TREES, CITIES, DROUGHT AND EXTREME HEAT

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"only a crisis – actual or perceived – produces real change. When that crisis occurs, the actions that are taken depend on the ideas that are lying around."

Milton Friedman (1962) in *Capitalism and Freedom*.

Abstract

Human-induced climate change continues to gain considerable publicity as our politicians in general follow rather than lead public opinion. Recent extreme flood and fire events have demonstrated what the future might look like and while we can be certain of nothing in the future, it would be irresponsible not to plan for continuing weather extremes. While summer floods on the east coast have been the latest large-scale catastrophe originating from extreme weather events, across most of Australia planning for urban areas must focus on what we should do to prepare for extreme drought and/or extreme heat in our cities and towns. While we have reached a point where we will require massive technological solutions to retain anything like our current life-styles, it is critical that we future-proof our cities as well as we possibly can. Urban vegetation has the capacity to play an important role in making our towns and cities more liveable and in providing some precious time for us to develop longer-term and more permanent solutions to climate change. This paper focuses on the key planning issues and what we can expect in the best case from well-planned urban vegetation in the changing climate.

Introduction

Climate change is rapidly gaining public acceptance as the major challenge for the present and for future generations, but there is little evidence that the likely full impact of climate change is well understood. While the focus remains on retaining future temperature increases within a 1.5-3.0°C range of mean annual temperature, there are signs that the inevitable growth in ferocity, duration and frequency of extreme weather events has emerged as a public concern. Clearly the focus must be on slowing, stopping and then reversing the output of the major greenhouse gases, but even if we are successful, a continuing set of challenges will remain for us to confront and survive if we are to have a positive future on our planet.

Given that more extreme future weather events are inevitable, we must do whatever we can to mitigate the impact and within cities this means we must find ways to reduce the impact of extreme heat, rainfall and flood events, prolonged droughts, high winds and rising sea levels. To plan for success we need a clear understanding of the likely extreme weather events we will be facing, the best use of urban vegetation in mitigating the impacts of these events, especially on human well-being and health, and how we should select and monitor plant species and the vegetation they are to be planted in for success in these challenging environments.

What are extreme weather events?

Extreme weather events are almost self-defining, but it is important to consider some of the details around these. From a human perspective, an extreme weather event can be considered as a crisis, where a crisis:

1. is an "event" in the sense of being an occurrence of short duration.
2. is unpredictable, or at least, it is generally not predicted by the participants. This implies an element of surprise and a lack of preparation.

3. results in fundamental changes in the natural order of a system. That is, post-crisis conditions are influenced either permanently or for some time by the effects of the crisis.

Some extreme weather events can be regarded as **threshold crises** in that they are the result of a gradual accumulation of adverse conditions until a breaking point is reached: e.g. drought and sea level rise; while others are best considered as **point crises**, where there is no build-up and for the participants the event comes at full force and without warning: e.g. fire, flood, extreme heat events. The important point is that some crises build relentlessly, others come swiftly and without warning (at least to the victim). Underlying all these events is a major threshold crisis – the increase in the level of greenhouse gases, which in turn is fundamentally linked to the rise in human population and increased expectations of living standards.

From the perspective of the value of urban vegetation and the risk it is exposed to, the focus here will be on drought and extreme heat events. Drought is a classic threshold crisis, where a lack of rainfall dries the environment until each plant is placed under stress, which, if it continues for long enough, will lead to the death of individual plants. The impact of drought is usually relatively long-term. Extreme heat events are much shorter and usually span from one to several days. Extreme heat can have a direct impact on the plant and especially on the leaves, which can reach lethal temperatures quite quickly. If extreme heat events occur during a drought the combined impact is profound.

Before considering the impact of drought and extreme heat on individual plants it is important to consider the rate at which these events might be increasing. There have been some significant drought events in Adelaide over the past few decades and there is concern that these are growing in frequency and severity, but the increase in extreme heat events can be shown most convincingly.

Data on daily maximum temperatures from well over a century are available from the Bureau of Meteorology in Adelaide, and while it is not completely comparable (the location of the readings changed during this time), it does provide a strong general guide to the problem. Over the period from the 1890s to the present, the mean average temperature in Adelaide has risen by what seems a relatively small amount. Often, the number of hot summer days is presented as the number of days above 35°C and figure 1 (blue circles) shows the number of days over 35°C for Adelaide on a per decade basis. It is quite clear from this that there were about 200 days per decade over 35°C during the 1890s to the 1910s and then the number declined, to a minimum of about 120 in the middle of the 20th century. The number then began to rise again, reaching more than 280 in the most recent decade. This is a clear and significant rise over the last 50-60 years, but should we be concerned by it? The answer to that lies in considering even more extreme temperatures. Figure 1 (red circles) shows the number of days per decade with temperatures in excess of 42°C. By any standard this presents a frightening result. There was a peak of 15 days over 42°C in the 1900s and then the number declined into the middle of the 20th century, similar to the data for days over 35°C. However, from the 1990s the numbers have increased alarmingly to a peak of about 40 days in the most recent decade. The clear rise in days of extreme heat is particularly worrying because the issue is exacerbated by the reality that these extremely hot days often come in groups, so plants are being exposed to potentially lethal temperatures for longer periods of time, especially during the last 20 years.

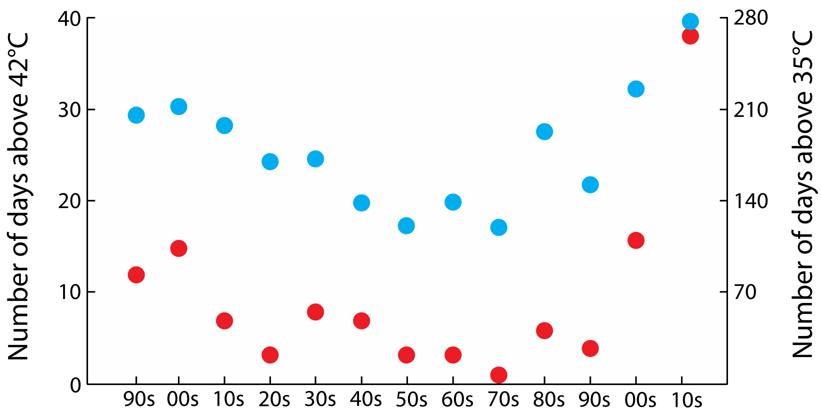

Figure 1. Days above 35°C (blue circles) and above 42°C (red circles) in each decade from the 1890s until the end of 2020. Data compiled from the Bureau of Meteorology in Adelaide.

What is the impact of prolonged drought and extreme heat?

Most terrestrial plants suffer the impacts of water stress at some time during their lives and many exist in a state of relatively low water supply. Given that plants lose water as part of the gas exchange cycle that is required for them to take up carbon dioxide for photosynthesis and expel the waste product oxygen, it is no surprise that lack of water is the major cause of terrestrial plant death. How does this happen?

When a plant is fully turgid and there is light available, it is likely that the stomates on the leaves will be open. They are turgor-operated valves and when full of water the pair of guard cells separate from one another to open the stomatal pore, allowing for gas exchange, and most importantly for the uptake of carbon dioxide, which in turn allows photosynthesis to occur at an optimal rate. However, when water becomes scarce, the guard cells lose their turgor and eventually the stomatal pore fully closes, blocking the uptake of carbon dioxide, but crucially also blocking the loss of water vapour – this is the point where the plant changes its priority from maximising carbon dioxide uptake to minimising water vapour loss.

While plants have open stomates, they are usually losing water vapour through them (unless the plant is growing in extremely high humidity), but even after they close their stomates, many plants continue to lose a significant amount of water via other pathways, and especially through the mostly water-impervious waxy cuticle that covers the leaf surface. This water is replaced in the leaves via the plant's water conducting system, which is made up of a series of interconnecting microscopic tubes that are mostly tracheids (conifers) or vessel elements (angiosperms). The water in these tubes is placed under negative tension as water evaporates at the leaf surface and the negative water pressure thus produced "pulls" water up through the plant from the root system. However, if water in the soil becomes too scarce, the individual conducting elements in the main plant axis (tracheids or vessel elements) can cavitate as microscopic bubbles are pulled into the conducting cells, where they expand and block the flow by causing cavitation. Woody plants have many alternative and microscopic pathways for water transport, so cavitation does not kill the plant until the situation becomes extreme and most or all pathways for water transport from the soil to the leaves are lost. Plants can recover from short-term cavitation, but this is the most likely killer of plants during drought.

Some plants have evolved to extremely dry environments and are highly efficient at reducing water loss when stomata are closed. In theory, such plants can remain in this state for a long time, but it may incur a significant cost. While a plant is alive it has some energy requirements and these are supplied via the process of respiration, which draws on the plant's food reserves even when the stomates are closed and photosynthesis has stopped. If this continues for long enough, as in a prolonged drought, then the plant may begin to starve as it uses up its carbohydrate reserves in life maintenance. Eventually it is also likely that plants under this kind of long-term stress become more susceptible to other damage (e.g. disease and insect attack) (McDowell *et al.* 2008).

Some plants have evolved in areas where summers are hot and dry and they may spend most of summer with their stomates closed – such plants are likely to be highly drought resistant but also probably quite slow growing. Other species, that evolved in environments where water is usually abundant, respond negatively and rapidly to drought, although the degree to which carbon starvation contributes to this is not well researched. An understanding of this range of responses is important in choosing species to grow in an urban environment.

As noted earlier, drought is a threshold crisis in that it develops over a relatively long period of time and each plant and plant species will succumb in its own way and in its own time – the impact is clearly cumulative. However, extreme heat events are much more short-term in their impact. Trees are mostly well adapted to survive short-term heat events, but heat stress and drought stress are often linked and each can amplify the impact of the other.

It has often been observed that days of extreme heat can quickly lead to direct leaf damage, with large areas of leaves browning off and dying within a single day. Experimental evidence on barley shows that this process can begin with a leaf temperature as low as 40°C (Lípová *et al.* 2010). Extreme heat can impact a wide variety of tree functions, most obviously at the leaf level, where photosynthesis is reduced, photo-oxidative stress increases leading to leaf tissue necrosis, leaves abscise and the growth rate of remaining leaves decreases (Teskey *et al.* 2015). If a plant is already suffering from drought stress it is inevitable that days of extreme heat will exacerbate the situation, especially given that the residual loss of water through pathways other than the stomatal pores is uncontrolled and is strongly impacted by high temperatures.

While plant responses to drought and heat stress have been extensively studied, post-stress recovery has received much less attention. Ruehr *et al.* (2019) found that the pace of recovery differs among physiological processes. For example, leaf water potential typically recovers within a few days upon rewetting, while leaf gas exchange-related variables lag behind. Brodribb & Cochard (2009) concluded that recovery of gas exchange was fast following mild stress, while recovery was slow and reliant on the efficiency of repair and regrowth when stress resulted in functional impairment and damage to critical plant processes.

How can urban vegetation reduce the impacts of extreme weather?

One of the most compelling reasons for an increase in urban vegetation is that it has the capacity to lower the impact of extreme heat events and thus provide a safer and healthier environment for the people who live there. We know that plants in drought-prone ecosystems can vary from anisohydric (plants that keep their stomata open and photosynthetic rates high for long periods during drought) to isohydric (plants that reduce stomatal conductance as necessary to limit transpiration during drought) (Sade *et al.* 2012). From the perspective of having an impact on the local microclimate, anisohydric plants should be a better option, since they continue to transpire longer than isohydric plants, thus leading to more local evaporative cooling. However, there is an obvious inherent risk in this, especially if a drought is long-term.

An excellent example of this risk was provided by Sinclair (1980), who demonstrated that following the unusually dry summer of 1977-8 in the Mt Lofty Ranges surrounding Adelaide, the anisohydric *Eucalyptus obliqua* was dying out in areas away from water sources, while the isohydric *E. fasciculosa* remained undamaged by the drought. In normal circumstances anisohydric species can be relatively drought tolerant, but clearly they may be a poor choice for urban plantings in the face of increasing drought conditions. Conversely, isohydric species will be more prone to carbon starvation during prolonged periods of stomatal closure during droughts but are more likely to survive prolonged droughts. However, such species will not be as effective in providing transpirational cooling. The selection of appropriate tree species for urban planting will involve important trade-offs between the capacity of the species to ameliorate local microclimates and the resilience of the species to adverse drought and heat conditions. Thom et al. (2022) considered the response to and recovery from drought conditions in street tree species commonly grown in Melbourne. They reported that *Tristaniopsis laurina* combined the desirable traits of high transpiration during periods of abundant water, high tolerance of drought conditions, and good recovery following periods of water stress. Species which performed moderately to highly across these three characteristics included *Lophostemon confertus*, *Prunus cerasifera*, *Lagerstroemia indica*, *Pyrus calleryana*, and *Quercus palustris.* Studies of this kind are essential to guide future species selection for urban tree plantings.

There is strong evidence that days of extreme heat can impact a wide diversity of Australian native plants in their natural environment. For example, two successive days of extreme maximum temperatures (>45°C) and hot winds in southwestern Australia in 1991 resulted in plant mortality and extensive crown damage in a sclerophyllous mallee heathland (Groom *et al.* 2004). The research suggested that relatively undamaged species had thicker leaves and were more exposed to wind, sun and bare soil (i.e. the plants were relatively acclimatised to the extreme conditions). Clearly the selection of appropriate tree species for planting in warm, dry cities like Adelaide, with a view to them surviving and thriving into the long-term future, is not going to be a simple process of looking for species that currently occur in dry environments.

To support urban heat island mitigation the species selected for planting need to sustain photosynthesis and therefore transpiration. To obtain the water they need, trees need access to adequate soil volume in sites accessible to water recharge from rainfall (Leake and Haege 2014), and it is important that water is not lost in drainage discharges rather than making it available to urban trees and vegetation generally. Alternative water sensitive urban design (WSUD) and engineering options exist, and Gleeson *et al.* (2022) showed that *Melia azedarach* trees with TREENET Inlets in their root zones had 21% higher transpiration per unit canopy area. However, stormwater harvesting for tree irrigation is rarely optimised in contemporary urban developments.

The effects of transpirational cooling are localised, so the urban tree canopy must be extensive and dispersed throughout communities. Trees in streets and roads that interconnect across towns and cities are obvious contributors to this essential green network, along with trees on parks and private property. The need for accessible and interconnected greenways for recreation and exercise has been highlighted during the Covid-19 pandemic, and the opportunities to integrate improved open space planning with more effective urban greening and stormwater management are obvious. Trees are clearly a major part of the solution to climate adaptation, particularly in arid and semi-arid regions, but their contribution depends on urban design and engineering providing them the space and other resources they need to thrive.

How should we select future urban vegetation?

There are many challenges in planning for future urban vegetation:

1. Climate change is a reality as are the extreme weather events that accompany it. I have focused here on drought and heat, but other challenges are also present and these too will increase in likelihood and severity.
2. We must be clear about our expectations of urban vegetation. Much of what we would like to achieve will run counter to the ability of the nominated species to survive – there is a classic trade-off to be managed here – human well-being in the short term against the long-term. Trees that may best address the issues facing us for the next 20 years may be inappropriate beyond that if the climate deteriorates even further.
3. We cannot simply select species that look about right and currently survive in what we regard as hostile conditions. It is imperative that a major research program is established to examine the way in which each target tree species behaves when exposed to stress, including the way in which it recovers from damaging events. For example, Ruehr *et al.* (2019) highlight three promising research directions: (i) the relationship of individual stress impacts and recovery rates, (ii) the carbon cost of stress and recovery, and (iii) the impact of post-event conditions on recovery dynamics. There is remarkably little information available on these at present. It will be important to instigate ongoing monitoring experiments that record tree health in target species. It is important that we understand the stresses a tree is suffering while it is alive, rather than wait until it is dead and try to reconstruct its history.
4. Most critically, we must decide what we believe the values of our cities will be and how we will integrate cities into the whole environment. At present, excellent work is being undertaken in rural Australia, demonstrating how farming systems can improve dramatically (including yield), by properly assisting the native vegetation to thrive (e.g. Massey 2017). This could be our best contribution as a nation to the global climate crisis. However, there has been little attempt to integrate the work being done on rural landscapes with the need for improved urban vegetation. We will obtain the best outcome if we consider our country as a highly variable whole and not regard towns and cities as something separate. If we do not adopt a holistic response to climate change, leading with the re-establishment of complex vegetation (not necessarily native), then we will have a much poorer outcome.

Conclusion

Climate change is an unprecedented global challenge. There have been many examples of human civilisations rising and falling on a local scale through historical time, with the fall often being associated with a localised environmental crisis (Diamond 2005). Now, for the first time, we face a global crisis that threatens all human societies. While we can and must work at global solutions to reduce and eventually reverse the growth in greenhouse gases, we also face an immediate challenge to mitigate the problem within our towns and cities, and urban vegetation must be a major contributor to this. Human health and well-being currently loom as the major challenge for governments everywhere and climate change will continue to exacerbate this. Even if we only take the inward-looking view of climate change as an issue impacting human health, we still face enormous hurdles. Urban vegetation is an effective tool in combatting this and small changes could transport cities like Adelaide from a current relatively green and healthy state to desert cities, where lifestyle will be severely compromised. Similarly, relatively small changes can bring such cities back from the brink and secure their future into the long-term. The choice is stark.

We urgently require detailed research on appropriate tree species for immediate mass planting. We need to investigate where and how to return large patches of vegetation (not just trees) to cities, and we need to understand how this ties in with the best work being done in rural Australia to work with the natural environment, not against it. If we succeed, we will not only mitigate against the more severe impacts of climate change, but we will provide an environment for future generations that will be part of the solution to the greatest problem humanity has faced.

References

Brodribb, T. & Cochard, H. 2009. Hydraulic failure defines the recovery and point of death in water-stressed conifers. *Plant Physiology* 149, 575-584.

Diamond, J. 2005. Collapse. Allen Lane, Camberwell. 575p.

Gleeson, X., Johnson, T., Lee, G., Zhou, Y. and Guan, H., 2022. Enhanced Passive Stormwater Infiltration Improves Urban Melia Azedarach Functioning in Dry Season. *Frontiers in Climate*, p.45. https://www.frontiersin.org/articles/10.3389/fclim.2022.783905/full?fbclid=IwAR0a4WizrBNATqJYO-JxrjrSsvFBlN_lUgmf1VIg3xlqhrEwn6gfqBUS1Nk

Groom, P.K., Lamont, B.B., Leighton, S., Leighton, P. & Burrows, C. 2004. Heat damage in sclerophylls is influenced by their leaf properties and plant environment. *Ecoscience* 11, 94-101.

Leake, S. and Haege, E., 2014. *Soils for landscape development: selection, specification and validation*. CSIRO Publishing, Collingwood, Victoria, Australia.

Lípová, L., Krchnák, P, Komenda, J. & Ilík, P. 2010. Heat-induced disassembly and degradation of chlorophyll-containing protein complexes in vivo. *Biochimica et Biophysica Acta* 1797, 63-70.

Massey, C. 2017. Call of the Reed Warbler. University of Queensland Press, St Lucia. 569p.

McDowell, N., Pockman, W.T., Allen, C.D., Breshears, D.D., Cobb, N., Kolb, T., Plaut, J., Sperry, J., West, A., Williams, D.G. & Yepez, E.A. 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New Phytologist* 178, 719-739.

Ruehr, N.K., Grote, R., Mayr, S. & Arneth, A. 2019. Beyond the extreme: recovery of carbon and water relations in woody plants following heat and drought stress. *Tree Physiology* 39, 1285-1299.

Sade, N., Gebremedhin, A. & Moshelion, M. 2012. Risk-taking plants. *Plant Signaling & Behavior* 7, 767-770.

Sinclair, R. 1980. Water potential and stomatal conductance of three *Eucalyptus* species in the Mount Lofty Ranges, South Australia: Responses to summer drought. *Australian Journal of Botany* 28, 499-510.

Teskey, R., Wertin, T., Bauweraerts, I., Ameye, M., McGuire, M.A. & Steppe, K. 2015. Responses of tree species to heat waves and extreme heat events. *Plant, Cell & Environment* 38, 1699-1712.

Thom, JK, Livesley, SJ, Fletcher, TD, Farrell, C, Arndt, SK, Konarska, J & Szota, C 2022, 'Selecting tree species with high transpiration and drought avoidance to optimise runoff reduction in passive irrigation systems', *The Science of the Total Environment*, vol. 812, pp. 151466–151466.