

Increasingly allergenic airborne pollen revealed in sediment of Lake Burley Griffin, Canberra

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Abstract

The incidence of allergy-related respiratory ailments in Australia is ranked amongst some of the highest in the world. Of interest is how European settlement and the introduction of numerous wind pollinated species from the Northern Hemisphere may have increased the impact on public health. Although anecdotally known as the hay fever capital of Australia, there is very little aerobiological data published for the city of Canberra [Davies, J. M. et al. (2015) 'Trans-disciplinary Research in Synthesis of Grass Pollen Aerobiology and Its Importance for Respiratory Health in Australasia', *Science of the Total Environment*, 534: 85–96]. Canberra, however, is a planned city, with the bulk of its expansion and construction occurring since the latter part of the 20th century. The well-documented development of Canberra provides a unique opportunity to assess the evolution of the allergenic environment in this region through the lens of palaeoenvironmental reconstruction. Sediments collected from Lake Burley Griffin were processed for their pollen content to assess how the allergenic load has changed since the founding of Canberra. The analysis reflected historical records of changing land uses and revealed an increasingly allergenic airborne pollen load over the past 90 years, coinciding with population increase and urban development, and underpinned by Canberra's tree planting scheme. In addition, fire was examined in the record, with the charcoal fractions revealing a complex fire history. Peaks that correspond to the 2003 Canberra bushfire are small relative to other peaks in the profile.

Key words: pollen, asthma, allergy

Introduction

A world-wide increase in respiratory allergies has been noted in the past 50 years particularly in urbanised areas (Ziello et al. 2012). Previous studies indicate that Australians experience one of the highest incidences of allergic rhinitis and allergic asthma in the world (Beggs et al. 2015). Exposure to airborne pollen is a recognised trigger for allergic rhinitis and allergic asthma, chronic ailments that negatively impact the Australian economy and account for a significant portion of the Australian public health budget (Cook et al. 2007).

The Australian Society of Clinical Immunology and Allergy (ASCLIA) suggests that most of the allergy causing pollen in Australia is produced by wind pollinated species introduced from the Northern Hemisphere. This contrasts with most Australian native species that are pollinated by insects, birds and other animals. As a designed cityscape, Canberra is a well-documented example of vegetative transformation during urbanisation, incorporating the introduction of exotic wind pollinated trees, shrubs and grasses (Pryor and Banks 2001; Ward 2005; Godden Mackay Logan Pty. Ltd. 2009; Coltheart 2011; Ryan 2011; Ling 2013).

In many parts of the world, air sampling is routinely carried out to monitor the incidence of airborne allergenic pollen, enabling public health institutions to better manage allergy-related conditions. It also provides sufferers of allergic rhinitis and asthma with the necessary information for self-management of these chronic conditions.

Long-term records of aerobiological sampling increase our understanding of the link between landscape change and health impacts. For example, decades of aerobiological pollen data have shown shifts in the incidence and types of allergenic pollen due to changing land use and climatological conditions in Switzerland (Frei and Leuschner 2000) and across Europe (Ziello et al. 2012). In Australia, Beggs et al. (2015) highlight the inadequacy of aerobiological pollen information and the need for more comprehensive monitoring. Although Canberra is anecdotally known as the hay fever capital of Australia, aerobiological data published for the city are limited (Haberle et al. 2014; Davies et al. 2015). In a response to this, the Canberra Pollen Count and Forecast site was recently established at the Australian National University with daily and weekly risk level forecasts during October to March published on line (AusPollen 2016).

Natural archives such as lake sediments have been used to explore complex environmental interactions through time increasing our understanding of biological and climatological relationships (Seppa 2007; Birks 2008). Fine resolution pollen analysis in particular may be used to assess the vegetation surrounding lakes in terms of changing land use (Green and Dolman 1988; Kelso and Beaudry 1990; Tinner et al. 2003).

Therefore, in the absence of comprehensive long-term aerobiological information for Canberra, a multiproxy analysis of a sediment core from Lake Burley Griffin was undertaken to investigate how the changing vegetation of this urban landscape may have impacted public health. We also construct and present an historical record of fire for the region, with changes in water quality and the transmission of contaminants in the landscape investigated in a forthcoming paper.

Climate

The Canberra climate is seasonal with hot summers and cool winters. January is the hottest summer month with a mean maximum daily temperature of 27.7°C and a mean minimum temperature of 13°C. July is the coldest winter month with a mean maximum temperature of 11.2°C and mean minimum of 0.2°C. Temperature extremes range between 42 and -10°C. The summer winds tend from the east to northwest and in winter from the west with an average of 25 strong wind days of between 40 and 50 km/h per year. The 90-year annual average rainfall is 629 mm with extremes between 261 and 1102 mm. Thunderstorms tend to proliferate during the summer months October to March. Periods of wet and dry are influenced by ENSO with droughts and major bushfires occurring during strong El Niño years and high rainfall and flood events during strong La Niña years (Australian Bureau of Meteorology 2015).

History of land use and vegetation change

The Canberra region was settled by Europeans in 1824. The pre-European vegetation has been described as eucalypt dry open forest on the hills and upper slopes, grassy woodlands on the lower slopes and river flats, and riparian forest (*Casuarina* and *Eucalyptus*) along the waterways (Godden Mackay Logan Pty. Ltd. 2009). Robert Hoddle's 1832 survey map of the Limestone Plains, County of Murray, New South Wales (MAP G8981) refers

to 'open plains' with discrete areas of 'open forest' and 'rocky outcrops'. A historical photograph taken in the 1910s show this general description could still be applied to the landscape in the early part of the 19th century (Fig. 1a). The Molonglo River formed the northern and southern boundaries of a series of seven properties. These properties were established primarily for livestock grazing. Historical photographs show that Black Mountain was cleared of forest vegetation by the mid-1800s (Ryan 2011). Black Mountain is now on the edge of Lake Burley Griffin and is covered by native open forest regrowth. Figure 1b–e demonstrates the progression of vegetation change to Black Mountain and surrounds from the 1920s to 1964. The current remnant native vegetation on Black Mountain and other elevated areas while modified give an indication of the dominant naturally occurring species. These include the red stringybark (*Eucalyptus macroryncha* F. Muell. ex Benth.), scribbly gum (*Eucalyptus rossii* R.T. Baker & H. G. Sm), brittle gum (*Eucalyptus mannifera* Mudie), yellow box (*Eucalyptus melliodora* A. Cunn. ex Schauer), Blakeley's red gum (*Eucalyptus blakeleyi* Maiden), red box (*Eucalyptus polyanthemus* Schauer) and apple box (*Eucalyptus bridgesiana* R.T. Baker). The dominant understorey is tussock grass (*Poa* spp.) (Godden Mackay Logan Pty. Ltd. 2009).

Urbanisation of Canberra

The Australian Capital Territory was created in 1911 and the city of Canberra was founded in 1913 (Ling 2013). The 1828 census recorded a population of 36 European settlers for the region. The Indigenous population was estimated by a local settler to be between 400 and 500 persons (Canberra District and Historical Society n.d.). A century later census records show the population had risen to 2572 and the location was recorded as rural (Commonwealth Statistician 1921). Aboriginals who were associated with European settlement were included in this record but those who continued a traditional lifeway were not. The populations recorded for the 1933, 1947, 1966 and 2011 censuses were 8766, 16905, 93311 and 356586, respectively (Commonwealth Statistician 1933 [1947]; 1966; Australian Bureau of Statistics 2011).

Lake Burley Griffin and the development of Canberra city was based on a design created by landscape architects Walter Burley Griffin and Marion Mahoney Griffin. The original design was sympathetic to the natural landscape and incorporated northern hemisphere species together with Australian native species on suburban streets and public parklands (Pryor and Banks 2001). This included a 120000 strong stand of American red woods (*Sequoia sempervirens* and *Sequoiadendron giganteum*) planted at Pialligo in 1918 by Charles Weston (head of Yarralumla Nursery) at the insistence of Walter Burley Griffin. Many died within the first year with only 400 surviving into the 1980s (Coltheart 2011). The central suburbs which now surround Lake Burley Griffin were established between 1920 and 1930. Urban development in Canberra was slow in the first half of the 20th century being negatively impacted by both world wars and the economic depression of the 1930s (Dawson 1990).

Methods

Lake Burley Griffin catchment

The catchment area spans 1865 km² (Caitcheon et al. 1988) and the lake is fed by two major tributaries; the Queanbeyan and Molonglo Rivers that comprise 37% of the Lake Burley Griffin catchment (Fig. 2). Two-thirds of the Molonglo River catchment is cleared grazing farmland consisting of native and improved

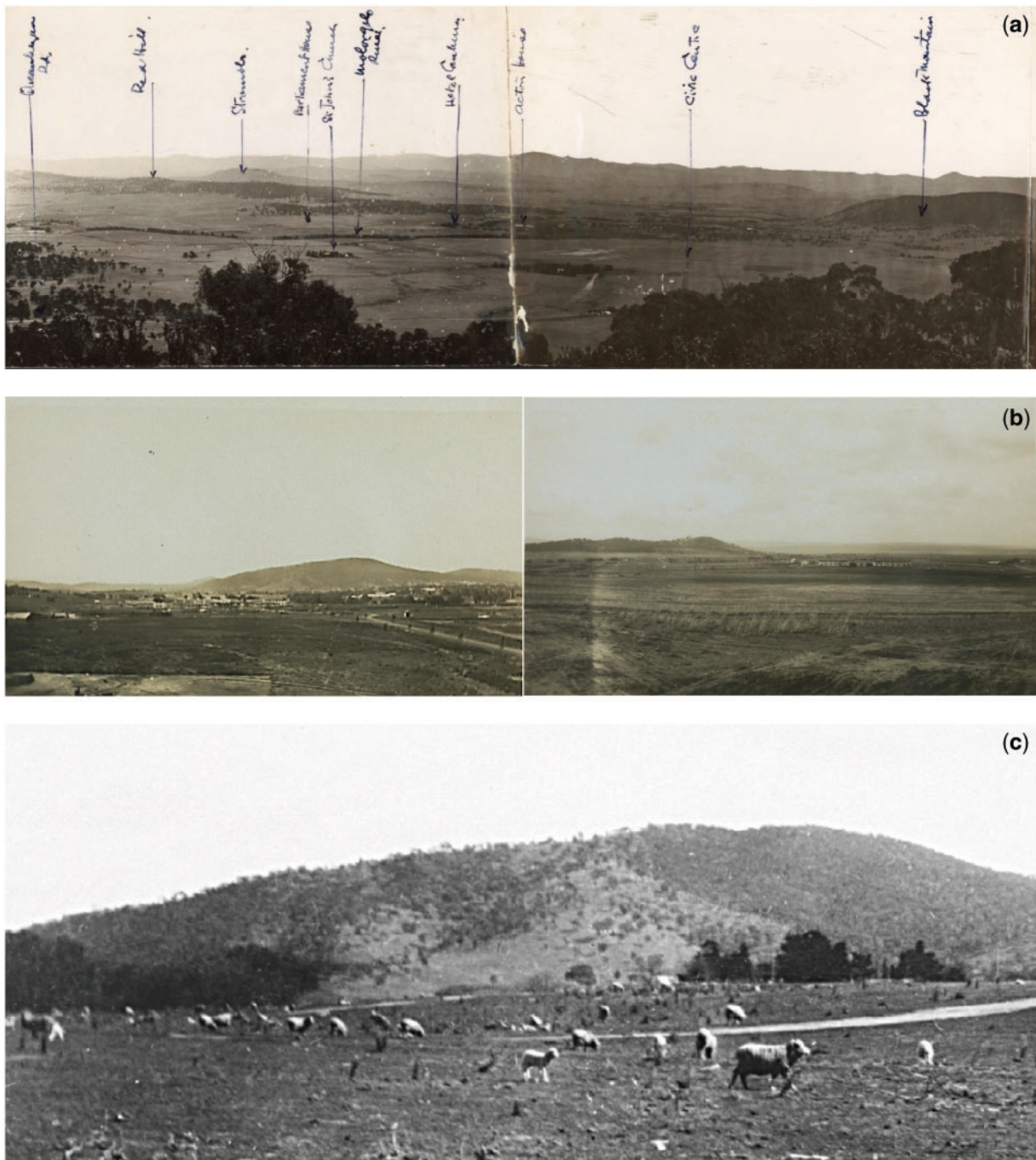


Figure 1: Historical photographs of the Canberra landscape. (a) Panoramic view of the site for Canberra in the 1910s taken from Mt. Ainslie. Courtesy National Library of Australia PIC/7358/24 LOC Album 1010 Photograph by Frank H. Boland. Retrieved April 22, 2018, from <http://nla.gov.au/nla.obj-146771261>. (b) (Left) Federal Capital site looking towards Black Mountain, Canberra, probably 1927, 1. Courtesy National Library of Australia PIC Album 1192 #PIC/15762/51. Retrieved April 23, 2018, from <http://nla.gov.au/nla.obj-153297455>. (Right) Federal Capital site looking towards Black Mountain, Canberra, probably 1927, 2. Courtesy National Library of Australia PIC Album 1192 #PIC/15762/5. Retrieved April 23, 2018, from <http://nla.gov.au/nla.obj-153297751>. (c) Black Mountain, Canberra in the 1920s with sheep grazing in the foreground. Courtesy National Library of Australia PIC/11208. Retrieved February 24, 2018 <http://nla.gov.au/nla.obj-137277837>

pastures. Early farming practices resulted in sheet erosion that has been dramatically reduced since 1964 with changing land management practices aimed at reducing the movement of sediment into the lake (Wallbrink and Fogarty 1998). The Queanbeyan River Catchment is 960 km² while the Molonglo River catchment is 780 km². Minor catchments include Jerrabomberra creek and Sullivan's creek. The Jerrabomberra

catchment is 128 km² and enters Lake Burley Griffin through the Jerrabomberra wetlands at the eastern end of the lake (Maunsell Australia, Pty Ltd. 2005). The Sullivan's creek catchment is 53 km² and feeds into the lake via West Lake (Dyer 2000).

The Lake Burley Griffin catchment is divided into urban, light industrial, rural, peri-rural, native and planted forest landscapes. In 1980, the catchment was approximately 3% urban,



Figure 1: (d) Black Mountain, Canberra in 1941 with sheep grazing in the foreground. Courtesy National Library of Australia Photograph by E. W. Searle. Retrieved April 22, 2018, from <http://nla.gov.au/nla.obj-141903690>. (e) Black Mountain, Canberra in 1964 with Lake Burley Griffin and Springbank Island in the foreground. Courtesy National Library of Australia, PIC P2214/339 Photograph by Richard Clough. Retrieved April 22, 2018, from <http://nla.gov.au/nla.obj-143767117>

66% agricultural and 31% native forest (Rosich and Cullen 1980). By 2012 the urban area of the Lake Burley Griffin catchment had almost doubled, to approximately 5.7%, with 63.5% defined as rural or agricultural, and 30.4% forestry and conservation (Neil 2012). Between 80 and 85% of the Lower Queanbeyan, Sullivan’s Creek and Lake Burley Griffin sub-catchment areas are heavily urbanised environments (Molonglo Catchment Group 2005).

Location

Lake Burley Griffin is an artificial lake situated in Canberra, the Australian capital. This urban lake was created with the construction of Scrivener dam across the Molonglo River in 1963 and the subsequent flooding of the Molonglo river flood plain in 1964 (Ling 2013). It flows in an east to west direction dividing Canberra into northern and southern regions. It is an

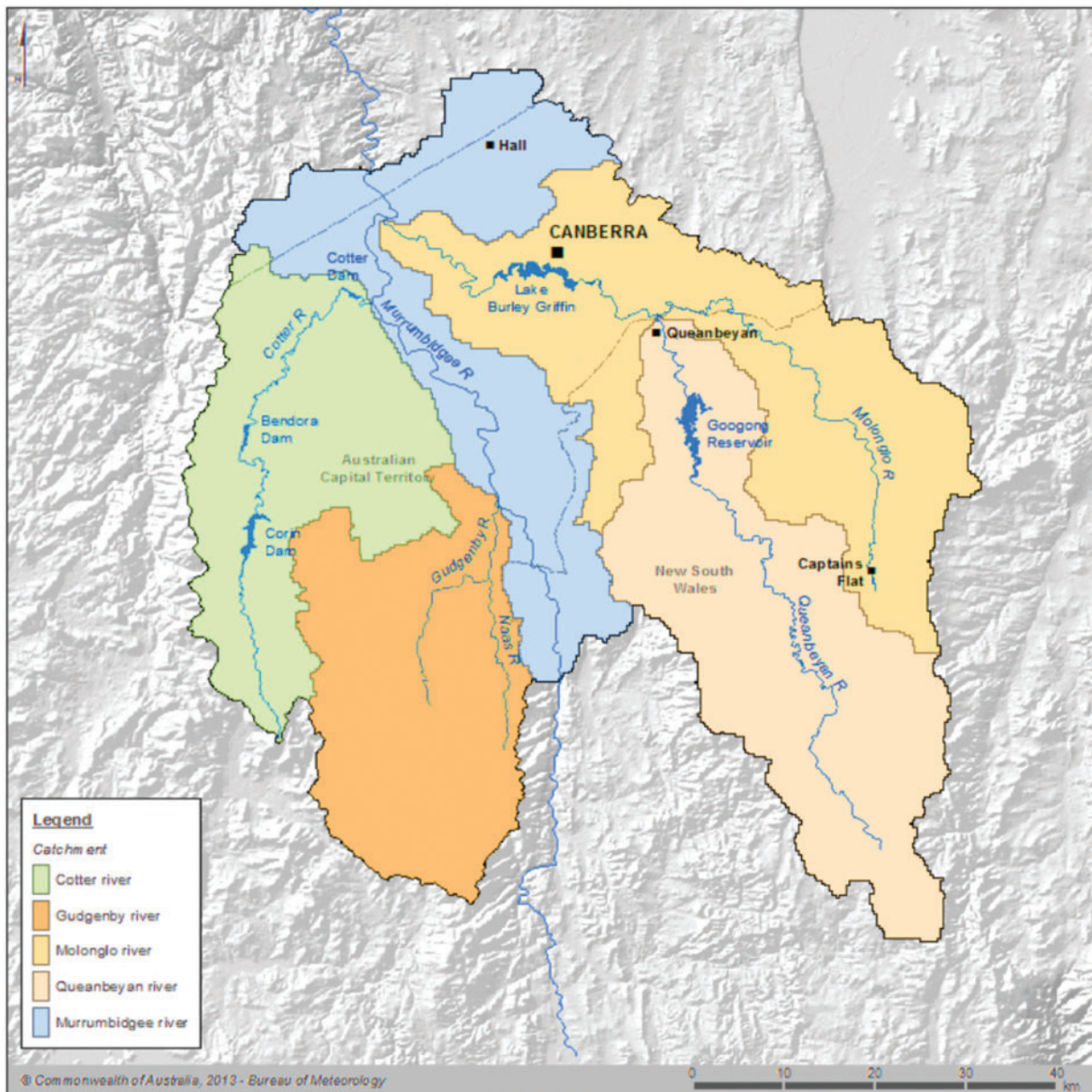


Figure 2: Map of the major river catchments surrounding Canberra including major tributaries of Lake Burley Griffin the Molonglo River and Queanbeyan River. <http://www.bom.gov.au/water/nwa/2013/canberra/contextual/physicalinformation.shtml>, accessed 10 October 2018

integral part of the region's water filtration system as well as a place of high aesthetic value. Managing the health of the lake ecosystem presents an ongoing challenge (Lawrence 2012).

The lake is characterised as shallow and turbid, being subject to mixing by wind. The aesthetic value of the lake is negatively impacted by this turbidity, which also creates variable deposition of the sediment. This has been noted as a confounding factor in previous sediment analyses (Caitcheon et al. 1988; Maher 1992; Lawrence 2012). However, the lake sediment does not behave as a single entity as the effect of wind decreases with increasing depth. West Lake is therefore notably less affected than the shallower eastern sections of the water body (Shepard 1965).

Sediment core collection

In 2011, a 25.5 cm core was collected using a single drive universal corer in a polycarbonate tube west of Acton peninsular in West Lake in 9 m of water at GPS coordinates 35°17'34.24"S 149°07'10.02"E. The position of LBG WL 2011 relative to the position of the old Molonglo River channel is shown in Fig. 3.

Age determination

Lead 210 dating (^{210}Pb) was used to establish a chronology for the sediment core. The upper 20 cm of LBG WL 2011 was sampled every 2 cm, dried overnight at 75°C, finely ground, and analysed for supported and unsupported ^{210}Pb by ANSTO (Australian Nuclear Science and Technology Organisation,

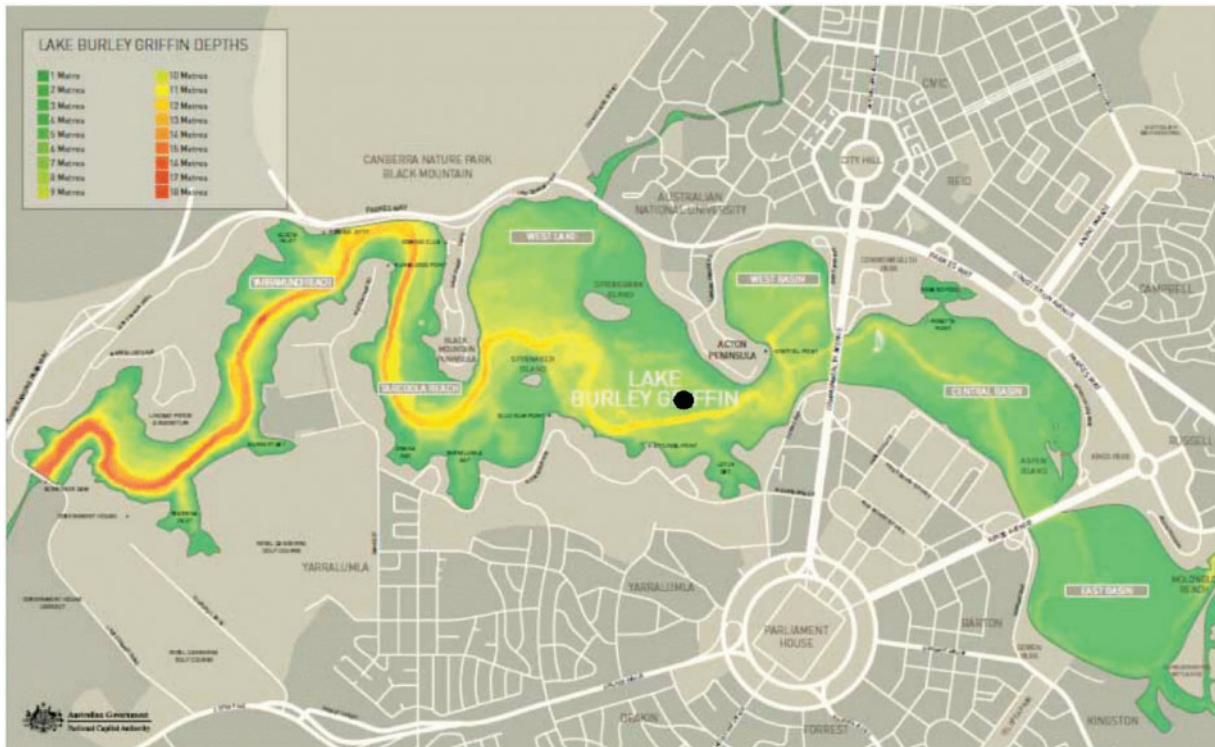


Figure 3: Bathymetric map of Lake Burley Griffin, Australian Capital Territory, Australia showing the position of the Molonglo River and estimated position of LBG WL 2011 sediment core. <https://www.nationalcapital.gov.au>, accessed June 7, 2015

Sydney, Australia). Sediment ages were calculated as years before 2011 between 0 and 15 cm using the Constant Initial Concentration (CIC) and Constant Rate of Supply models (Appleby and Oldfield 1983). Below 15 cm the unsupported ^{210}Pb activities were not included in the calculations, as the activities do not exhibit a monotonic relationship with increasing depth (Fig. 4).

Pollen analysis

Subsamples for pollen analysis were taken at 0.5 cm intervals and processed using standard techniques (Supplementary material 1). Pollen identification was aided by the Australasian Pollen and Spore Atlas (apsa.anu.edu.au) as well as the creation of a targeted reference collection (Supplementary material 2, Table 1).

Pollen types were assigned to vegetation categories, native trees and shrubs, exotic planted street trees, aquatic plants, herbaceous species, grasses (Poaceae) and *Pinus* species grouped into Pinaceae. This sedimentological study did not differentiate between native and introduced grasses as they cannot reliably be differentiated through light microscopy. Pollen types were also split according to mode of pollination and their relative allergenicity. This information was obtained from published sources including websites www.pollenlibrary.com, <http://www.asthmawa.org.au> and www.allergy.org.au. The species included in these broad vegetative groupings are provided in Supplementary material 3, Tables 1 and 2.

Micro- and macro-charcoal

Sedimentary charcoal can be used to reconstruct past fire activity where the small- or micro-charcoal fraction (less than $125\ \mu\text{m}$ is found on pollen slides) reflects regional fires and the

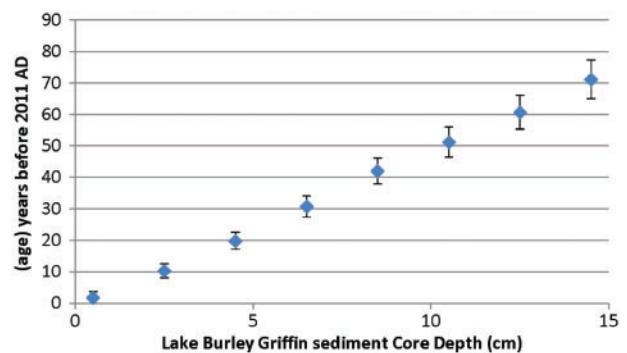


Figure 4: CIC age depth model for LBGWL 2011 based on ^{210}Pb dating

larger or macro-charcoal fraction ($>125\ \mu\text{m}$ is sieved from the sediment) reflects fire at a local scale. Both charcoal fractions are primarily deposited through air fall, with smaller particles travelling greater distances than larger particles (i.e. $<125\ \mu\text{m}$ fraction may be deposited several kilometres from the source of the fire while the $>125\ \mu\text{m}$ fraction is deposited closer) (see Whitlock and Larsen (2001) and Conedera et al. (2009) for reviews).

Micro-charcoal was counted along the same transects as the pollen, while the macro-charcoal samples were prepared and counted according to Stevenson and Haberle (2005). Accumulation rates for the micro-charcoal were calculated by the above method substituting pollen counts with micro-charcoal counts. The accumulation rates for the macro-charcoal were calculated by determining the total number of charcoal particles in a fixed volume and then multiplying by the sediment accumulation rate ($\text{particles}/\text{cm}^2/\text{year}$).

Results

Chronology

The measurements have an associated error margin ranging between 2 and 6 years which increase with depth (Fig. 4). The unsupported ^{210}Pb shows a linear decrease to 15 cm which corresponds to 71 ± 6 years and gives a sedimentation rate of 0.2 cm/year. The error margins are implicit wherever a date is used in discussing the results. The ^{210}Pb dating chronology reveals that the upper 10 cm encapsulates the lake, while the lower 15 cm are sediments from the pre-lake floodplain. As a consequence, the upper 10 cm have been sampled at a higher resolution (every 0.5 cm) while the lower half of the core was sampled every 2 cm.

Sediment profile

Particle size analysis reveals that the sediment composition in the pre-lake period is dominated by silts and remains relatively constant, with a peak in deposition around the late 1930s to early 1940s. This peak coincides with two major floods in the Molonglo River (Fig. 5). More variability in particle size is evident in the upper 10 cm, partly due to the higher resolution sampling. Of note in the upper 10 cm is the gradual decrease in the silt sized particles and consequent increase in larger sand particles, no doubt as a result of decreased energy within the system with lake formation.

Organic matter ranged between 0.18 and 11.68% with an overall average of 5.67% in the lake sediment and 5.73% in the pre-lake sediment. The highest peak of organic matter at the top of the profile may be due to high rainfall and urban runoff through storm water drains during a 1 in 20-year flood that broke the drought in 2010. A similarly high peak of organic matter in the pre-lake sediment coincides with the wettest year on record in 1950. Although the mechanism that would result in this is uncertain, it may be due in part to detrital in-washing from the surrounding landscape and increased productivity of river flood plain species. Indicators of internal productivity were not examined. Such investigations may be difficult as it is known that diatoms are not preserved in Lake Burley Griffin.

Pollen

As noted above, the lake sediment has finer sampling resolution than the pre-lake sediment. The upper 10.5 cm of LBG WL 2011 was analysed at 0.5 cm intervals and the lower pre-lake sediment portion was analysed at 2 cm intervals.

Pollen analysis of the sediment core reveals that at least 32 families and 41 genera are represented (Supplementary data 4, Table 1 for detailed counts). The level of unidentified pollen types did not significantly alter the reconstruction of the vegetation with fewer than 10 unknown pollen types at very low frequencies across the entire core profile (data not shown).

There are significantly lower pollen counts from the pre-lake sediment. This is to be expected in a floodplain setting where flowing water would both inhibit and mix the deposition of pollen. The lower pollen counts may reflect poorer preservation conditions in a more variable environment with periods of wet and dry coincident with the natural ebb and flow of the river. There is a decline in the diversity of pollen categories represented with increasing depth with between 30 and 38 pollen categories represented in the uppermost 7 cm and between 20 and 27 in the lowest 7 cm (Supplementary data 4, Table 1).

All but trace amounts of exotic tree species are absent from low-est 7 cm of the pre-lake sediment, with *Prunus* (possibly flowering cherry, pear or other fruit trees) and Salicaceae (poplar and willow) the predominant types at the base of the core.

The presence of *Sequoia* (American red woods) pollen types at the base of LBG WL 2011 (Fig. 6) suggests that the recovered sediments are unlikely to predate 1928. *Sequoia sempervirens* and *S. giganteum* do not produce substantial amounts of pollen before 10 years of age which provides a relative means of dating the base of LBG WL 2011. This relative dating suggests a higher sedimentation rate of 0.8125 cm/year on the flood plain in the pre-lake period during a time of early European land use compared to a rate of 0.2 cm/year after the creation of the lake. This finding is consistent with early agricultural practices which caused sheet erosion in the landscape. Management practices were changed to mitigate this after the construction of the lake.

The total pollen accumulation rate (Fig. 6) is relatively stable in the pre-lake sediment, which in part may reflect the averaging effect of the flowing river, coarser sampling and CIC age model. Percentage data reduce the confounding effects of differential pollen deposition and preservation conditions and reveal that native trees and shrubs, herbaceous species, grasses and aquatic species are a greater proportion of the pollen in the pre-lake sediment. The native and exotic street tree pollen peaks coincide with peaks in rainfall. The Poaceae pollen appears to peak in drier periods when native tree and shrub pollen are decreased. There is also a broad Pinaceae pollen peak centred on the 1940s. The exotic street tree pollen is present at relatively low levels at the base of the core at around 11.5% which increases from the 1940s reaching 31.6% by the late 1950s. The opposite is evident in the pollen of native trees and shrubs which is 25.4% at the base of the core and declines from the late 1950s to 14.1% by the time Lake Burley Griffin is built. This coincides with increasing population in Canberra and the expansion of exotic street tree plantings over time.

The pollen accumulation rate becomes more nuanced in the upper part of the record partly as a result of continuous high-resolution sampling. Peaks and troughs in this part of the pollen record reflect the increased atmospheric pollen load from increased planting around the region with a major peak in the early to mid-1970s, coincident with above average rainfall centred around 1974. A series of troughs coincide with low rainfall years. Two significant troughs centred around 1980 and 2003 coincide with extended periods of drought. The uppermost of these also follows the extreme bushfire event of 2003 (Fig. 6).

Trends in the percentage data show that while peaks of Poaceae pollen tend to coincide with drier periods, the extended drought between 1997 and 2009 shows a more complex pattern. The Poaceae pollen is depressed in the early phase of this drought and peaks following the 2003 bushfire. The fluctuations of Pinaceae pollen follow a similar pattern also reaching its maximum peak following the 2003 bushfire. There is a significant drop in native trees and shrubs and herbaceous species pollen types across the period coincident with the 2003 bushfire. The exotic street tree pollen peaks around 2000 then declines during the height of the 1997–2009 Millennium drought. This sustained drop does not rise again until after the drought is broken in 2010.

Incidence of allergenic pollen

The percentage data in Fig. 6 show that windborne pollen increases from 64.2% at the base to 78.6% at the top of the



Figure 5: Diagram of LBG WL 2011 sediment core with micro- and macro-charcoal accumulation rates plotted against CICV age depth model, the filling of Lake Burley Griffin and the 2003 Canberra Bushfire

sediment core. The relative proportions of moderate and severely allergenic pollen have fluctuated from year to year in the lake sediment as may be expected with inter annual variation in climatic conditions. However, there has been an overall increase of allergenic pollen from 76% to 95% of the total pollen deposited in the pre-lake and lake sediments from the base to the top of the sediment core. The highest peak of severely allergenic pollen is centred around 2005 which coincides with the highest peaks of windborne pollen.

Charcoal as a proxy for fire

Similar to the pollen profile, the pre-lake micro-charcoal profile remains relatively constant, while the pre-lake macro-charcoal profile is higher at the base of the core decreasing from the 1930s. In contrast the sediment from the lake period shows a series of peaks including micro- and macro-charcoal peaks that may coincide with local and regional fire histories. The largest micro- and macro-charcoal peaks in the lake sediment tend to obscure other peaks of fire activity, and so have been truncated

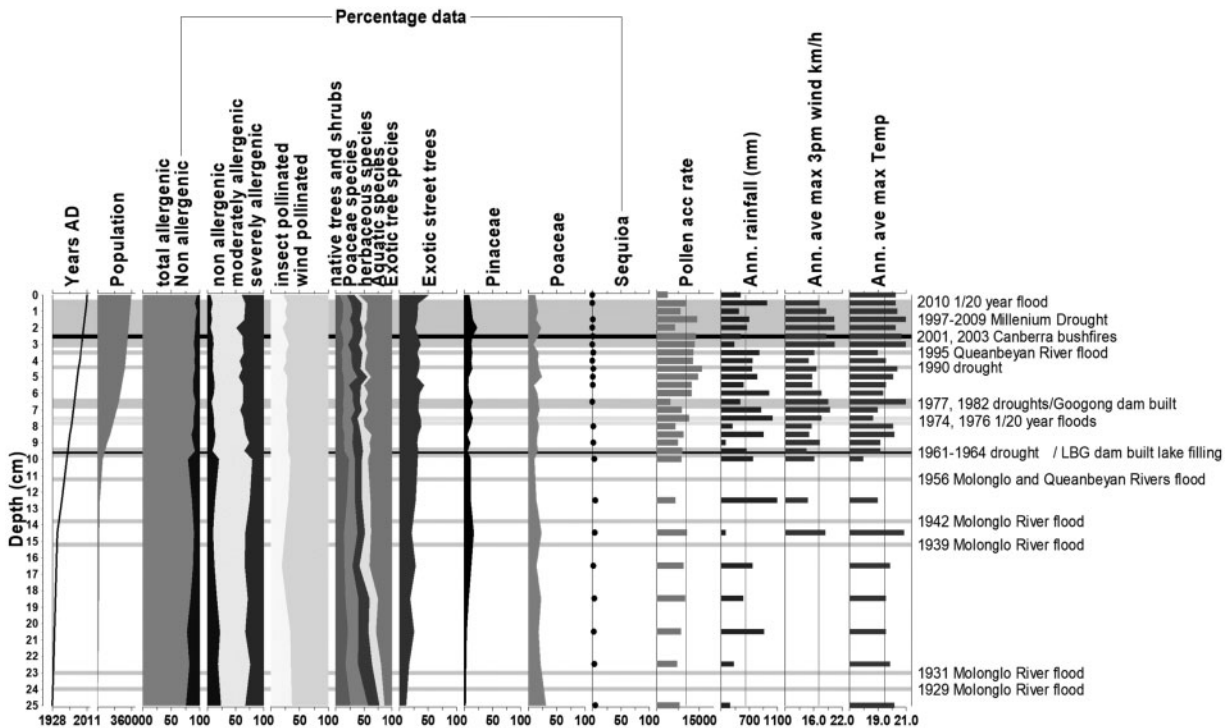


Figure 6: Diagram of LBG WL 2011 sediment core showing the population growth of Canberra, relative proportions of severe, moderate, non-allergenic, insect pollinated, wind pollinated, native and introduced pollen types, pollen accumulation rates (with maximum pre-lake mark), annual rainfall, mean annual maximum temperatures and average annual 3 pm wind speeds (with BOM 30 year averages between 1961 and 1990) plotted against the age depth model with the two major dam developments of LBG and Googong, significant periods of drought, flood and the 2003 Canberra bushfire

in Fig. 5. The largest macro-charcoal peak is flanked by two periods of drought and coincides with the building of Googong dam in 1979 while other macro-charcoal peaks occur around 1988 and 1998–2003. The largest peak of micro-charcoal appears at 10 cm which corresponds to the early 1960s during an extended period of drought and coincides with the building and filling of Lake Burley Griffin. Other micro-charcoal peaks are centred around 1968, 1974–5, 1980, 1985, 1993, 2001 and 2008.

Discussion

Vegetation reconstruction assessed against historical records of local vegetation change

The vegetation reconstruction from LBG WL 2011 reveals a pre-lake landscape dominated by Australian native trees, shrubs and grassland with introduced weeds and traces of introduced trees from the northern hemisphere. This is typical of many Australian landscapes post-European settlement following the establishment of farmsteads and European agriculture. Species of *Prunus* (cherry) and *Salicaceae* (willow) were some of the earliest northern hemisphere trees planted by European settlers in the region (Cooke and Folger 2008). This could account for their presence at the base of the sediment core as there were a number of homesteads established where Lake Burley Griffin now flows. While there is evidence of an averaging effect in the pre-lake sediment, the presence of *Sequoia* (red wood) pollen provides a relative means of dating the base of LBG WL 2011; post 1928.

The genera represented in the lake sediment of LBG WL 2011 are dominated by introduced taxa from the northern hemisphere, corresponding to the exotic street tree plantings in the suburbs surrounding the lake (Pryor and Banks 2001). The

apparent lag in exotic tree pollen accumulation following suburban development and tree plantings in the 1920s can be accounted for by the fact that many northern hemisphere trees do not produce significant amounts of pollen before 20 years of age with some exceptions such as *Prunus* and *Salicaceae* species (Verdu 2002).

The peak of native pollen types around the 1950s could reflect *Eucalyptus* plantings carried out by Lyndsey Pryor, the then head of the Yarralumla nursery, on Black Mountain which later became part of the Australian National Botanic Gardens (Coltheart 2011). While the Pinaceae pollen peak around 1940 possibly reflects the early establishment of *Pinus radiata* plantations in the ACT (Wu et al. 2007).

The native and herbaceous vegetation groups show a marked drop in pollen across the period coinciding with the 2003 Canberra bushfire while the Poaceae and Pinaceae increase. This is evidence of vegetation change at a regional level. While some nearby suburban areas were devastated by the fire, the major effect on vegetation was regional. The vegetation in the suburbs immediately surrounding the lake was not impacted by the fire; however, the commercial pine forest where the National Arboretum now stands was severely impacted.

Assessment of micro- and macro-charcoal against recorded bushfires

The presence of charcoal in sedimentary profiles is used as a proxy for fire where micro-charcoal represents regional fires and macro-charcoal results from local fires. The deposition of charcoal is episodic as a result of discrete fire events in contrast to the more continuous deposition of pollen throughout the year. Also, charcoal can readily fragment, becoming less visible



Figure 7: Changing vegetation in the mid to late 20th century. (a) Acton, Golf Links, 1951 with Molonglo River flowing through (future site of Lake Burley Griffin Westlake) Courtesy ACT Heritage Library, 17/10/1951, from Department of Capital Territory albums 'Pictorial Record of Canberra 1951–1953', Reference no 001420. (b) View of Molonglo River flowing through West Lake area prior to the construction of Lake Burley Griffin (pre-1964) from Black Mountain, Canberra. Courtesy National Library of Australia PIC P2214/321 Photograph by Richard Clough (1921–2014). Retrieved April 23, 2018, from <http://nla.gov.au/nla.obj-143765195>

in the sedimentary record than pollen. The LBG WL 2011 sediment profile does not capture all of the fire activity in the pre-lake sediment due to the much coarser and isolated sampling at 2 cm intervals compared to the contiguously sampled 0.5 cm intervals in the lake sediment. The conditions of the pre-lake river flood plain would both inhibit and average the deposition of charcoal. These factors all taken together account for the relatively flat micro- and macro-charcoal profiles in the pre-lake sediment.

The macro-charcoal profile is significantly higher at the base of the core trending down from the 1930s. This may reflect the early farming history on the Molonglo River Flood Plain given that land clearing by fire was a common farming practice in the first half of the 20th century (ACT Government 2009). The ACT Government (2010) reports that there were 76 fires on Black Mountain between 1975 and 2003. Of these, 58 fires were deliberate; 22 were in the 1993–4 season and 24 occurred in the 1994–5 season. The number of fires on Black Mountain showed a sudden decrease after this time. The remaining 28 fires occurred in

the remaining years and may account for the extreme macro-charcoal peak centred on 1979.

The ACT government (2009, 2010) notes the following as significant periods of bushfire for the Canberra region; 1978–9 (16 500 ha), 1982–3 (33 000 ha), 1984–5 (28 000 ha), 2001 (1200 ha) and 2003 (164 000 ha). The fires between 1978 and 1985 could account for the micro-charcoal pattern in the profile. The major bush fire that occurred in Canberra in 2003 appears to be represented by both micro- and macro-charcoal peaks as would be expected from a fire that was both local and regional. However, this signature is relatively small in the profile given the extreme nature of the fire. The smaller fire in 2001 reached the edge of Lake Burley Griffin. This may account for the higher peak of macro-charcoal at this point in the profile.

The micro-charcoal profile is elevated between 1975 and the early 1960s. A distinct micro-charcoal peak occurs between two 1 in 20 years flood events in 1974 and 1976. The NSW Rural fire-fighting service reported that 1975 was the most severe fire season for 30 years. The largest fire on record to be extinguished by

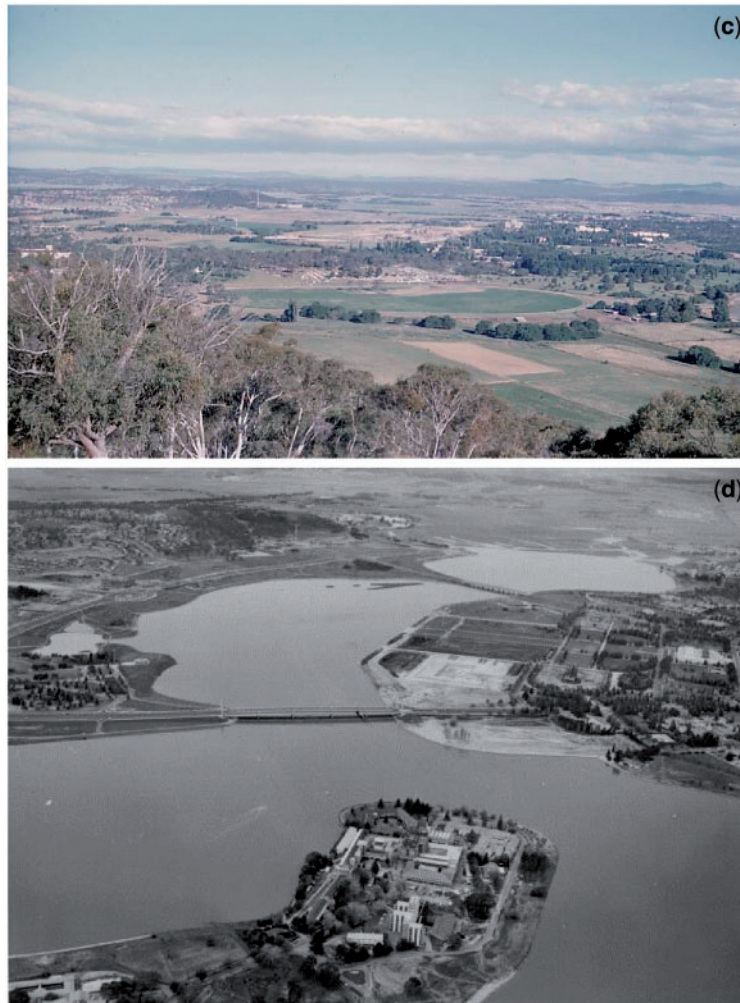


Figure 7: (c) View of Westlake area from Black Mountain, Canberra prior to the construction of Lake Burley Griffin Courtesy of National Library of Australia PIC P2214/320 Photograph by Richard Clough (1921–2014). Retrieved April 23, 2018, from <http://nla.gov.au/nla.obj-143765050>. (d) Lake Burley Griffin soon after filling in 1964, aerial view looking southeast from Royal Canberra Hospital on Acton Peninsula across the formal basins and the Parliamentary Triangle to Duntroon (core sampling site bottom right corner) Courtesy ACT Heritage Library, 1964, from Department of Capital Territory albums 'Pictorial Record of Canberra 1951-1953', Reference no 000175

firefighters occurred near Moolah-Corinya in New South Wales 700 km northwest of Canberra involving 4.5 million hectares during that same year. Another peak is centred around 1968. Major fires that overlap with this period occurred in Kosciuszko National Park in 1972 (45 539 ha) and 1965 (86 065 ha), the Snowy Mountains more generally in 1964 (250 000 ha). During the same period there was a significant fire in the Blue Mountains (1968; 15 000 ha). All of these fire events have potentially left micro-charcoal signatures in the profile. There is no corresponding macro-charcoal peak for these elevated micro-charcoal signatures which is consistent with the signature of major regional fires.

Has allergenic pollen increased in Canberra?

Until recently, the only published aerobiological study of pollen in Canberra was conducted in the late 1950s (Sands 1967) before the flooding of the lake. The pollen collection took place in open grassland in the middle of a suburban lawn in Yarralumla with 'no garden nearby to overload the results' (Sands 1967: 208). A comparison of the common pollen types recorded by Sands' study and the corresponding sedimentological data of this

study showed only broad similarities between the total percentages of Pinaceae and exotic street trees (Supplementary data 5, Table 1). There are significant differences between the proportions of exotic tree pollen types, native, herbaceous and grass pollen types, with 40% of the pollen recorded in the sedimentary samples not captured by the Yarralumla data set. This is due largely to the 1959 aerobiological data set being comparatively small and skewed toward the vegetation adjacent to the sampling location. As a result, it fails to capture the full breadth of the pollen load for the region at that time and suffers from an overrepresentation of grass pollen. Sands (1967) suggested the collection site may have been close to a source of Plantaginaceae which is also overrepresented compared to the sedimentological data. Comparison of historical images in Fig. 7 demonstrates the changes in vegetation near the sample collection sites between the 1950s and 2009.

A comparison between aerobiological data collected in 2010 and the corresponding sedimentological data show greater similarities (Supplementary data 4, Table 1). Although it should be noted that the 2010 aerobiological sampling location at the Australian National University was surrounded by planted



Figure 7: (e) West Lake from air—Lake Burley Griffin completed 1964—Black Mountain Peninsula in foreground, Canberra. Courtesy National Library of Australia PIC P2214/345 Photograph by Richard Clough (1921–2014). Retrieved April 23, 2018, from <http://nla.gov.au/nla.obj-143767760>. (f) View of Westlake area of Lake Burley Griffin in 2009 taken from the top of Black Mountain showing the increase in planted trees. Springbank Island is to the right of centre and the sampling site is to the left of Springbank Island just off Acton peninsula. Courtesy Meegan Summers

exotic and native trees and shrubs (Dass 2010). In particular there is a stand of *Callitris* beside the collection site which would account for the high levels of Cupressaceae pollen in this aerobiological data. However, there is a significant under representation of the moderately allergenic Plantaginaceae and Polygonaceae pollen types while the exotic street trees and herbaceous taxa, such as Asteraceae, Urticaceae and sedges (Cyperaceae), are comparatively overrepresented in the sedimentological data.

In addition to the proximity of a sampling location to populations of specific windborne pollen species, the sample collection time frames should also be considered. The greater capacity of the lake for continual pollen accumulation from local and regional sources averaged over a full year is likely to provide a more extensive collection of species compared to the much shorter collection time frames for aerobiological data and provides insights into changing patterns over the longer term. Aerobiological data are collected for the specific purpose of gaining a snap shot of the allergenic pollen load at a specific point in time to provide allergy sufferers the necessary information to take steps to mitigate its effects.

Australian native grasses are reportedly less allergenic than introduced grasses. Sands (1967) noted a high proportion of the

highly allergenic introduced Rye grass in his aerobiological study and suggested that the pollen could be from extensive pastures throughout NSW, Victoria and South Australia carried on the westerly winds. While this is a reasonable assumption it is difficult to substantiate using pollen evidence given the issue of separating various genera of grass (see Methods). Consequently, the grasses in the current study are all placed in the severely allergenic group, possibly leading to an overestimation of the allergenic load in the early part of last century, assuming there has been a transition from native to introduced grasses. If this is the case, then the increase in allergenic pollen load over the latter part of the 20th century to the present could be as high as 45%. Regardless of this conundrum, however, the sedimentological pollen profile clearly shows a 20% increase in allergenic pollen during the 90-year period prior to 2011.

Conclusion

Pollen analysis within Lake Burley Griffin has produced a picture of vegetation change that is consistent with historical records. The study demonstrates that pollen data from urban water bodies may provide useful insights over the longer term to augment limited aerobiological information. Native open

forest/grassland was transformed into a landscape dominated by northern hemisphere tree species, overlapping with increased population and urban development. One consequence of transforming Canberra's landscape in this way is the increase in allergy inducing species, with a marked increase in both moderate and severely allergenic pollen types, with the proportion of allergenic pollen in the inner Canberra region increasing by 20% over the last 90 years.

This planned transformation of the landscape has no doubt significantly impacted public health and the results of the study emphasise the importance of ongoing direct measurements, such as those published by AusPollen for the Canberra region. The expansion of the AusPollen Network across Australia is a much-needed forecasting tool for the increasing need to better inform public health practices and to assist the public with management of chronic allergy-related respiratory conditions, especially during peak pollen periods. Importantly, this study shows that urban water bodies have the potential to provide historical context for the changing allergenic pollen loads in our urban environments.

Supplementary data

Supplementary data are available at JUECOL online.

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