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Vulnerability of timber in ground contact to fungal decay under climate change

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Abstract Attack of decay fungi on wood-based material depends primarily on the natural durability of wood, the local climatic conditions, and the likely climatic change. This study investigates the vulnerability of wood and structural timber in ground contact to decay fungi under high and medium emissions scenarios specified by the Intergovernmental Panel on Climate Change, and a future scenario in which the global emissions have been limited to 550 ppm through a range of successful intervention schemes. Nine general circulation models are applied to project the local climates of Brisbane, Sydney, and Melbourne in Australia. It was found that, under the three emissions scenarios, the median decay rate of wood by 2080, relative to that in 2010, could increase up to 10 % in Brisbane and Sydney, but could decrease by 12 % in Melbourne. For timber of less durable wood species 50 years after installation, the residual strength under climate change could be almost 25 % less than that without climate change. The coefficients of variation (COVs) of decay rate of wood are in the vicinity of 1.0 regardless of wood species. For residual strength of timber pole after 50 years of installation, the COVs range from 0.2 to 1.1, depending on the natural durability of timber and the site location. The high COVs due to the variability of natural durability of wood and of climate change, in combination with the likely changes in median residual strength of structural elements, will cause significant structural reliability issues of wood construction and need to be addressed in engineering design codes.

1 Introduction

Structural timber is widely used in buildings and infrastructure; for example, more than five-million timber utility poles were in service throughout Australia's energy networks (Francis and Norton 2006), a stock worth more than $2.5 billion Australian dollars. Existing use of forest products in the US supports more than 1 million direct jobs and contributes more than

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$100 billion US dollars to the US gross domestic product (Ritter et al. 2011). Wood-based material is susceptible to the attack of decay fungi. The risk of fungal attack on wood exposed to weather depends significantly on the local climatic conditions. The durability issues of wood construction under current climate have been studied in Australia (Foliente et al. 2002; Mackenzie et al. 2007; Leicester et al. 2008; Nguyen et al. 2008; Wang et al. 2008; Leicester et al. 2009). The performance of wood construction under future climate is not known and recent Australian and international developments (ABCB 2002; ISO 2008) show how durability issues are considered.

This study investigates the vulnerability of wood and structural timber in ground contact attacked by decay fungi under projected emissions scenarios. The term 'vulnerability' referred to in this study is defined in Ionescu et al. (2009), in which it requires the specification of (1) the entity that is vulnerable, (2) the stimulus to which it is vulnerable, and (3) the preference criteria to evaluate the outcome of the interaction between the entity and the stimulus. With regards to the current study, the entities which are vulnerable are wood and structural timber, the stimuli are the decay fungi under projected climate (more specifically, the projected temperatures and rainfalls), and the preference criteria for outcome evaluation are the temporal changes/variability of fungal decay rate of wood and residual strength of structural timber.

Wood-based material has been widely used as a manufacturing material for tools, shelters, and as an energy source since the dawn of civilisation. Wood, being rich of carbon and hence a natural carbon sink, could be beneficial to the climate through its role in the global carbon cycle as a substitute to other materials (Schlamadinger and Marland 1996). Wood construction is the predominant type of housing in many regions of the world; for example, Australia, New Zealand, and the US. Therefore, when used in the construction sector, wood-based material could be a good source for mitigation of climate change (Werner et al. 2006; Eriksson et al. 2011). Ritter et al. (2011) reviewed 22 peer-reviewed articles documenting the US production of 17 wood products and found that using wood in building products yields fewer greenhouse gases than using other common materials. Buchanan and Honey (1994) compared wood-framed versions to steel-framed and reinforced concrete-framed versions of several types of buildings in New Zealand. They found that in all cases the wood emitted less fossil and processed CO_2 emissions during material production. Similar conclusions were reached in a comparison of multi-storey buildings either of wood frames or of concrete frames in Sweden (Börjesson and Gustavsson 2000), analysis of single-family houses constructed with either wood or brick in central Europe (Scharai-Rad and Welling 2002), and analysis of the use of various wood materials in place of non-wood materials in Norway (Petersen and Solberg 2002, 2003, 2004). Furthermore, because wood-framed construction requires less energy and emits less carbon-dioxide to the atmosphere than concrete- and steel-framed construction, its carbon mitigation efficiency, in terms of biomass used per unit of reduced carbon emission, is considerably better if wood is used to replace concrete as building material than if wood is used directly as biofuel (Gustavsson et al. 2006). The study findings reviewed in the preceding indicate that, dependent on the market situations and policy/regulations, there is a likelihood of increased use of wood for buildings and construction as a means for mitigation of climate change and an aide for sustainable materials resource use.

Wood, being rich in cellulose and lignin, is susceptible to the attack of decay fungi. Wood construction is under similar threat from fungal attack; therefore, if not properly constructed and maintained, its structural integrity will deteriorate over time due to the loss of wood mass to fungal decay. During the past few decades, many sophisticated concepts have been introduced into timber engineering for consideration of system effects in structural analysis and design, load uncertainties and combinations, serviceability requirements, and damage analysis (Kasal et al. 2004; Collins et al. 2005a, b; Wang and Foliente 2006; Breyer et al.

2007; AS 1720.1 2010; Liang et al. 2011). One significant deficit, however, has been the lack of consideration for climate-related durability issues (Foliente et al. 2002; Wang et al. 2008).

It is recognised that fungal spores require that the surface of wood to be wet in order for them to germinate. In addition, fungi require that the moisture content of wood be above the fibre saturation point to establish a viable mycelial mat (Viitanen and Ritschkoff 1991; Zabel and Morrell 1992). Once the mycelial mat has been established, the growth rate of the fungus is dependent primarily on wood moisture and ambient temperature.

For moisture contents of wood up to the fibre saturation moisture content (about 30 %) the moisture is adsorbed into the walls of the cells and decay is minimal as the decay fungi do not have enough suction strength to access this adsorbed moisture. Above this value, the moisture is in the form of free water and is easily accessible to the decay fungi, which then proceeds to rapidly decay the wood. High values of moisture content may occur when rainwater is sucked into wood through capillary action via a narrow slit or check. This moisture cannot evaporate easily through the narrow slit and it must do so through other faces of the wood substrate. If it can not do this fast enough, then the moisture will accumulate in the wood substrate to a value above the fibre saturation point.

Under a specific temperature, the growth conditions for fungi vary from species to species (Zabel and Morrel 1992). As a rough generalisation, it has been observed that for temperatures below 5 °C, the fungus will lie dormant, while at temperatures above 65 °C the fungus will be killed within a few hours.

It is clear that the vulnerability of wood to fungal attack depends significantly on the local climatic conditions. Therefore, the future climate, which is projected to change, will dictate the performance of wood and timber elements. Climate change can be caused by natural driving forces or human activities or both. To address the climate change due to the increasing greenhouse gases in the atmosphere from anthropogenic activities, the Intergovernmental Panel on Climate Change (IPCC) defined a set of four emissions scenario families—i.e. A1, A2, B1, and B2—in its Special Report on Emission Scenarios (IPCC 2000) for projection of future greenhouse gas emissions related to population, economy, technology, energy, land use, and agriculture. The A1 scenario assumes very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies, as well as substantial reduction in regional differences in per capita income. In addition to these assumptions, the A1 sub-categories further refine the scenario into:

- A1FI that assumes intensive fossil energy consumption
- A1B that has balanced fossil and non-fossil energy consumption

Besides, the scenario of CO_2 emission stabilising at 550 ppm by the year 2150 is also introduced to take into account the effect of policy intervention.

A compelling reason for considering the intensive emissions scenario A1FI is that the global mean surface temperature between 1990 and 2006 has been found to be in the upper part of the range projected by the IPCC (Rahmstorf et al. 2007). Therefore, this study investigates the vulnerability of wood and structural timber in ground contact to the attack of decay fungi under the A1FI, A1B, and 550 ppm stabilisation scenarios, which represent high emissions, medium emissions, and the emissions under policy influences, respectively. An emissions scenario based on the year 2010 climate, representing the current climate, is considered to provide a reference for the considered emissions scenarios.

It is apparent that uncertainties are prevalent in vulnerability assessment under climate change. Three sources of uncertainties are considered in this study: (1) The projected trend curves of climate variables (temperature and rainfall), (2) the variability of climate variables in each individual year conditional on given trend curve values, and (3) the variability inherent in the progress of fungal decay of wood materials.

2 Temperature and rainfall

Various atmosphere–ocean general circulation models (GCMs) have been developed at the continental scale to account for the spatially dependent climate variables for projection of emissions scenarios. The IPCC suggested that due to the varying sets of strengths and weaknesses of various GCMs, no single model can be regarded as the best. It is necessary, therefore, to use multiple models for consideration of the modelling uncertainties in a vulnerability assessment. Nine climate models (see Wang et al. 2010 and IPCC 2007 for more details) are used in this study.

The population distribution and industrial activities of Australia concentrate on the east and southeast coastline of the continent. We choose three cities to study because, collectively, almost 50 % of the nation's 22 million population call them home: Sydney (33°52′ S, 151°13′ E) in New South Wales, Melbourne (37°49′S, 144°58′ E) in Victoria, and Brisbane (27°28′ S, 153°01′ E) in Queensland. Incidentally, the characteristics of climate in the three cities are quite different: Brisbane has a humid subtropical climate with warm to hot and humid summers and dry, moderately warm winters, Sydney has a temperate climate with warm summers and mild winters, and Melbourne has a moderate oceanic climate with cool to cold winters and changeable weather conditions round the year.

2.1 Trends of temperature and rainfall

Figure 1 shows the medium projected temperature and rainfall trends for each of the nine GCM projections, for A1FI, A1B, and 550 ppm emissions scenarios for Brisbane, Sydney, and Melbourne. Comparing these projected curves, it is seen that the three cities have similar trends and spread for temperature. For rainfall, Brisbane has a much larger spread than the other two cities. Both Brisbane and Sydney are projected to have slightly downward trends for rainfall but with wide spread, whereas about all medium projections for Melbourne point to a drier future.

For a specific emissions scenario, each of the nine GCMs gives low, medium, and high estimates for the projected trend of a climate variable to describe the uncertainty of trend curve. If the low, medium, and high estimates are taken as 10 percentile, median, and 90 percentile values, respectively, of a Weibull distribution of the smallest value (Ang and Tang 1984), and the projected trends of the nine GCMs are assumed to be equally probable as implied in the IPCC report, then the probability distribution of future trend may be regarded as a mixture of equally weighted distributions projected by the nine GCMs. Accordingly, the mixture distribution can be readily estimated by Monte Carlo simulation as shown in Fig. 2, in which the 10 percentile, median, and 90 percentile values are plotted.

2.2 Uncertainty of temperature and rainfall given trend curves

In addition to the uncertainty of projected trend curves as shown in Fig. 2 for temperature and rainfall, another notable source of uncertainty is the fluctuation of climatic variables in each individual year around the trend curves. This component of uncertainty may be deduced from historical data, as shown in Fig. 3, in which the data points represents the

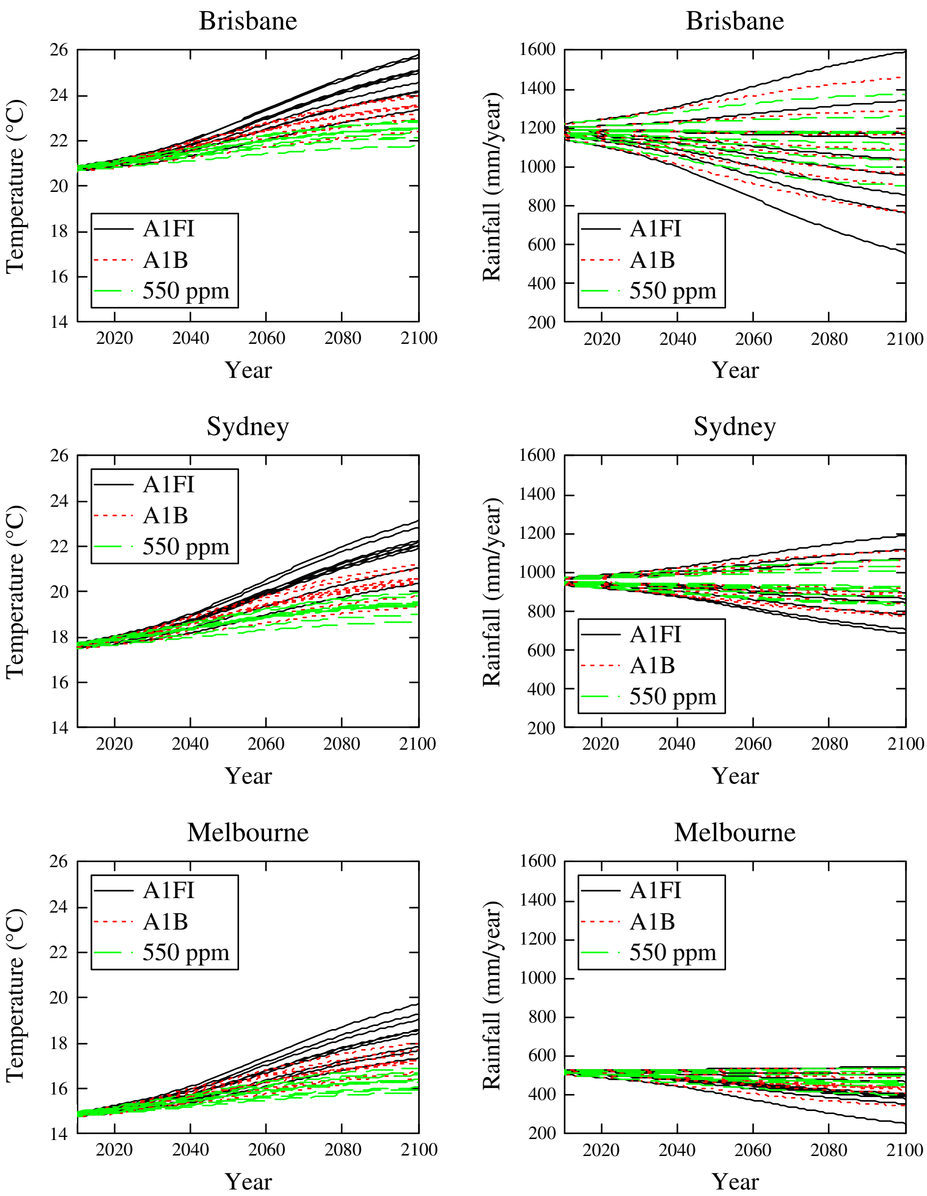


Fig. 1 Projected medium temperature and annual rainfall from nine GCMs for the A1FI, A1B, and 550 ppm emissions scenarios for Brisbane, Sydney, and Melbourne

average annual temperature (or annual rainfall), the solid lines indicate the regression lines, and the dash lines and dash-dot lines are (regression line) ± (one estimated standard deviation). The residuals (obtained by subtracting the data point values by the corresponding regression line values, not shown) of both average annual temperature and annual rainfall in all three cities are approximately normally distributed with uniform standard deviations over the 30 observed years. The estimated standard deviations are given in Table 1.

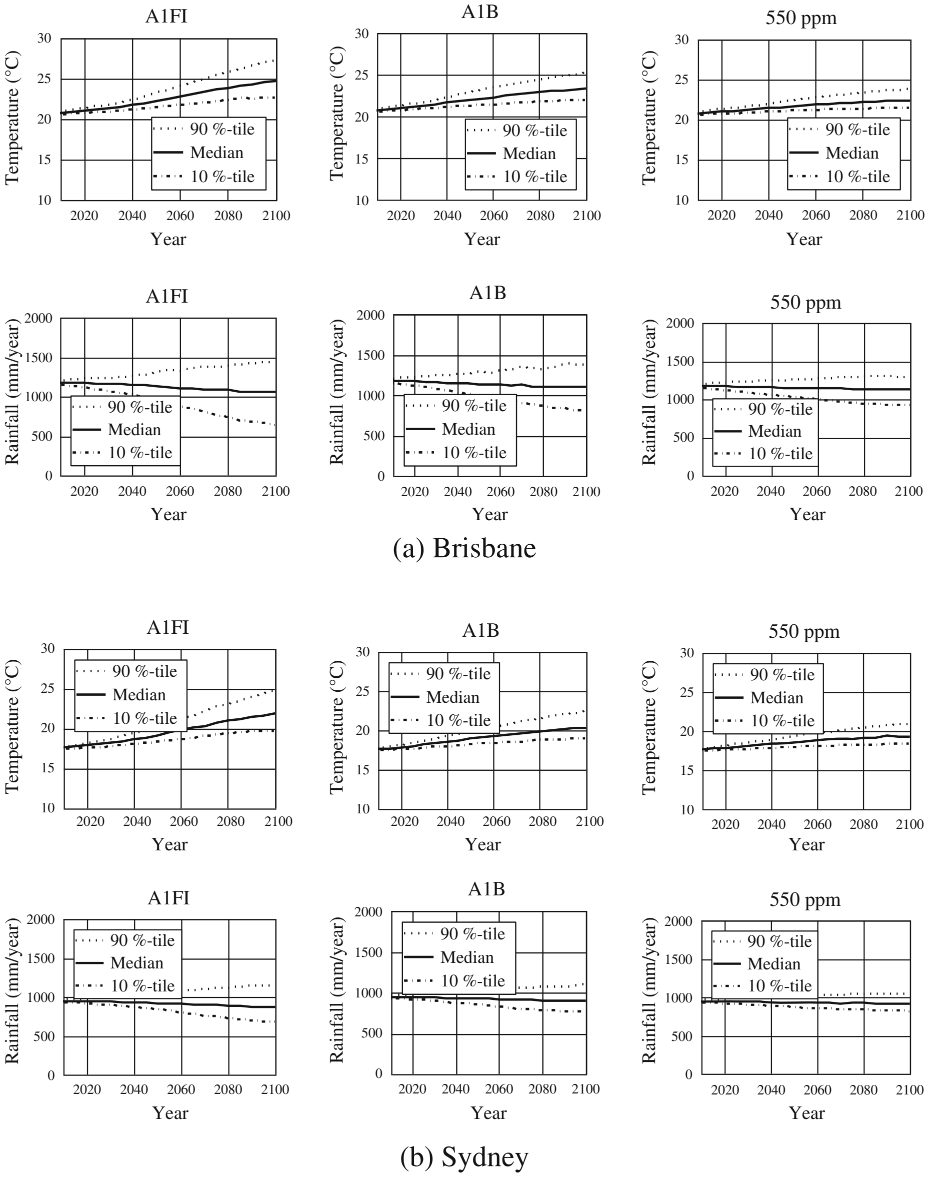


Fig. 2 Projected 10 percentile, median, and 90 percentile values of temperature and rainfall based on the mixture distributions from nine GCMs for **a** Brisbane, **b** Sydney, and **c** Melbourne

3 Probability distributions for decay rate of wood

Figure 4 summarises schematically the relative decay rate of different types of wood taken from a timber log, in which the dashed line labeled 'for treated sapwood' represents the relative rate of decay of sapwood impregnated by some chemicals such as copper chrome arsenic (CCA) and creosote. The natural durability of a wood species refers to the natural resistance to decay of its outer heartwood, the most durable part of a timber log.

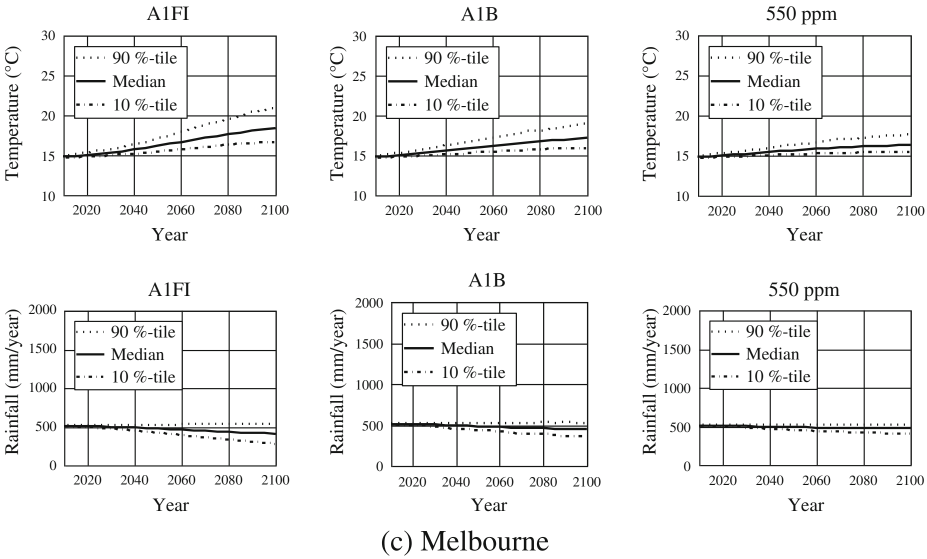


Fig. 2 (continued)

Investigation on natural durability of clear wood stakes in Australia was conducted by the former Division of Forest Products, CSIRO, Australia, at five test sites in eastern and southern Australia over the period of 1968–2004, a test period of 35 years (Thornton et al. 1983). A clear wood stake is a stake composed of outer heartwood only. The five test sites are located at: (1) Walpeup, Victoria, (2) Melbourne, Victoria, (3) Sydney, New South Wales, (4) Brisbane, Queensland, and (5) Innisfail, Queensland. Details of the setup of the program are found in Thornton et al. (1983). The planning and implementation of this test program were designed to randomise the selection of specimens and the placement of specimens on the test sites so as to avoid systematic biases.

A total of 77 commonly used commercial Australian timber species were chosen for the testing. Timber from the outer heartwood of butt logs was taken for the test specimens. Each species had 10 specimens installed at each test site. The air-dry size of the specimens, cut intentionally free of any defect, was of 50×50 mm in cross-section and 450 mm in length, with two thirds of the length being embedded in the ground. Inspection and assessment of decay by penknife probing were carried out at intervals of around 2 years. Originally, the effects of the decay were recorded in terms of score ratings. These ratings were then converted to an effective depth of decay measured from the outer surface and progressing inwards (Leicester et al. 2003). In this way, the data were used to measure the progress of in-ground decay for the test duration of 35 years. The data at each site was processed to obtain the decay depth of each specimen. It was found that the decay depth versus time generally exhibits a bilinear relationship, with an initial time lag before decay commences followed by a decay depth progressing at a roughly uniform decay rate.

For engineering purposes, the commercially used species have been classified into four natural durability classes with class 1 the most durable and class 4 the least durable, as defined in the Australian Standard (AS 5604 2005). The decay rates of specimens made of wood species of the same durability class were collected for inferences of appropriate probability distribution of decay rate. As a result, the decay rates for the four durability classes are modelled by the Weibull distributions of the smallest value. The cumulative distribution functions (CDFs) of

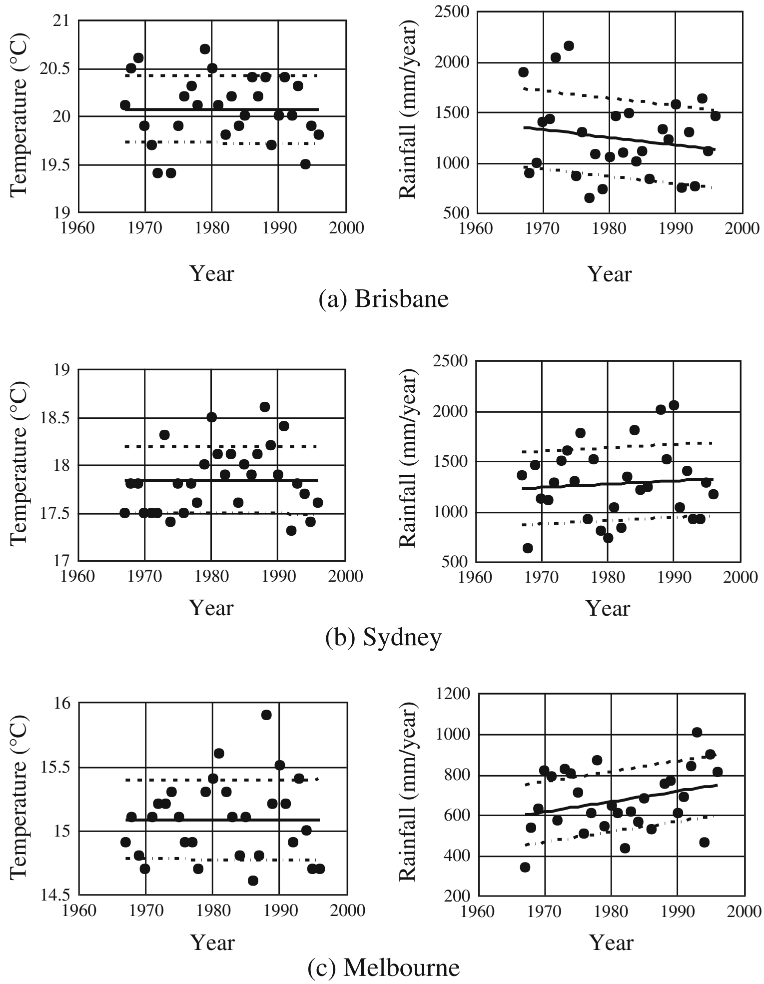


Fig. 3 Historical average annual temperature and annual rainfall for **a** Brisbane, **b** Sydney, and **c** Melbourne

decay rate for the four durability classes at Brisbane, Sydney, and Melbourne are plotted in Fig. 5, in which the four curves from left to right are for timber of classes 1–4, respectively. The distribution functions of decay rate represent, given a specific location and climatic condition, the inherent variability of the loss of wood attacked by decay fungi.

For engineering applications, typically the durability class-4 timber is used as structural timber only when it is treated by chemicals (e.g. creosote or copper chrome arsenic) to improve its resistance to fungal decay. As such, this study concentrates on the analysis of untreated wood and structural timber of durability classes 1, 2, and 3.

Table 1 Standard deviation of residuals of historical average annual temperature and annual rainfall

City	Temperature (°C)	Rainfall (mm/year)
Brisbane	0.34	386
Sydney	0.34	362
Melbourne	0.31	148

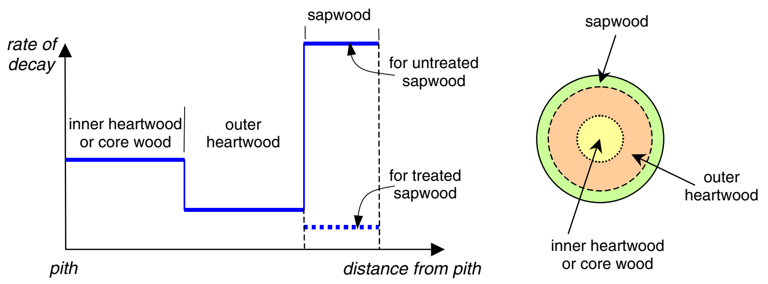


Fig. 4 Schematic illustration of relative decay rates of different types of wood

4 Projection for fungal decay of wood and timber element

4.1 Fungal decay attack model

The rate of fungal decay of outer heartwood, r (mm/year), given average annual temperature (°C) and annual rainfall (mm/year) has been established as follows (Wang et al. 2008):

$$r = k_w f(R)^{0.3} g(T)^{0.2} \tag{1}$$

where

$$k_w = \begin{cases} 0.23, & \text{for class 1;} \\ 0.48, & \text{for class 2;} \\ 0.76, & \text{for class 3.} \end{cases} \tag{2}$$

$$f(R) = \begin{cases} 10\left[1 - e^{-0.001(R-250)}\right]\left(1 - \frac{N_{dm}}{6}\right), & \text{if } R > 250\,\text{mm and } 0 \le N_{dm} \le 6; \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

$$g(T) = \begin{cases} 0, & \text{if } T \le 5°\text{C;} \\ -1 + 0.2T, & \text{if } 5 < T \le 20°\text{C;} \\ -25 + 1.4T, & \text{if } T > 20°\text{C.} \end{cases} \tag{4}$$

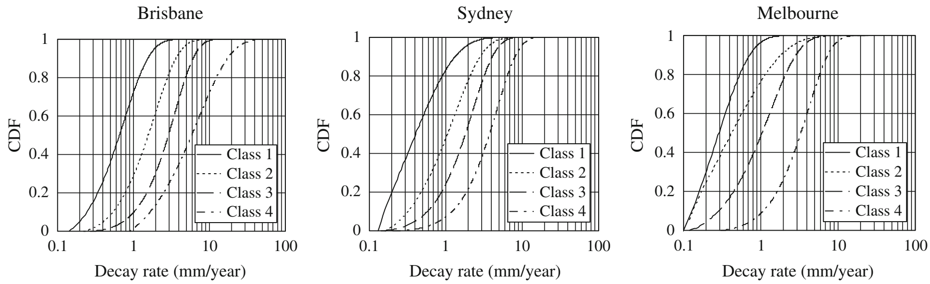


Fig. 5 Cumulative distribution functions of wood decay rate

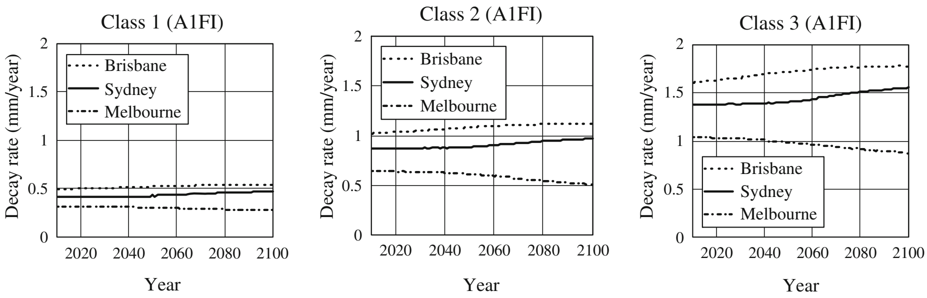


Fig. 6 Fungal decay rates of wood of durability classes 1–3 in Brisbane, Sydney, and Melbourne

in which N_{dm} is the number of "dry months" per year. A dry month is defined as the month during which the total rainfall does not exceed 5 mm. In addition, the time lag before decay commences, t_{lag} (years), is related to the decay rate by

$$t_{lag} = 5.5r^{-0.95} \tag{5}$$

4.2 Projected decay rate of wood

Based on the attack model presented in the preceding subsection, the median decay rates for wood of durability classes 1–3 in Brisbane, Sydney, and Melbourne from 2010 to 2100 under the A1FI emissions scenario are shown in Fig. 6. The median decay rate curves shown are similar to that under scenarios A1B and 550 ppm. We see that Brisbane and Sydney have increasing decay rates over time, with Sydney increasing faster than Brisbane after around 2060 because the decay rate turns faster when the annual temperature exceeds 20 °C as implied in Eq. (4). Melbourne has a decreasing decay rate over time, mainly due to its more definite decreasing rainfall (Fig. 2): there is a probability of around 0.9 that Melbourne will have future rainfall below the 2010 level.

The coefficients of variation (COVs) of decay rates, as shown in Fig. 7, are around 0.8 with the exception of durability class-2 wood in Melbourne, which is around 1.5. All the COVs have an upward trend over time. Note that under logarithmic scale the 10 and 90 percentile values of decay rate (as shown in Fig. 8 for Sydney as an example), are approximately symmetric with respect to the median. Therefore, the projected decay rate

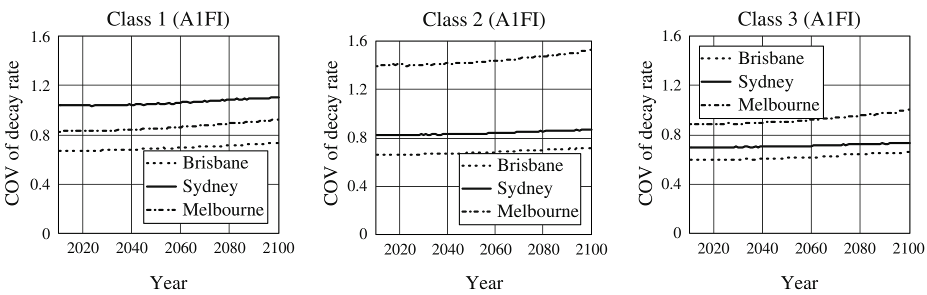


Fig. 7 Coefficient of variation of fungal decay rates of wood of durability classes 1–3 in Brisbane, Sydney, and Melbourne

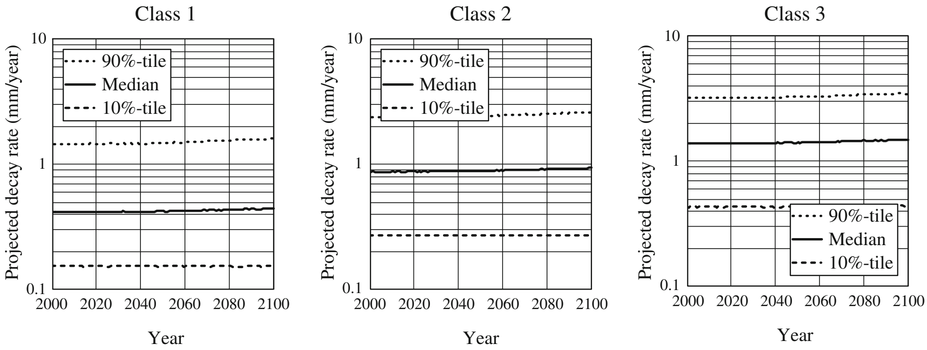


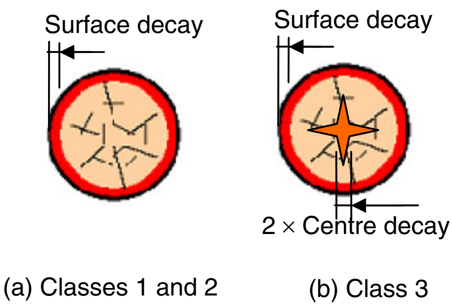
Fig. 8 Projected 10 percentile, median, and 90 percentile decay rates of wood of durability classes 1–3 in Sydney

at a specific year may be approximated by a lognormal distribution with the logarithm of decay rate shown in Fig. 6 as the location parameter and $\sqrt{\ln\left(\mathrm{COV}^2+1\right)}$, where COV is taken from Fig. 7, as the scale parameter.

4.3 Projected residual strength of timber pole

For wood construction, the timber elements should be designed to possess adequate strength for structural integrity throughout its service life. Timber elements in ground contact are most often used as load-bearing elements such as columns, house stumps, and fencing posts. In these cases, typically bending moment is of the most critical type of external forces and, hence, is of the dominant failure mode. In this section, we assess the performance of structural timber subjected to fungal decay over time by examining the residual bending strength of de-sapped (i.e. no sapwood present) hardwood timber pole of 300-mm diameter installed in 2010. Timber of durability classes 1 and 2 is assumed to undergo perimeter decay only, while that of durability class 3 is subject to internal quarter-width '+' check in addition to perimeter decay, as shown in Fig. 9. The parametric value of k_{w}, needed in Eq. (1), for hardwood core wood is twice the k_{w} value of the respective durability class of outer heartwood given in Eq. (2). The radius of core wood and the thickness of outer heartwood of the timber pole are assumed to be equal. For ease of computation and between-city comparison of residual strength, we assume that no uncertainties in the decay patterns and no maintenance procedures that postpone the progress of decay are applied after installation of the timber pole.

Fig. 9 Decay patterns for hardwood timber poles: **a** durability classes 1 and 2, **b** durability classes 3 and 4



Because of progressive cross-sectional loss due to fungal decay, the bending strength decreases with the progress of decay. The residual strength ratio, defined as the ratio of residual strength to the original non-decayed strength, is shown in Fig. 10 for a timber pole installed in Sydney. It is seen that, under the uncertainties associated with wood decay, climatic change and climatic variability, the performance of timber pole is highly variable. For example, for durability class-2 timber pole in 2060 (i.e. 50 years after installation), there is a probability of 0.8 that the residual strength ratio lies between 0.02 and 0.8. Alternatively, if the time at which the strength falls to, say 70 % of the original, before replacement or demolition takes place, then this may happen to durability class-2 pole with a probability of 0.8 between 15 years and 75 years after installation, with a median time around 30 years.

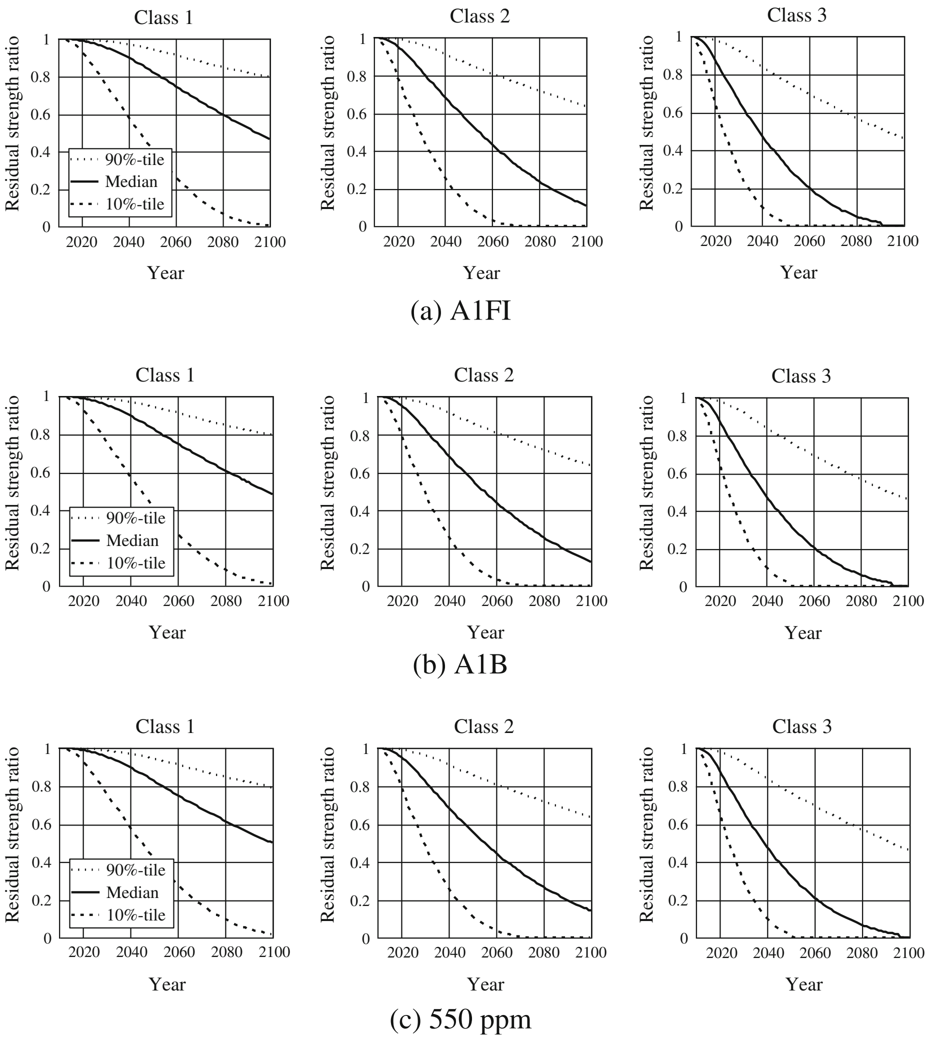


Fig. 10 Ten-percentile, median, and ninety-percentile residual strength ratio of 300-mm diameter timber poles of hardwood in Sydney under **a** A1FI, **b** A1B, **c** 550 ppm

4.4 Percent changes of wood decay rate and timber pole strength subject to climatic change

While the projected changes of temperature for different locations have in general a definite upward trend, the projected changes of rainfall are less so. This section compares the decay rates of outer heartwood and the residual strengths of de-sapped timber poles of 300-mm in diameter installed in 2010 with and without projected climate change in Brisbane, Sydney, and Melbourne.

Figure 11 shows the change of median decay rate under the three projected emissions scenarios as opposed to that under the current climate. It shows that the decay rate changes

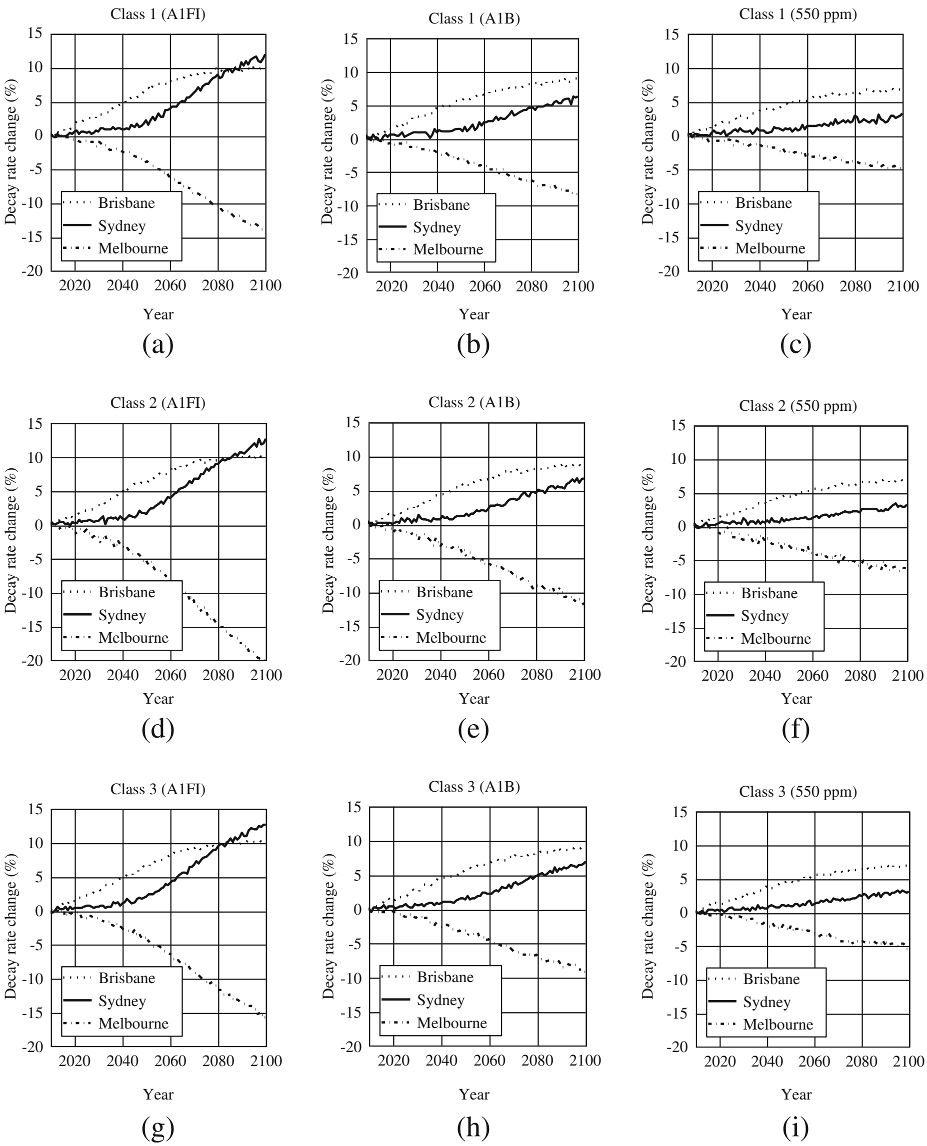


Fig. 11 Percent change of median decay rate of wood durability classes 1–3 under emissions scenarios A1FI, A1B, and 550 ppm in Brisbane, Sydney, and Melbourne

for wood of durability classes 1–3 are comparable in magnitude at a given location under a specific scenario (e.g. see Fig. 11a, d, and g for class-1 timber). Observe the decay rate changes in the three cities up to 2040, 2060, and 2080 (corresponding to 30, 50, and 70 years, respectively, after installation). As expected the 550 ppm scenario causes the least change while the A1FI scenario causes the largest change; e.g. up to 2060 Brisbane undergoes a 5.4 % increase in decay rate under 550 ppm but a 7.8 % increase under A1FI (Fig. 11a and c). Under the A1FI scenario, the decay rate change in Brisbane is greater than Sydney before 2080, but it is reversed after 2080 (e.g. Fig. 11a). Melbourne has decreased decay rate changes, ranging, for instance, from −12 to −5 % in 2080 under the three scenarios (Fig. 11g, h, and i). This is because Melbourne is most likely to become drier, as elucidated previously, than the other two cities.

The changes of residual bending strength of timber pole under projected emissions scenarios versus that under the current climate are shown in Fig. 12. It is noted that a timber pole of durability class 3 has zero median residual strength around 2080 in Brisbane and around 2090 in Sydney (Fig. 12g, h, and i). It is apparent that the magnitude of percent change in residual strength depends on the durability class of wood and the emissions scenario. The residual strengths in Brisbane and Sydney under a specific scenario decrease because of increases in decay rate, while that in Melbourne increases because of decreases in decay rate. In general, the timber of lower natural durability and the scenario of higher greenhouse gas emissions result in a greater change of residual strength, as seen in Fig. 12. For reference, note that prior to 2040 the strength changes are mostly under 5 %, meaning that strength change due to climate change may be neglected for timber poles of any durability class intended for a service life of under 30 years. On the other hand, the strength decreases up to 2080 in Brisbane and Sydney are large for timber of durability class 3, greater than 20 % under both A1FI and A1B (Fig. 11g and h), indicating that poles of durability class 3 are inadequate for construction up to 70 years of service life.

Figure 13 shows the COVs of residual strength over time under A1FI. The COVs under A1B or 550 ppm scenario are similar to that under A1FI. It shows that timber of durability class 1 has much lower COV than other durability classes. Timber installed in Melbourne has lower COV than that installed in Brisbane and Sydney. Overall, however, these COVs are significant for reliability estimation of service life, hence deserves consideration in engineering design. As given in Table 2, for a timber pole designed for services of around 50 years (i.e. in 2060), the COVs for durability classes 1, 2, and 3 may be taken approximately as 0.4, 0.7, and 1.0, respectively, when installed in Brisbane and Sydney, and as 0.2, 0.6, and 0.8, respectively, when installed in Melbourne.

5 Conclusions

To serve as a step toward codification of durability issues of timber in structural design, we investigated the attack of decay fungi on deterioration of wood construction and the vulnerability of wood as well as structural timber pole to decay fungi under the projected future climates of emissions scenarios A1FI, A1B, and 550 ppm CO_2 stabilisation. Wood and timber of durability classes 1–3 installed in Brisbane, Sydney, and Melbourne are investigated. The results are compared to that under the current climate.

Under all emissions scenarios considered in this paper, the natural durability of wood species generally has a negligible effect on the changes of decay rate of wood, but has a significant effect on the change of residual strength of timber. Under the three emissions scenarios, the median decay rate of wood by 2080, relative to that in 2010, could increase up

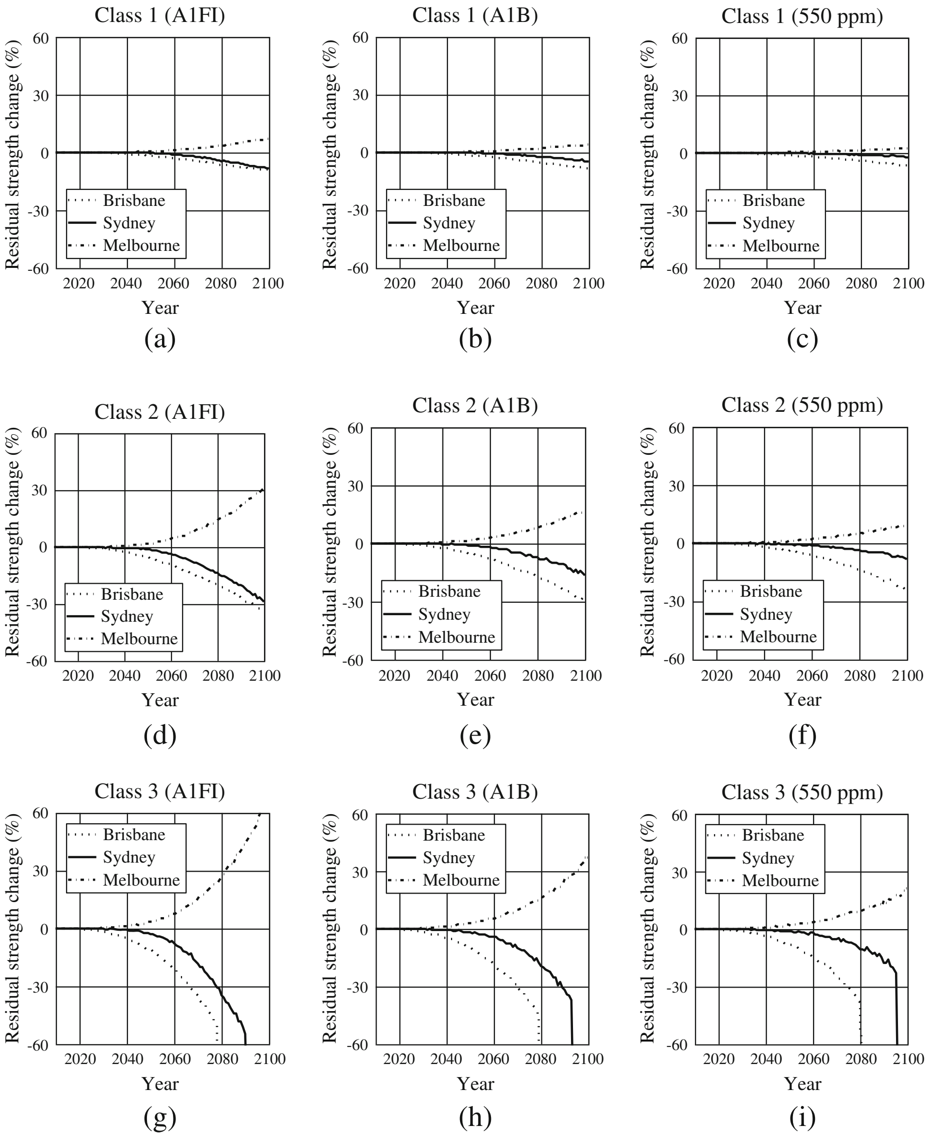


Fig. 12 Percent change of residual strength of 300-mm diameter de-sapped timber pole of durability classes 1–3 under emissions scenarios A1FI, A1B, and 550 ppm in Brisbane, Sydney, and Melbourne

to 10 % in Brisbane and Sydney, but could decrease by 12 % in Melbourne. For timber of less durable wood species 50 years after installation, the residual strength under climate change could be almost 25 % less than that without climate change. The rates of decay progress are found to have COV values around 1.0 for all durability classes in the three cities studied. For residual strength of timber pole after 50 years of installation, the COVs range from 0.2 to 1.1, depending on the natural durability of timber and the site location. Such high COVs will cause significant performance variability of wood materials and structural timber. If acceptable level of structural safety is to be achieved, this variability needs to be taken into

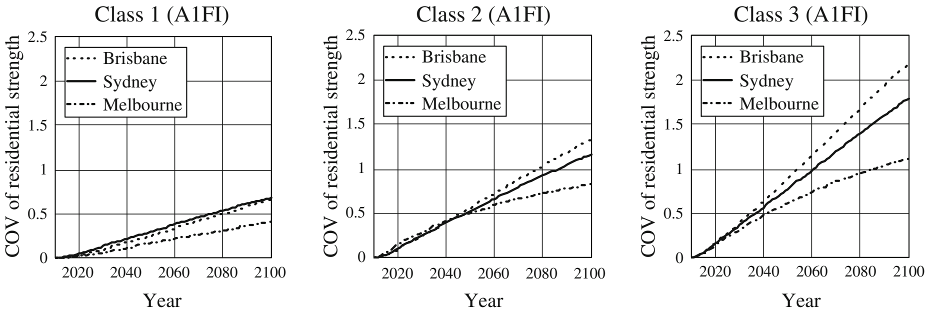


Fig. 13 Coefficient of variation of residual strength of 300-mm diameter timber pole of durability classes 1–3 under emissions scenario A1FI in Brisbane, Sydney, and Melbourne

account in the structural design code specification. For this purpose, a timber pole designed for services of around 50 years, the COVs for durability classes 1, 2, and 3 may be taken approximately as 0.4, 0.7, and 1.1, respectively, when installed in Brisbane and Sydney, and as 0.2, 0.6, and 0.8, respectively, when installed in Melbourne.

The projected trends of temperature and rainfall dictate the changes in the median residual strength of timber poles. For Brisbane and Sydney, the decay-accelerating effect of the upward trends of temperature dominates the decay-slowing effect of the slightly downward trends of rainfall. For Melbourne, in contrast, the decreasing rainfall has a benign effect more than compensating for the malevolent effect of increasing temperature on decay. As for the uncertainties of residual strength, generally more durable timber species have lower COVs than less durable species. For the three cities assessed, timber installed in Melbourne has the lowest COVs and that installed in Brisbane has the highest COVs.

Compared to the projections for temperature, the projections for rainfall by the various GCMs have notable disagreements, some of them even give opposite trends. This causes the combined projected trend to have a large uncertainty; for example, for the nine GCMs considered herein, the combined 80 % confidence interval of rainfall trend for Brisbane in 2100 ranges from 600 mm/year to about 1,500 mm/year under the A1FI emissions scenario. The relative influence of uncertainties on natural durability of timber under different hazard exposures versus uncertainties on climate scenarios and projections need to be studied further.

Assessments on the natural durability of clear wood stakes in ground contact were conducted at only five locations along the east and southeast coasts of Australia (Thornton et al. 1983). For locations of different characteristics in climate such as Darwin, Northern Territory, similar natural durability studies need to be carried out. Durability of timber

Table 2 Coefficients of variation of residual strength in Brisbane, Sydney, and Melbourne up to 2040, 2060, and 2080

Year	Brisbane			Sydney			Melbourne		
	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3
2040	0.17	0.40	0.6	0.21	0.4	0.6	0.11	0.40	0.50
2060	0.31	0.7	1.1	0.37	0.6	1.0	0.22	0.60	0.75
2080	0.47	1.0	1.6	0.51	0.9	1.3	0.32	0.75	1.0

construction depends markedly also on the effectiveness of maintenance and repair schemes; if maintenance procedures are to be applied, they should be taken into account for a more realistic vulnerability assessment. Because of its importance level, mission-critical or business-critical infrastructure needs to be investigated by considering the impact of potentially updated climate change projections, say every 10 years or so, to incorporate the latest data, measurements, and modelling techniques for more accurate assessment.

Durability issues in Australia under current climate are addressed in a timber service life design guide (Mackenzie et al. 2007) that is referenced in the recently amended Australian Standard for design of timber structures (AS 1720.1 2010). It is hoped that durability issues under projected future climate could be addressed directly in the future version of Australian Standard. This research represents one step forward toward that objective.

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