively, fall within +/- 10 degrees latitude of the equator in three global regions. These regions are the Amazon basin in western South America, the Congo in central Africa, and in Southeast Asia from Malaysia to eastern New Guinea (Kottek et al. 2006). A simple characterization of these forests is aseasonal annual precipitation of over 2,000 mm, with each month receiving at least 60 mm of rainfall (Kottek et al. 2006) and resulting in no distinct dry season.

Since water is not limiting, wet evergreen forest species compete for more limited nitrogen and light (Graha et al. 2003). Wet evergreen species typically have shallower root systems than do monsoonal dry forest species (Schenk and Jackson 2005). Shallower roots are more effective at scavenging scarce nitrogen from forest-floor dry matter decomposition (Santiago et al. 2004). With less biomass needed for deep root production, wet evergreen species invest more biomass in leaves (Santiago et al. 2004) that are long lived and more efficient at nitrogen use (Wright et al. 2002). Light is particularly limiting for seedling recruitment. Whole plant shade tolerance is a key adaptation that allows seedlings to persist in the understory until a gap allows enough light for vigorous growth (Baltzer and Thomas 2007).

As a trade-off for adaptation to light and nitrogen scavenging, aseasonal climate wet evergreen species are less tolerant of soil and atmospheric water deficits (Brenes-Arguedas et al. 2008). That is, wet evergreen species are less drought tolerant at the physiological level than species found in monsoonal dry habitats (Baltzer et al. 2007), with less desiccation-tolerant leaves (Baltzer et al. 2008) and xylem hydraulic properties (Baltzer et al. 2009), particularly at the seedling stage (Kursar et al. 2009). The wet evergreen members of co-generic species pairs have higher aboveground growth rates than do related species from monsoonal habitats with distinct dry seasons (Baltzer et al. 2007). Wet evergreen species are also not tolerant to atmospheric water deficits. Adapted to year-round wet and humid conditions, upper canopy tree species in aseasonal wet forests maintain high photosynthesis rates at low levels of vapor deficits, but exhibit steep stomatal closure and reduced photosynthesis as vapor deficits increase (Cunningham 2006).

Tropical wet evergreen forest species are essentially specialists attuned to a relatively specific set of environmental conditions (Woodruff 2010), where drought is absent (Baltzer et al. 2007). Wet evergreen forests also function within a narrow temperature range (Woodruff 2010), thus physiological and morphological mechanisms to survive greater water and temperature ranges are not evident (Baltzer et al. 2007; Baltzer et al. 2008; Baltzer et al. 2009; Kursar et al. 2009).

A subset of wet evergreen tropical forest habitats includes montane forests. These forests exist in cooler, higher elevation climates than do lowland wet evergreen forests in a broader latitudinal range within the tropics (Bubb et al. 2004). Higher elevation translates to cooler temperatures and lower vapor deficits and evapotranspiration, resulting in a more favorable water balance (Tanaka et al. 2003). Montane forests may be subject to monsoonal dry periods. Evapotranspiration peaks during the dry season, and the general presence of deep soils suggests that water stress is not a decisive factor in characterizing this forest type (Tanaka at al. 2008). Likely due to their temperature limits and limited adaptability to water stress (Foster 2001), montane species are not typically found in urban tree populations in either monsoonal or wet equatorial cities. In general, wet evergreen forest species are not typically used in monsoonal sub/tropical cities because they are, in essence, specialists (Woodruff 2010) adapted to nutrient and light limited habitats, and unlikely to tolerate soil and atmospheric water deficits during monsoonal dry periods (Kjelgren et al. 2011).

WATER STRESS – TROPICAL URBAN TREES

Urban heat island effects are characteristic of all cities and arise from increased sensible and re-radiated heat from impervious surfaces (Rizwan et al. 2008). In tropical and subtropical regions, cities with pronounced monsoonal dry seasons may experience particularly intense heat islands (Roth 2007). While vegetation can mitigate against heat islands (Roth 2007), urban vegetation in tropical cities will be affected nonetheless by elevated temperatures from climate change, in general, and through attendant increased heat loading from asphalt (Kjelgren and Montague 1998) and other non-transpirating surfaces (Montague and Kjelgren 2004). In particular, the crowns of freestanding isolated street trees will be subject to higher heat loading (Kjelgren and Clark 1993). The degree of heating depends on sensible heat dissipation as a function of leaf size (Leuzinger et al. 2010) and stomatal conductance, which determines the degree of coupling of the leaf with the atmosphere (Jarvis and McNaughton 1986). Temperature interacts with limited soil water due to confined root zones, due to either limited volume or depth (Bondarenko 2009), to impose water stress on urban trees (Close et al. 1996).

Studies of street tree populations in Bangkok, Thailand (Thaiutsa et al. 2008), and Bangalore, India (Nagendra and Gopal 2010), suggest that dry-deciduous species are more tolerant of monsoonal dry urban climates. Both of these cities have pronounced monsoonal climates with a four- to six-month dry season and a majority of deciduous species in their street tree populations. In each city, evergreen species comprised only one-third of the top 15 most commonly used street tree species, and those evergreen species used as street trees were largely from drier and harsher habitats than most species from wet equatorial forests (Kjelgren et al. 2011).

The use of deciduous tree species in tropical cities in Asia appears to be the result of informal selection processes. Thaiutsa et al. (2008) also surveyed older, large specimen trees (growing on private property not along a city street) in Bangkok that were much older than the street tree population. These specimen trees were dominated by evergreen species from dry evergreen forests, particularly in the genus *Ficus*, rather than by deciduous species. However, only four of the most common specimen trees were also common as street streets, and two of these four were deciduous. Limited crossover between old specimen and street tree species suggests that evergreen species even from dry habitats did not perform as well as deciduous species in urban areas, resulting in proportionally greater adoption of deciduous species as street trees. The apparent heat tolerance limitation of evergreen species is consistent with Woodruff's (2010) observation that the current distributions of evergreen tropical forests, certainly from aseasonal, but possibly also seasonal habitats (Trisurat et al. 2009), reflect their temperature limits. Thus, the circumstantial evidence suggests that evergreen tropical tree species are less suited to higher urban heat island temperatures in subtropical and tropical cities.

Empirical Studies

Recent studies illustrate the differences in adaption among sub/tropical evergreen versus deciduous species used as urban street trees. Kjelgren et al. (2008) investigated water use of three tropical tree species varying in leaf habit and commonly used in Bangkok's streetside population. In plotting the frequency distribution of water use rates expressed as the ratio of daily water use (mm day^{-1}) to local reference evapotranspiration (the plant factor, Kp), the dry deciduous species *Lagerstroemia loudonii* (closely related to Star of India, *Lagerstroemia speciosa*) had the highest use (Figure 1, modified from Kjelgren et al. 2008). Consistent with reports that dry deciduous species have hydraulic architecture (Choat et al. 2005) supporting higher stomatal conductance (Ishida et al. 2006), *L. loudonii* Kp values reached a maximum of between 40%–50% of reference evapotranspiration (ET_o). Higher stomatal conductance and transpiration

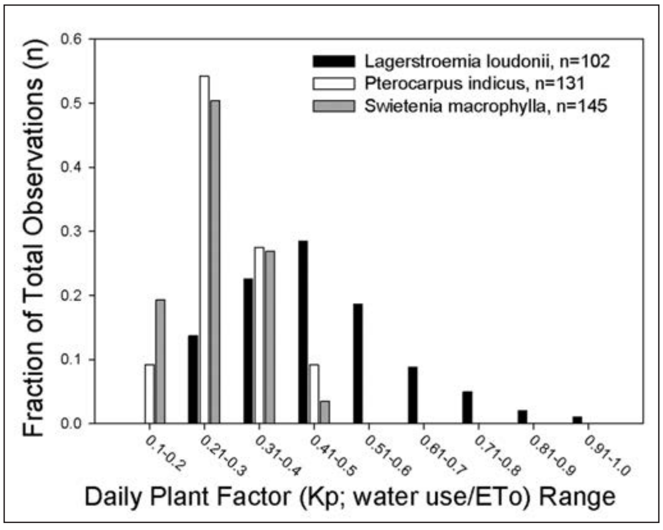

Figure 1. Monsoonal dry season (January–April) water use normalized to depth units (mm/day) for container grown *Pterocarpus indicus, Swietenia macrophylla*, and *Lagerstroemia loudonii*, three sub/tropical trees species common in Bangkok, Thailand's streetside population, where n is the number of daily observations over six replicates per species (modified from Kjelgren et al. 2009).

rates for sub/tropical dry deciduous species would be consistent with high carbon gain over the monsoonal wet period, in contrast to evergreen species that can photosynthesize year round.

By contrast, the Kp of both *Pterocarpus indicus* (angsana) and *Swietenia macrophylla* (mahogany) was lower at 20%–30% of ET_o. *Swietenia macrophylla* is a dry evergreen species from monsoonal regions in South America. Its lower transpiration rate would slowly deplete soil water during the monsoonal dry period and allow extended carbon gain. *P. indicus* can be facultative deciduous when conditions become dry, but is otherwise evergreen. *P. indicus* is found along sandy seashores, suggesting tolerance to drought and salt under stressful conditions. However, it can aggressively grow and expand habitat under more favorable conditions. Notable in comparing these three species is that the distribution of Kp values is much broader for *L. loudonii*, approaching ET_o on occasion. High stomatal conductances imply greater sensitivity of transpiration to environmental factors that can affect stomatal opening, such as vapor deficits and wind.

When subjected to drying conditions, all three species exhibited a similar response to water stress (unpublished data). All of the trees were growing in containers when subjected to substrate drying. The stomatal conductance quickly declined in all three species, moderating internal water potential. Since isolated trees are well ventilated (Jarvis and Morison 1981), stomatal conductance to water vapor is closely coupled to the atmosphere, exerting close to a direct 1:1 relationship between incremental stomatal closure and transpiration rate (Jarvis 1985). Stomatal closure at incipient substrate drying reduces evaporative strain on internal water potential, an isohydric response to water stress that slows the depletion of root zone water (Schultz 2003). All three species maintained an isohydric response as stomatal conductance declined to approximately 30% of well-watered levels. However, at this point, *P. indicus* isohydric control failed and internal water potential declined quickly as conductance fell to about 10% of well-watered levels. Total leaf area of *P. indicus* was substantially greater than the other two species, such that the obvious explanation is that it depleted substrate water content to what was, in effect, the permanent wilting point.

The studies in Bangkok's monsoonal climate indicate that three commonly used sub/tropical tree species exhibit an isohydric water stress response strategy, similar to many temperate woody species (Shultz 2003). This isohydric response favors lower stomatal aperture, transpiration, and possibly photosynthesis in exchange for slower depletion of root zone water—in essence, a "save it for a rainy day" strategy (Kjelgren et al. 2009). Combined with the deep rooting common in monsoonal forest species (Schenk and Jackson 2005), and traits that either favor drought avoidance or drought tolerance through leaf morphological characteristics (e.g., smaller, denser leaves; Wright et al. 2002), monsoonal dry forest species that are either deciduous or evergreen appear to be well-equipped to tolerate drought as street trees in subtropical and tropical cities.

Acknowledgments. Thanks to the U.S. State Department and Council for International Exchange of Scholars Fulbright Fellowship program and the University of Queensland for their support that led to this publication.

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Zusammenfassung. Ein Verstehen der natürlichen Habitate von Baumarten, die erfolgreich als tropische und subtropische Arten im urbanen Raum leben, führt zu der Einsicht, wie der urbane Wassermangelstress während der Trockenperioden im Monsun minimiert werden kann. Äquatoriale und montane Regenwaldarten, die selten Trockenheit erleben, sind in subtropischen und tropischen Städten mit monsunaler Trockenheit selten zu finden. Endemische Arten aus monsunalen Trockenwäldern hingegen scheinen eine breite Toleranz zu haben und sind in vielen tropischen Städten erfolgreich am Standort etabliert. Die Trockenwald-Baumarten haben die Tendenz, tief zu wurzeln um Trockenheit zu vermeiden und lassen innerhalb ihres Toleranzspektrums auch mal die Blätter fallen. Trockene, sommergrüne Arten, die typischer Weise auf mehr fruchtbaren Böden gefunden werden, maximieren ihr Wachstum während der monsunalen Regenperioden mit hoher Photosynthese und Transpirationsrate, und lassen dann während der Trockenzeit die Blätter fallen. Immergrüne Baumarten, die typischerweise auf weniger fruchtbaren Böden gedeihen, haben einen höheren Kohlenstoffanteil in den Blättern, die weniger photosynthetisieren und transpirieren als sommergrüne Arten. Sommergrüne, Trockenheitstolerante Arten sind häufiger als immergrüne, Trockenheitstolerante Arten in den Städten zu finden, insbesondere wegen der größeren Blütenpracht, aber auch explizit wegen ihrer Eigenschaft, ihren Blattfall und die Dauer dessen mit den Trockenperioden zu koordinieren. Eine empirische Studie an drei tropischen Baumarten, die eine Bandbreite von Blatteigenschaften aufweisen, zeigten ein isohydrisches Verhalten, welches die Transpiration mildert und das Bodenwasser während der Trockenheit konserviert. Dennoch können immergrüne Arten weniger Anpassung an die tropischen urbanen Bedingungen von ausgeprägter Trockenheit, intensiver Hitze und begrenztem Wurzelraum zeigen als die sommergrünen Arten mit den anpassungsfähigen Blatteigenschaften.

Resumen. El entendimiento de los hábitats de especies nativas exitosas como árboles urbanos subtropicales y tropicales da pistas sobre cómo minimizar el estrés del déficit de agua urbana para el árbol, experimentado durante los períodos secos monzónicos. Las especies de regiones húmedas ecuatoriales y de bosques montanos rara vez están sometidas a la sequía y están generalmente ausentes en las ciudades subtropicales y tropicales con estaciones monzónicas marcadamente secas. Las especies nativas de los bosques secos monzónicos parecen tener amplias tolerancias ambientales, y tienen éxito como árboles urbanos de muchas ciudades tropicales. Las especies monzónicas de bosque seco tienen una tendencia a estar muy arraigadas para evitar la sequía, con hábitos de hoja caediza a lo largo de un espectro para lograr la tolerancia. Las especies de hojas caducas, que suelen encontrarse en suelos más fértiles, maximizan el crecimiento durante la temporada del monzón húmedo con alta fotosíntesis y transpiración, entonces se defolian para evitar el estrés durante la estación seca. Las especies de árboles de hoja perenne, que suelen encontrarse en suelos menos fértiles, tienen una inversión de carbono más altos en las hojas en la fotosíntesis y transpiran menos el año que lo que hacen las especies de hojas caducas. Las especies de hoja caduca son árboles urbanos más comunes que las especies siempre verdes, debido a arreglos florales más ornamentales, pero también implícitamente debido a su capacidad para ajustar el tiempo y la duración de la defoliación en respuesta a la sequía. Un estudio empírico de tres especies tropicales que presentan una serie de hábitos foliares mostró un comportamiento isohídrico para la transpiración moderados, conservando la humedad del suelo durante la sequía. Sin embargo, las especies perennes pueden ser menos adaptables a las condiciones urbanas tropicales de sequía pronunciada, calor intenso, y los limitados volúmenes de enraizamiento que las especies de hojas caducas con hoja de hábito maleable.

Arboriculture & Urban Forestry 2013. 39(3): 132-135

Urban Trees and Water: An Overview of Studies on Irrigation Needs in the Western United States and a Discussion Regarding Future Research

Laurence Costello

Abstract. A review of the literature concerning water needs and water loss from landscape plants is presented. Studies conducted in the field, using lysimeters, and in containers are summarized and discussed. In some studies, crop coefficients or water use coefficients are included. A discussion of the variability found in research methods and the need for a standardized protocol for tree water needs studies is presented.
Key Words. Crop Coefficients; Irrigation; Lysimeter; Plant Water Loss; Reference Evapotranspiration; Tree Water Needs; Urban Trees; Water Conservation.

This report provides an overview of studies that have evaluated the performance of urban trees under differing levels of irrigation, and summarizes findings that can be used to help determine tree water needs. Papers that measure water loss from tree crowns are included, although they do not necessarily provide an assessment of water needs. The scope of studies is limited to work conducted in the western United States, including the states of California, Nevada, Arizona, Utah, Colorado, and New Mexico. These states receive little precipitation in the summer months and water management for urban vegetation is of paramount importance. The focus is on urban trees, but other types of vegetation are included, such as shrubs and ground covers. For an extensive listing of literature on landscape water conservation and management topics prior to 1995, see Santos and Burger (1995). They include nearly 1,300 citations of books, articles, and manuals that address design, construction, and maintenance issues related to small and large commercial landscapes, small and large residential landscapes, and public works. For a more recent review of the literature on efficient landscape irrigation, see Hilaire et al. (2008). Thirteen authors from 11 different academic institutions in six U.S. states contributed to this paper that summarizes how the following factors impact the efficient use of water in urban landscapes: irrigation and water application technologies, design and management strategies, reuse of water resources, social considerations, incentives (economic and noneconomic), and public policy. Similarly, Kjelgren et al. (2000) address key issues associated with water use and conservation in landscapes: plant water needs, irrigation system uniformity, conservable water, and methods of conservation and their implementation.

In order to group studies similar in nature, reports have been sorted first according to vegetation type: 1) trees and 2) other plant types. Tree studies are then separated into two categories: 1) studies conducted in the field, and 2) studies conducted in containers or lysimeters. For studies conducted in the field, both broadleaf species and palms are included. From a management perspective, studies evaluating tree performance following irrigation treatments are of greatest interest because they provide guidance regarding how much water may be needed to maintain a species in good condition.

TREES

Field Studies

Very few field studies have been conducted evaluating water needs of urban trees in the western U.S. Only three studies are reported here, two for broadleaf species and one for palms.

Most recently, Schuch et al. (2010) evaluated the performance of nine tree species commonly planted in the low desert of Arizona. Trees were planted in field plots and established for 19 months prior to the initiation of three irrigation treatments: available soil moisture in the root zone was depleted by 30%, 50%, and 70%. Twelve months after treatments began, no differences in tree height, caliper, or growth index were found for seven species, while two species receiving the lowest irrigation treatment (70% depletion) showed signs of water stress. Overall quality of all trees was rated as being good based on an assessment of visual appearance. Note that this is an ongoing study and only first-year results have been reported.

Costello et al. (2005) evaluated the growth response of three California native oak species to three irrigation levels (0%, 25%, and 50% evapotranspiration, or ETo) in Santa Clara, CA. Container-grown trees were planted into a cultivated loam soil and irrigated uniformly during a one-year establishment period. After a four-year treatment period, no significant differences in trunk caliper were found for any of the irrigation treatments for all three species (*Quercus agrifolia*, *Q. lobata*, and *Q. douglasii*).

Basically, tree growth and visual appearance for trees receiving no irrigation were not different from those receiving 25% or 50% of reference ETo. Average annual rainfall at the study site is 40.6 cm.

To assess the effect of irrigation level on the performance of palm species, Pittenger et al. (2009) conducted a study in Irvine, CA. Five landscape species (*Archontophoenix cunninghamiana*, *Chamaerops humilis*, *Syagrus romanzoffiana*, *Trachycarpus fortunei*, and *Washingtonia filifera*) were irrigated at three levels of reference ETo: 0%, 25%, and 50%. All species maintained at least minimally acceptable visual quality at the 0% ETo treatment (no irrigation), and two species were found to have near optimum performance with no irrigation, while two species produced more leaves with additional irrigation. The authors note that the water needs of landscape palms are considerably less than that those of commercial palms, such as date, oil, and coconut palms.

Container or Lysimeter Studies

To measure tree water use and/or determine species water needs, a number of studies have been conducted using plants in containers or lysimeters. Here, studies are sorted into two groups depending on whether plant water supply was limited or not.

Water supply limited

In these studies, experimental design included treatments where the supply of available water was limited to some extent. In a two-year study, Devitt et al (1994) measured water loss from three landscape species in Las Vegas, NV. Three container stock sizes (3.8, 18.9, and 56.8 L) of *Prosopis alba*, *Chilopsis linearis*, and *Quercus virginiana* were planted into 190-liter lysimeters. After a three-month establishment period, three irrigation treatments were imposed as leaching fractions of +0.25, 0, and –0.25 (drainage volume/irrigation volume). Although water loss from species (ETa) was affected by tree size and leaching fraction treatments, there was little or no effect of irrigation level on trunk diameter growth.

In a similar study, Devitt el al. (1995) measured water loss from three tree species (*Washingtonia robusta*, *Pinus eldarica*, and *Cercidium floridum*) planted as container stock (#5 and #15) into 190-liter lysimeters. Treatments were similar to Devitt et al. (1994) with irrigation levels expressed as leaching fractions of +0.25, 0, and -0.25. After a three-month establishment period, treatments were imposed for a six-month period. Although significant differences in water use were found for species resulting from planting size and leaching fraction (irrigation level), no significant effect on canopy volumes or basal canopy areas were found, and few significant differences in trunk diameter were found across irrigation treatments for all species.

Water supply not limited

In these studies, experimental design did not include treatments where the supply of available water was limited to some extent (i.e., water was continuously available to the plant).

In a three-month study, Levitt et al. (1995) measured water loss from *Prosopis alba* (Argentine mesquite) and *Quercus virginiana* (southern live oak) growing in containers in Tucson, AZ. A gravimetric method was used to determine actual plant water loss, and water-use coefficients were calculated as the ratio of water loss to reference evapotranspiration for the study site. Water-use coefficients of 0.5 for southern live oak and 1.0 for mesquite were reported using water loss values for the total leaf area, and 1.4 (oak) and 1.6 (mesquite) for water loss on a projected canopy basis.

To determine water needs of balled and burlapped (B&B) stock during the first year after planting in a semi-arid climate, Montague et al. (2004) conducted a one-year study in Logan, UT. The performance of five species (*Platanus* × *acerifolia*, *Salix matsudana*, *Tilia cordata*, *Acer platanoides*, and *Fraxinus pennsylvanica*) was evaluated using locally grown field stock planted into lysimeters. Water loss was measured from trees under nonlimiting conditions, and a water loss coefficient (Kc) was calculated as the ratio of actual water loss (based on total leaf area) to total daily ETo. Tree water loss varied with species, and water loss coefficients ranged from 0.19 for *A. platanoides* to 1.05 for *S. alba*.

To quantify the influence of shading on water loss, Costello et al. (1996) conducted a study using container plants in Palo Alto, CA. Three tree species (*Sequoia sempervirens*, *Magnolia grandiflora*, and *Liquidambar styraciflua*) and one shrub species (*Pittosporum tobira*) were placed in full sun (86,000 lux) or a shaded environment (820 lux) and water loss was measured gravimetrically over a two-week period. Plants in the shaded environment were found to lose on average 58% less water than those in the full sun environment.

OTHER PLANT TYPES (GROUND COVERS, SHRUBS, AND HERBACEOUS PLANTS)

Field Studies

In a relatively early report, Sachs (1991) conducted a two-year study at two sites in California (San Jose and Irvine), evaluating the performance of hedgerow and ground cover plantings irrigated at 0%, 12.5%, and 100% ETo. Species included were *Ligustrum lucidum*, *Pittosporum tobira*, *Nerium oleander*, *Coprosma baueri*, *Xylosma congestum*, *Eugenia uniflora*, *Hedera canariensis*, and *Carpobrotus* sp. Plantings were established in 1965 and treatments were initiated six years later (1971). At both study sites, an irrigation level of approximately 12.5% ETo was sufficient to maintain all plants in a healthy condition with good appearance. Higher amounts of water caused increasing amounts of growth, which also increased their pruning requirements.

A two-year study to assess the performance of three groundcover species irrigated at 0%, 25%, 50%, 75%, and 100% of ETo was initiated in 1991 by Staats and Klett (1995). A principal goal of the study was to identify water-conserving species that could serve as alternatives to Kentucky bluegrass (*Poa pratensis*). They reported that an optimum irrigation level for *Cerastium tomentosum* and *Sedum acre* was 25% ETo (after becoming established), while *Potentilla tabernaemontii* required 75% ETo.

In 1990, Pittenger et al. (2001) initiated an evaluation of the performance of six groundcover species at four irrigation levels: 20%, 30%, 40%, and 50% ETo. All species had been established for a one-year period in 1989 at 25%, 50%, 75%, and 100% ETo (Pittenger et al. 1990). After a 17-month treatment period, they reported that *Drosanthemum hispidum*, *Baccharis pilularis*, and *Hedera helix* performed well at 20% ETo, while *Vinca major* required 30%. Both *Potentilla tabernaemontii* and *Gazania* sp. were found to need greater than 50% ETo.

In 1996, Shaw and Pittenger (2004) evaluated the performance of 30 species of shrubs in Encinitas, CA. Following an establishment period of approximately 18-months, plants were irrigated for one year at 12%, 24%, and 36% ETo, while in 1997 and 1998 irrigation treatments were adjusted to 0%, 18%, and 36% of ETo "because initial treatments were not affecting plant quality." Irrigation frequency was determined using a projected soil moisture deficit of 13 mm. The authors reported that "many species performed well at 36% and 18% ETo treatments, but suffered at 0 ETo." Eight shrub species performed well with no irrigation, while 13 species performed well at 18% ETo. Three species did not become established in the study plot, and the remaining species required irrigation levels greater than 18% ETo.

In an evaluation of herbaceous species, Reid and Oki (2008) conducted a one-year study in Davis, CA. After a one-year establishment period in 2005, six species of California native plants were irrigated at four irrigation levels: 20%, 40%, 60%, 80% ETo. Plant performance was evaluated using a growth index. For all six species, no significant differences in summer growth or physical appearance were found for the four irrigation levels. Ongoing performance evaluations of the same species are being conducted in seven climate zones throughout California.

Container and Lysimeter Studies

Using both containers and lysimeters, Garcia-Navarro et al. (2004) measured the water use of four shrub species in Davis, CA. After a one-year establishment period, two parallel experiments (using containers and lysimeters) were conducted during the summer of 1998. The authors state that "the relative water use of the same species in 3.8-liter containers would be representative of the water use of the same species in the landscape." Lysimeter plants were irrigated at 30% and 100% of ETo, while container plants received either daily irrigation or water was withheld until available water was depleted. Crop coefficients for the well-irrigated container plants (all four species) were found to range from 1.30 to 5.51, while three species showed a three-fold reduction in water use when water-stressed. At 30% ETo, water use was reduced by 52% to 55% for plants in lysimeters (three species). Growth of all species was affected by reduced irrigation, and visual appearance declined substantially for two species.

DISCUSSION

From the results of field studies, water needs assessments were found to vary according to vegetation types and species. For trees, seven species of arid-adapted trees were reported to perform well under a 70% soil water deficit treatment, while two species performed better at a 50% depletion level (Schuch et al. 2010). Oaks receiving no irrigation performed as well as the same species receiving 25 and 50% ETo (Costello et al. 2005). Similarly, two palm species were found to perform optimally at 0% ETo, while three others were assessed as having acceptable quality without irrigation (Pittenger et al. 2009).

Field studies of other vegetation types show a somewhat wider range of species water needs. An irrigation level of 12.5% ETo was found to be sufficient for eight hedgerow and groundcover species (Sachs 1991); while in another study (Staats and Klett 1995), two groundcover species performed well at 25% ETo, yet one species needed 75% ETo). For shrubs, eight species were reported to perform well at 0% ETo, while another 13 species required an irrigation level between 18% and 36% ETo (Shaw and Pittenger 2004). In a study evaluating six herbaceous species, all species performed well at 0% ETo (Reid and Oki 2008).

In lysimeter studies where water supply was limited, no effect of reduced irrigation was found on trunk diameter growth for three species of trees (Devitt et al. 1994). In a follow-up study by Devitt et al. (1995), similar results were found for an additional three species of trees. In a container and lysimeter study where water supply was limited for four shrub species, water use reductions resulted in growth reductions for all species and a decline in visual appearance for two species.

In a lysimeter study where water supply was not limited (Levitt et al. 1995), water-use coefficients were found to range from 0.5 to 1.0 for two tree species (based on a total leaf area) and from 1.4 to 1.6 (based on a projected canopy). For B&B stock planted into lysimeters, water-use coefficients ranged from 0.19 to 1.05 for five tree species.

Collectively from field and lysimeter studies, many of the woody and herbaceous species evaluated were found to perform well at irrigation levels less than 25% ETo. Indeed, a number of species were found to perform well without irrigation (0 ETo). These findings are important for landscapes in climate zones where precipitation is limited during the year, such as in arid, semi-arid, and Mediterranean zones. The use of landscape species that require little or no irrigation once established will be of great value in creating and maintaining water-conserving landscapes.

Certainly, a considerable amount of research still needs to be done. For instance, evaluations for only 17 tree species are reported in this review. Clearly, this number is not sufficient to provide useful guidance regarding the water needs of landscape species. For trees in particular, much more research is needed to identify the needs of the hundreds of species used in urban forests in the western U.S. In addition and most importantly, a standardized protocol for conducting such research is critically needed. From this review, it is evident that a substantial level of variation exists in experimental design and methods. For the species evaluated, many differences can be found in treatment levels, methods for quantifying water supplied to individual plants, use of soil moisture measurements to schedule irrigations, length of establishment and treatment periods, stock types, irrigation systems used, and measures of plant performance. These are critical elements of an experimental design that affect the outcome of water-needs studies, making it difficult to compare study results. This leads to an important question: What is the best method of conducting water-needs studies? Unfortunately, as yet, there is no standardized method—but one needs to be established.

A number of other questions regarding experimental methods used for water-needs evaluations of trees can be listed:

- What are reasonable levels of ETo for treatments? Certainly, no irrigation (0% ETo) should be included, but what amounts should be used for irrigation levels (10%, 30%, and 50% ETo)?
- What is the best way to determine the amount of water that matches the desired level of reference evapotranspiration? For example, how much water should be applied to a 2.5 cm caliper tree for 50% ETo? How much for a 5 cm caliper tree? What irrigation frequency should be used?

- What is a reasonable period for irrigation treatments? Should they last for 1, 2, 3, 4, or more years? What is a reasonable period for plant establishment? In the studies reviewed, establishment periods ranged from three months to six years.
- Which performance parameters or variables are most relevant to the scientific community? Is it most meaningful to measure shoot elongation, crown size, trunk diameter, and/or leaf area? Certainly, physiological parameters such as stomatal conductance, leaf temperature, and/or water potential should be considered where possible. In landscapes, plant aesthetics is an important performance parameter to assess, but a standardized method of quantification is needed to maintain consistency across studies and allow comparative analyses of species performance.
- Can results from trees with confined root zones, such as lysimeter and container studies, be applied to the field management of trees? Do limitations in soil volume (relative to field conditions) affect water needs? Even though root systems have more volume for growth in lysimeters compared to containers, they are still limited compared to field conditions. For instance, Schuch and Burger (1997) found water-use and crop coefficients of woody plants in containers varied considerably among species, location, and time of year.

These and other questions need to be addressed in order to establish a dependable protocol for evaluating the water needs of trees. With such a standardized approach, a consistency in methods will be maintained from one study to another, and results will be readily comparable.

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Zusammenfassung. Hier wird eine Literaturübersicht zum Thema Wasserbedarf und Wasserverlust von Landschaftspflanzen vorgestellt. Feldversuche mit Lysimetern und in Containern werden zusammengefasst und diskutiert. In einigen Studien sind die Ertragskoeffizienten oder Wasserverbrauchkoeffizienten eingeschlossen. Es wird hier ein Diskussion zum Thema der vorgefundenen Bandbreite in den Forschungsmethoden vorgestellt sowie auf den Bedarf nach einem standartisierten Protokoll für Wasserbedarfsstudien hingewiesen.

Resumen. Se presenta una revisión de literatura sobre las necesidades hídricas y la pérdida de agua de las plantas en el paisaje. Se resumen y comentan los estudios realizados en el campo, usando lisímetros y contenedores. En algunos estudios se incluyen los coeficientes de cultivo o coeficientes de uso del agua. Se presenta un análisis de la variabilidad encontrada en los métodos de investigación y la necesidad de un protocolo estandarizado para los estudios de las necesidades de agua para el árbol.

Arboriculture & Urban Forestry 2013. 39(3): 136-145

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.

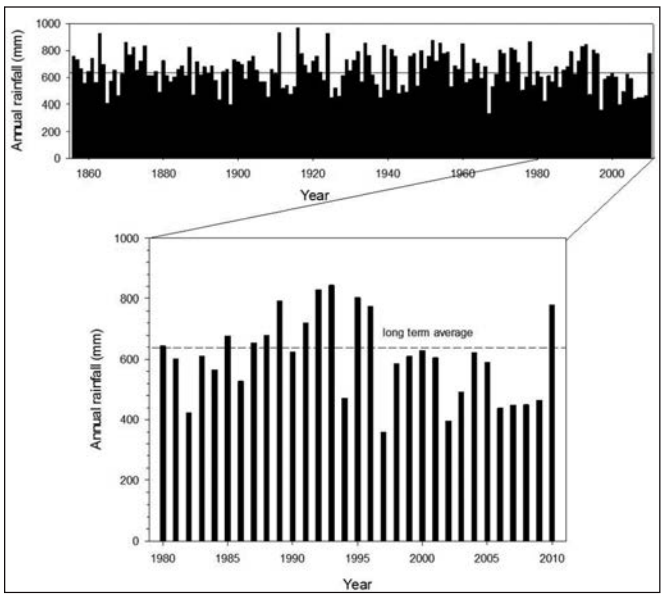

Figure 1. Annual rainfall (mm) for Melbourne CBD 1855–2010 (Bureau of Meteorology, Australia, www.bom.gov.au).

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,

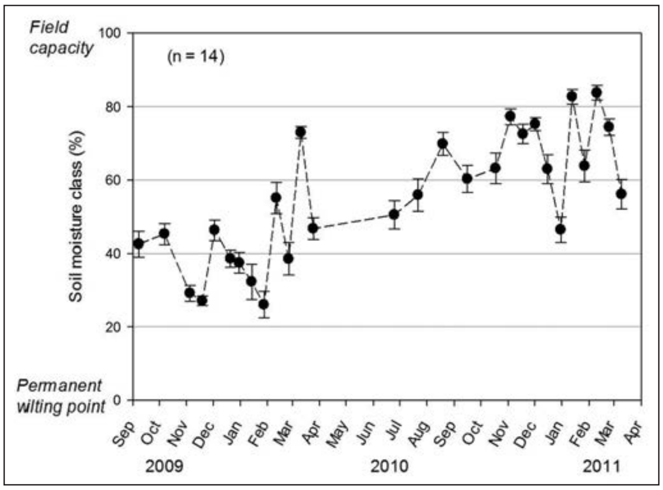

Figure 2. Available soil moisture (%) in The Domain Park from September 2009 to March 2011 in relation to monthly rainfall (mm).

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 Tree contribution to landscape is not compromised	
At Risk (blue)		Stress evident, including: • Leaf yellowing / defoliation • Minor epicormic growth • Minor die back • Minor pest / disease damage	
Declining (orange)		Stress evident, including: • Epicormic growth • Die back • Evidence of dead branches • Severe pest/disease infestation or damage	
Dying (red)		Stress evident, including: • Extensive epicormic growth • Extensive die back • 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

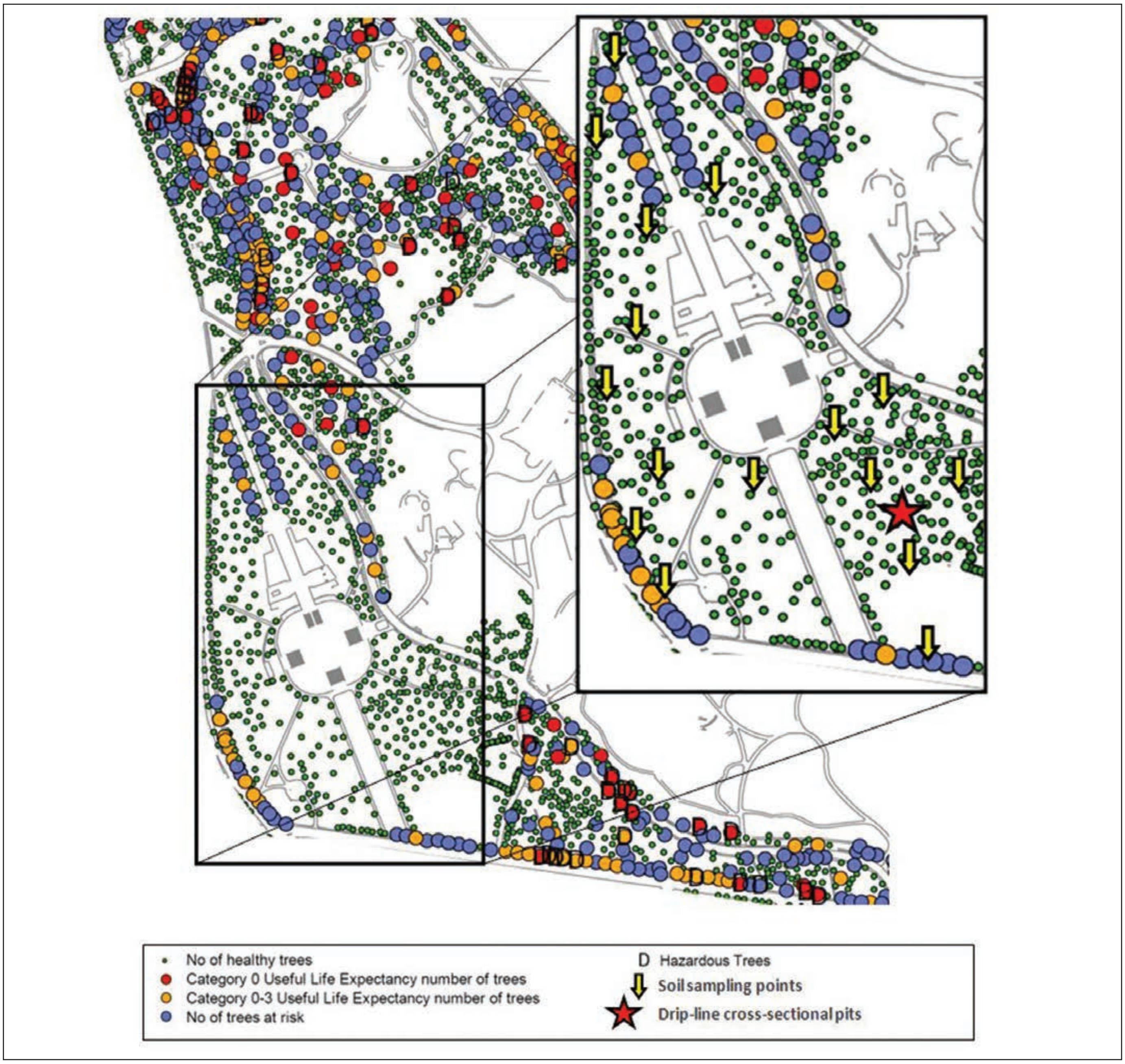

Figure 4. Map of The Domain Park, Melbourne, showing assessed tree canopy health stages, soil moisture monitoring locations, and sites of trench dug investigations of drip irrigation.

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.

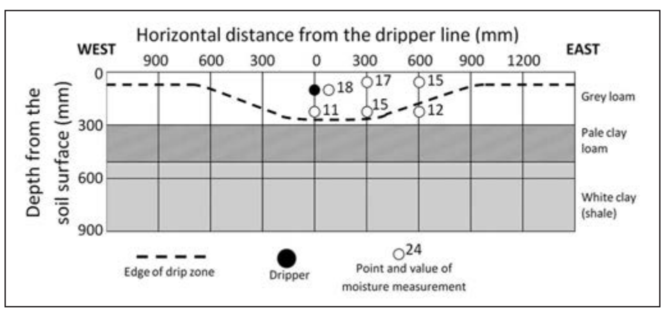

Figure 5. Soil moisture data (% soil water v/v) at the Polo Lawn, Domain Park (north) in March 2009 (early autumn).

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.

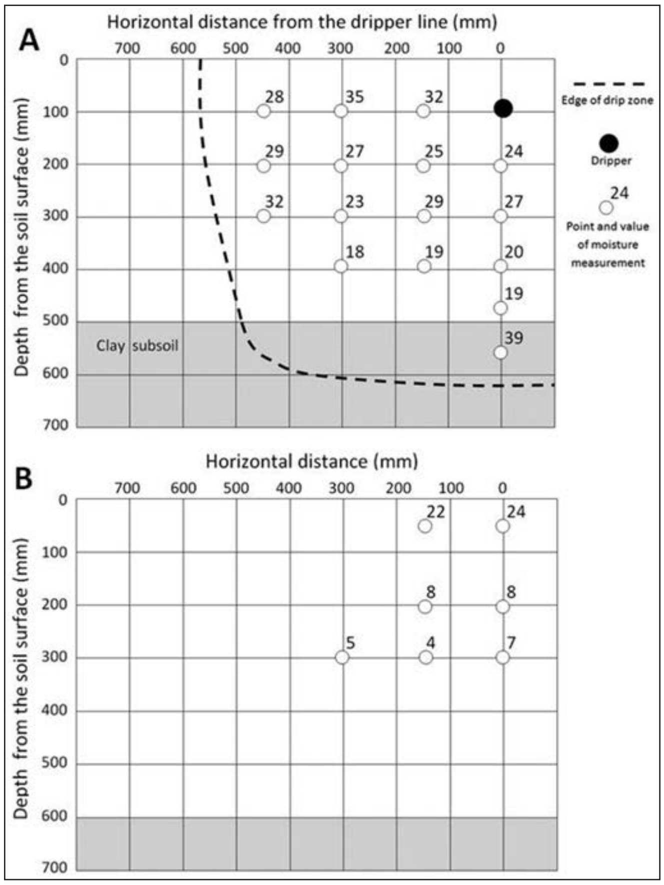

Figure 6. Soil moisture data (% soil water v/v) after winter irrigation in Domain Park (south) in August (winter) 2009 (A is the irrigated site, B is a neighboring site without irrigation).

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.

Acknowledgments. The authors would like to thank the anonymous reviewers, who have greatly improved the paper, David Callow for providing some of the soil moisture data, and the City of Melbourne's arboriculture staff for access to their data and advice.

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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.

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Abstract Coverage: Articles in *Arboriculture & Urban Forestry* are indexed in Bibliography of Agriculture (online database AGRICOLA), Biological Abstracts (BIOSIS), CABI (CAB abstracts, Forestry Abstracts, Horticultural Abstracts, Ornamental Horticulture, Review of Plant Pathology), and Biological & Agricultural Index Plus.

ISSN 1935-5297 (print) ISSN 2155-0778 (online)

International Society of Arboriculture

Arboriculture & Urban Forestry is published by the International Society of Arboriculture, a worldwide professional organization dedicated to fostering a greater appreciation for trees and to promoting research, technology, and the professional practice of arboriculture and urban forestry.

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