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The overlooked carbon loss due to decayed wood in urban trees

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Highlights

- Decayed wood is a common issue in urban trees that deteriorates tree vitality over time, yet its effect on biomass yield therefore stored carbon has been overlooked.
- The distribution pattern and extent of decay documented in this study was species-dependant and can be aggravated by arboticultural practices. Decay was found to be distributed in three different ways in the three different species evaluated. Central column, cone-shaped and pockets of decay of variable size for *U. procera*, *P. acerifolia* and *C. maculata*, respectively.
- Decay was more frequent and extensive in *U. procera*, than *P. acerifolia* and least in *C. maculate*. Decayed wood is not correlated with tree vitality in *U. procera* and may occur even in visually healthy standing trees within the genera.
- The absence of wood as a result of decay significantly reduces the standing volume of all three species examined. The standing volume of *U. procera* trees with DBH ≥ 40 cm needs to be discounted by a factor of 13% due to internal decayed wood regardless of the species vitality index.
- Calculations of stored carbon by urban trees may need to be discounted by a species-decay factor rather than a standard factor that account only for differences in biomass yield between natural and urban trees. The detrimental effect of decayed wood on the standing volume cannot longer be overlooked and need to be considered to better assess urban tree benefits.

Abstract

Decayed wood is a common issue in urban trees that deteriorates tree vitality over time, yet its effect on biomass yield therefore stored carbon has been overlooked. We mapped the occurrence and calculated the extent of decayed wood in standing *Ulmus procera*, *Platanus x acerifolia* and *Corymbia maculata* trees. The main stem of 43 trees was measured every metre from the ground to the top by two skilled arborists. All trees were micro-drilled in two to four axes at three points along the stem (0.3 m, 1.3 m, 2.3 m), and at the tree's live crown. A total of 300 drilling profiles were assessed for decay. Simple linear regression analysis tested the correlation of decayed wood (cm^2) against a vitality index and stem DBH. Decay was more frequent and extensive in *U. procera*, than *P. acerifolia* and least in *C. maculata*. Decay was found to be distributed in three different ways in the three different genera. For *U. procera,* decay did appear to be distributed as a column from the base to the live crown; whereas, decay was distributed as a cone-shape in *P. acerifolia* and was less likely to be located beyond 2.3 m. In *C. maculata* decay was distributed as pockets of variable shape and size. The vitality index showed a weak but not significant correlation with the proportion of decayed wood for *P. acerifolia* and *C. maculata* but not for *U. procera*. However, in *U. procera*, a strong and significant relationship was found between DBH and stem volume loss (R^2= 0.8006, P= 0.0046, n=15). The actual volume loss ranged from 0.17-0.75 m^3, equivalent to 5 % to 25% of the stem volume. The carbon loss due to decayed wood for all species ranged between 69 to 110 kg per tree. Based on model's calculation, the stem volume of *U. procera* trees with DBH ≥ 40 cm needs to be discounted by a factor of 13% due to decayed wood regardless of the vitality index. Decayed wood reduces significantly the tree's standing volume and needs to be considered to better assess the carbon storage potential of urban forests.

Key words: *urban tree benefits, decay assessment, tree vitality, carbon storage, Melbourne.*

Introduction

Urban trees are valuable assets for modern cities and they deliver key functions and benefits that enhance city liveability (Davies et al., 2011; McPherson et al., 2013; Nowak et al., 2008). The various function and benefits of urban forests have been well documented elsewhere (Baumgardner et al., 2012; Escobedo et al., 2008; Livesley et al., 2016; Nowak et al., 2002). Numerous researchers and arborists agree that the urban landscape imposes several adverse environmental conditions that impact tree survival, growth, vitality and longevity of urban forests (May et al., 2013; Sjöman et al., 2012). While many functions and benefits of urban forests are linked to tree size, height and appearance of the crown, stored carbon in mostly a function of tree bole. In the broadest sense, the bigger and healthier the tree, the greater the carbon storage potential of urban trees over time (Dwyer et al., 2003; McHale et al., 2007; McPherson et al., 2012).

Above-ground biomass estimation is a key parameter in accounting for the carbon stock of trees outside forest (FAO, 2013; McHale et al., 2009). During the last decade, there has been considerable research effort to quantify the carbon storage potential of urban forests worldwide. Although, stored carbon in urban forests is relatively small in scale compare to forest stands and plantation trees, the proximity of urban forests to emission sources mean that their carbon storage potential should not be neglected (Frank et al., 2006; Moore, 2009). Researchers have attempted to calculate and value the carbon stock in urban trees ranging from single species, through to city-wide urban tree populations (Brack, 2002; Davies et al., 2011; Dobbs et al., 2011; McPhearson et al., 2013; Nowak et al., 2013; Peper et al., 2014; Russo et al., 2014; Stoffberg et al., 2010; Strohbach et al., 2012). Approaches and methodologies aimed at calculating the standing biomass, therefore stored carbon, vary widely in their suitability, reliability and replicability (Fatemi et al., 2011; Lefsky et al., 2008). In addition, the majority of stored carbon studies rely on forest-based allometric equations developed in the United States of America (USA), therefore, when applied outside the defined range of diameter, climatic region and scale of use, these equations yield less reliable estimates (McHale et al., 2009; McPherson et al., 2012).

The development of species-specific allometric equations based on destructive sampling is the most correct way towards an accurate estimation of carbon pools in trees (Jenkins et al., 2004; McHale et al., 2009). Although feasible, destructive sampling is not always practical in an urban context and alternative techniques are needed. Non-destructive methods such as terrestrial LiDAR, Ariborne LiDAR, as well as partially-destructive (non-fatal) sampling methods; namely randomized branch sampling (RBS); are now available (Dobbs et al., 2011; Jung et al., 2011; Shrestha et al., 2012). While the utilization of remotely sensed data to capture urban trees biomass is cost-effective, recent research has shown that they are less accurate than those calculations based on stem diameter measurements and allometric equations (Kankare et al., 2013; McHale et al., 2009; Vonderach et al., 2012). Finally, Chirici et al. (2014) tested RBS against full tree measurement and argued that unless a minimum of three paths are followed, above-ground biomass estimations based on RBS can yield an estimation error of up to 15%.

Little is known about the biomass loss due to decay in both natural and urban forests (Hutyra et al., 2011). Recently, Cousins et al. (2015) pointed out that decayed wood reduces up to 18 % the amount of stored carbon in natural forests. Similarly, Brazee et al. (2010) estimated that the actual carbon stock in a decayed portion of a tree was only 57% of the amount of stored carbon estimated for the decay-free stem. The study conducted by McPherson et al. (1997)

estimated biomass and stored carbon in urban trees in Chicago city, USA, but only 30 trees out of 8000+ measured were assessed for decay. Decay was evident in 10 of those trees (i.e. 0.33%) but was considered “not significant” to be included as a detrimental factor of biomass yield when developing the allometric equations (Brazee et al., 2010; Luley et al., 2009). Instead; a “discount” factor of 0.8 was proposed to account for differences in biomass yield between urban trees and natural stands. As a result, models that are currently used to quantify stored carbon in urban trees do not take into account differences in biomass allocation nor the biomass loss due to internal decay (Koeser et al., 2016).

Urban trees are credited as suitable tools to reduce carbon emissions within cities, therefore accurate estimations of above-ground biomass that consider the volume loss due to decayed wood is key in accounting for the contribution of urban forests to carbon storage worldwide (Davies et al., 2011; McHale et al., 2009). When a tree is decayed the standing biomass decreases and its carbon stock declines, therefore, decayed trees become a source of carbon emissions affecting the net carbon balance of urban forests (Brazee et al., 2010; Cousins et al., 2015; Luley et al., 2009). Decay, and the hollows that result, are usually linked to ageing urban trees, yet previous research has documented a high occurrence of decay in trees of various size growing in a wide range of urban settings (Eisner et al., 2002; Koeser et al., 2016).

Luley et al. (2009) reported that decay occurred in *Acer.* spp. trees of different diameters (30-80 cm DBH) and damaged up to 25% of a tree’s cross-sectional area. The authors claimed that decay can take place early in the tree’s life, but is most severe in larger (and therefore older) trees that compartmentalize decay poorly. Likewise, Terho et al. (2008) examined the stage and extent of decay in 181 park and street trees and found that decay damaged between 70-

80 % of the trunk's cross-sectional area in some large trees. Recently, Koeser et al. (2016) examined the amount of decay presented in +400 *Quercus* spp. (DBH: 25-157 cm) and found that 58 % of sampled trees were significantly decayed or showed trunk's hollow of considerable size. These findings support the high occurrence of stem decay in urban trees regardless of tree size and location.

The assessment of decay is key element in arboriculture aim to maintain the stability and safety of trees in public spaces (Gilbert et al., 2004; Larsson et al., 2004). The science of detecting and quantifying decay in trees has evolved considerably over time. Decay can be detected from field visual assessment conducted by experienced arborists and for those trees deemed 'unsafe' the level of decay within cross-sectional discs can be evaluated from harvested trees (Koeser et al., 2016; Pearce, 2000), however; this requires whole tree destructive harvesting. Overall, visual inspections can be reliable ways to predict the presence of internal decay and hollows, but are limited in calculating the extent of decayed wood in standing trees (Koeser et al., 2016; Terho et al., 2005). New equipment and approaches may provide opportunities to more accurately assess the existence, distribution and extent of decay in urban forests without the need for destructive harvesting (Castello et al., 1999; Larsson et al., 2004; Leong et al., 2012). These new methods vary considerably in their invasiveness, interpretation and reliability (Johnstone et al., 2010a).

Among those methods, stem core sampling is the most common non-destructive technique that allows a rapid assessment of decay in standing trees, yet the coring holes may play a role for decay infection (Helliwell, 2007; Kersten et al., 2005). The use of less-invasive portable drills has been widely applied in urban contexts with consistent results (Koeser et al., 2016; Leong et al., 2012; Luley et al., 2009; Wang et al., 2008). In addition, an expert system that combines the “assessments” of drill outlines and the widely accepted model of “Compartmentalization of Decay in Trees” (CODIT) was developed and proposed as a reliable way to locate and calculate the area of decay in trees (Johnstone et al., 2007). Overall, visual assessment of tree vitality coupled with decay assessment is a well stablished approach aimed at documenting decay incidence in urban trees (Dobbertin, 2005; Johnstone et al., 2013). The aim of the present study was to detect the occurrence and calculate the extent of decayed wood along the stem in the three most abundant species (*Ulmus procera*, *Platanus x acerifolia*, *Corymbia maculata*) growing in the city of Melbourne. In addition, we wanted to explore the association of tree vitality index (Johnstone et al., 2012) and stand and tree attributes on the predictability of both decayed wood and volume loss in standing urban trees. To this end we addressed the following research questions: 1) Does decay wood progress in a similar pattern along the stem of the three species under study? 2) Does decayed wood occur only in large-mature trees within each species evaluated, and 3) Does the vitality index function as a reliable indicator of the occurrence and extent of decayed wood and volume loss among sampled species?.

Materials and Methods

Study site

The research was carried out in the City of Melbourne, Australia (Latitude 37°48’S, Longitude 144°57’E). The climate is “temperate” with uniform annual precipitation of 656 mm. The annual average temperature is 19.7°C. The highest average temperature is recorded in February (25.7°C) and the lowest in

July (13.4°C) (www.bom.gov.au). The City of Melbourne has a population of +100000 residents over 3760 ha of highly urbanized land. The city centre contains 486 ha of parks, 286 ha built space and 1112 ha of roads (City of Melbourne, 2012). The city council maintains more than 70,000 trees in both parks and streets. The City of Melbourne's urban forest has an average tree density is 26.5 ha^{-1} (±18 ha^{-1}) with a canopy cover of 12.3% (3-20%). The four most common species were *Eucalyptus camandulensis*, *Platanus x acerifolia*, *Ulmus* spp. and *Corymbia maculata* which together accounted for 29% of the total tree population (Dobbs et al., 2013).

The CODIT model and the assessment of decay

A framework for the present study is the CODIT (Compartmentalization of Decay in Trees) model by (Shigo, 1965) which states that decay spreads faster in a longitudinal direction (up or down the stem) rather than in a cross sectional direction (the diameter, since trees have four walls that isolate decay with variable "rate of success"). The CODIT theory is then applied as part of an "expert system" to assess wood decay similar to Johnstone et al (2007). The CODIT model also describes that the "capacity" of a tree to isolate decay is dictated by its vigour and vitality over time.

Tree measurements and vitality assessment

A total of 43 trees of the three most dominant species (*Ulmus procera*, *Platanus x acerifolia* and *Corymbia maculata*) in the Melbourne's urban forest were measured and assessed for vitality in summer 2015 (January-April). These trees were situated in parks, and general had stems >40 cm in diameter and a height between 15 and 20 m (Table 1). Trees were selected in conjunction with two skilled arborists and based on the following criteria: 1) species natural canopy structure, 2) located where a pedestrian risk was low, 3) trunk not obviously damaged due mechanical injury and, 4) safe tree climbing was possible.

Age structure of the sampled trees varied widely according to species. Most *U. procera* trees evaluated were over mature planted between 1900-1920 but a few juvenile trees were also sampled (2000-2010). *P x acerfolia* trees measured in this study were planted during 1950-1960 and included both mature and juvenile trees (1990-2000). *C x maculata* individuals measured were juvenile and mature trees planted during 1970-1980 (City of Melbourne, 2012).

Tree vitality was visually assessed (score 1 to 25) following the method devised by Johnstone et al. (2012). The method incorporates a score for crown position in relation to other trees, crown size, crown density, the number of dead branches and epicormic growth. Vitality index of sampled trees included individuals with medium vitality (15 points) to high vitality (more than 25 points). Tree vitality assessment was done during the 2014-215 growing season when trees exhibited the full canopy foliage. The range of age class, tree diameter, wood properties, and vitality index for the tree species evaluated is shown in Table 1.

Stem volume calculation

The main stem and branch taper diameter of each tree was measured (using a diameter tape) every metre from the ground to the top by two independent skilled arborists. All measurements were recorded in the field in cm. The top of the tree was defined as the stem/dominant branch reaching a diameter greater than 5 cm within the canopy. The standing volume of the main stem of each tree was then calculated using the Smalian equation:

$$V = (Ga + Gb)/2 * L$$

Where G is the cross-sectional area of the lower (a) and the upper (b) section of the stem, L is the length of the stem in meters, and V is the volume of the stem expressed in m^3.

Tree stem micro-drilling

Trees were micro-drilled using an IML PowerDrill® with the following specifications: diameter needle shaft: 1.5 mm, diameter needle tip: 3.0 mm and 40 cm in length. The drill feed speed (penetration) and needle speed (rotation) was adjusted according to the wood density of the species *(www.imlaustralia.com)*. The defined settings were 25 cm/min and 5000 rpm for *C. maculata*, 100 cm/min and 3000 rpm for *U. procera* and 50 cm/min and 3500 rpm for *P. x acerifolia*. All trees were micro-drilled at three fixed points (base-0.3 m, DBH-1.3 m, trunk-2.3 m) and a fourth point at the tree's live crown position. Taper diameter was taken from each point in order to calculate its corresponding cross-sectional area. At each point the tree was micro-drilled at between two to four axes, depending upon the stem diameter at that given point. Trees with diameter ≤ 80 cm were micro-drilled in two perpendicular axes (N, W); for those trees with diameter greater than 80 cm, three to four drilling axes were taken (N, E, S and W). The IML PowerDrill® was evenly positioned to perform the drillings at each position along the stem. In this study, a total of 300 micro-drilling profiles were used for decay assessments on 43 trees.

Assessing decayed wood

The process of decay assessment was 1) in each drilling profile, the “average curve” function in the IML PowerDrill® was activated to capture the overall trend in wood resistance, 2) segments with amplitude value of ≤ 5% were considered as decayed wood. Those segments with amplitude value of 0% were recorded as absence of wood, 3) only segments of decayed wood, segments of absence of wood and sections showing absence of “annual rings” greater than 1 cm were considered significant for decay assessment, 4) both “pockets” and larger areas of decay wood identified in each drilling profile were not considered linear but in fact circular or rounded. Thus, the area of decayed wood (expressed in cm^2) for each drilling point was calculated using the formula of either a circle or ellipse using AutoCAD (2017), 5) in order to account for volume loss, both categories of decay (decayed wood + absence of wood) was added as decayed wood within a single tree. The protocol to assess decay followed in this study is in line with the guidelines proposed by Mattheck et al. (1997) and in accord with the approach developed by Johnstone et al. (2007). A summary of the steps taken in the process is presented in Fig.1.

Decayed wood area and volume loss calculation

The extent of decayed area (cm^2) was calculated for each drilling point (Base, DBH, trunk, and live crown). In order to convert from decay area to decay volume (m^3) we apply the equation below:

$$VD_{TOTAL} = (AD_{BASE} + AD_{DBH}) * 1.3\text{ m}) + (AD_{DBH} + AD_{Trunk}) * 1\text{ m}) + (AD_{Trunk} + AD_{crown} * L)$$

where VD_{TOTAL} is the total volume of decay (m^3), AD_{BASE} is the cross-sectional area of decay at the base, AD_{DBH} is the cross-sectional area of decay at DBH point, AD_{TRUNK} is the cross-sectional area of decay at 2.3 m, AD_{CROWN} is the cross-sectional area of decay at the live crown position and L is the length (m) of the log between the trunk and the crown's point. The length varied from 1.3-3.3 m according to tree size and species' canopy structure. Finally, the volume loss estimated for each species/tree was then subtracted from the total standing volume of the main stem (m^3) per tree previously calculated. The conversion of volume (m^3) to carbon mass was determined by multiplying wood volume (m^3) x carbon factor. The carbon factor = Specific gravity x 1000 kg (weight of 1 m^3 of water) x ratio of percent C in the species (Brazee et al., 2010). Published specific gravity and %C values were used in the calculation of carbon loss (Lamlom et al., 2003; Miles et al., 2009).

Data management and statistical analysis

Simple linear regression analysis tested the correlation of the proportion of decayed wood against a vitality index and stem DBH. Descriptive statistics were generated to summarize the extent of decay along the trunk of the sampled trees. Trees severely decayed due to arboriculture treatments (heavy pruning) or branch loss due to strong winds or mechanical injury were considered as outliers, therefore these individuals were not included in the regression test against vitality index but were taken in to account for the calculation of the extend of decay along the stem. An explorative analysis was carried out seeking to identify variables that could predict the decayed volume loss in *U. procera*. This species was selected since the extent and distribution of decay were widespread along the trunk. A linear model was fitted to predict the actual volume loss in standing *U. procera* trees. In addition, a correlation matrix was devised in order to visually explore the potential effects that tree and stand attributes may have on the predictability of volume loss in standing trees.

Variables selected for correlation analysis were DBH (cm), total height (m), crown height (m), crown surface (m^2), stem volume (m^3), competition status (number of trees within 10 m radius) and vitality index. Simple linear regression tested the correlation of the proportion of volume loss (m^3) against a vitality index and stem DBH per species. All statistical analysis was performed in R (R Core Team, 2015).

Results

Occurrence of decay among species

In the whole sample of 43 trees, 37 trees (87%) showed some level of decay, 20 trees (47%) showed decayed wood and 12 trees (27%) showed absence of wood internally. Significant variation was found in the cross-sectional area affected by decay among the sampled species. Decay was more frequent and extensive in *U. procera*, than *P. acerifolia* and least in *C. maculata*. In *U. procera*, the cross-sectional area of decay at the base, DBH and trunk (2.3 m) positions was statistically different from the decayed area recorded for other two species but not for the live crown position. The cross-sectional area of decayed wood at the stem base was twice as large in *U. procera* than in the other two species. The decayed cross-sectional area at the DBH and trunk level was approximately 50% greater in *U. procera* than in the other two species (Fig. 2). The mean decayed cross-sectional area at the DBH point for *U. procera*, *P. x acerifolia* and *C. maculata* was 983 cm^2 (±625.2), 359.5 cm^2 (±545.2) and 255.6 cm^2 (±234.4), respectively. The maximum proportion of cross-sectional extent of decayed wood recorded at the DBH point ranged from 15.6% to 29.2% for all species. The cross-sectional area of decayed wood at the live crown position showed a decreasing trend according to the species since the extent of decayed was greater in *U. procera*, followed by *C. maculata* and least *P x* *acerifolia*. In both, *C. maculata* and *P. x acerifolia*, the extent of decay at the stem and live crown position was lower than 10%. In these last two species, decay was only present in the crown for individuals that had been severely pruned or had broken branches within their canopy. Appendix 1 provides a detailed summary of the extent of decay along the trunk of the three species.

Decay distribution within species

Decay was found to be distributed in three different ways in the three-species evaluated. In *U. procera*, decay was distributed as a column from the base to the live crown point, affecting on average 17.5% (±6.2%) of the cross-sectional area. In contrast, in *P. acerifolia*, decayed wood was distributed in a cone-shape affecting on average 7.5% (±2.3%) of the cross-sectional area from the base to the trunk position (2.3 m) (Fig. 2). In *C. maculata,* pockets of decayed wood of variable shape and size were distributed throughout the stem affecting on average 6.7% (±1.3%) the cross-sectional area from the base to the trunk position. Although, the distribution pattern of decay differed between *C. maculata* and *P x acerifolia*, the average value of the proportion of decayed wood along the trunk of both species was similar and ranged between 6%-9%.

Relationship between vitality index and decayed wood

The vitality index showed a weak but not significant correlation with the calculated proportion of decayed wood at the base (0.3 m) and DBH (1.3 m) positions along the stem of *C. maculata* and *P. acerifolia* but not for *U. procera* (data not shown). This suggests that wood decay is not correlated with tree vitality in *U. procera* and may occur even in visually healthy standing trees within the genera. However, since the relationship between vitality index and the proportion of decay area for *C. maculata* and *P. acerifolia* are reliant on two or three points, there is a risk of few points driving the statistical significance of the analysis.

Stem volume loss

The absence of wood as a result of decay significantly reduces the standing volume of all species examined. The average volume loss varied from 0.25 to 0.46 m^3, equivalent to 5 % to 13.8% of the actual stem volume per tree. The actual volume loss was more frequent and extensive in *U. procera*, than *C. maculata* and was least in *P. acerifolia*. In *U. procera* the proportion of volume loss along the stem (13%) was twice as large then the other two species. The average proportion of stem volume loss for *P. acerifolia* and *C. maculata* was less than 10%. The total volume loss calculated for all species ranged from 0.17-0.75 m^3, equivalent to 5 % to 25% of the stem volume (Table 2). The carbon loss due to decayed wood ranged between 69 to 110 kg per tree and was more severe in *U. procera*, then *C. maculata* and least in *P x acerifolia*.

Relationship between vitality index, diameter and stem volume loss

Decayed area (cm^2) and volume loss (m^3) were two different calculations made in this study. The former is the cross-section area affected by decay at a given point along the stem of the sampled trees, and the latter is a calculation derived from the totalled decayed area within a tree. In our study, no significant relationships were found between vitality index and the volume loss for all species (data not shown). This suggests that internal volume loss is not correlated with tree vitality in *U. procera, P. acerifolia* and *C. maculata*. However, in *U. procera*, a strong and significant relationship was found between DBH and stem volume loss. Since decayed volume loss within *U. procera* trees was distributed as central column from the base to the live crown position, the relationship detected was quite linear regardless of the vitality index (Figure 3). In general terms, the larger the stem tree diameter (range of 55-110 cm), the greater the volume loss internally. In *P. acerifolia*, the relationship between volume loss and DBH was weak and not significant, while in *C. maculata* the association between DBH and stem volume loss was absent.

In *U. procera,* DBH (cm), vitality index and competition status (number of trees within 10 m radius) showed a relative importance value of R=0.84, R=0.61 and R=0.35; respectively (Figure 4). Moreover, Individual categories within the vitality index score such as crown density and presence of dead branches within the tree canopy also showed a moderate and positive association with internal volume loss (R=0.45, R= 0.56, respectively). The linear model that better projected the actual volume loss in standing *U. procera* trees was $Y = 0.0074x - 0.1279$ ($R^2= 0.8006$, $P= 0.0046$, $n=15$). Based on model's calculation, the standing volume of *U. procera* trees with DBH ≥ 40 cm needs to be discounted by a factor of 13% due to the extent of internal decayed wood regardless of the species vitality index.

Discussion

Decay distribution pattern along the trunk

In this study the assessment of drilling profiles coupled with advanced climbing techniques, both framed in the CODIT model, allowed us to map and quantify the distribution of decay along the stem of standing trees. Based on our findings we demonstrated that decay reduces significantly (between 5-25%) the standing volume of the three most abundant species in the city of Melbourne. The presence and extent of decay differed according to tree species. As expressed in the CODIT model, the occurrence of decay among species found in this study are suggestive of the species-capacity to limit the longitudinal spread of decay (Boddy, 1994; Shigo, 1965). In this study, decay was found to be distributed in three different ways in the three-species evaluated. For *U. procera,* decay did appear to spread as a column whereas, decay spread as a cone-shape in *P. acerifolia* and in *C. macualta* decay was distributed as pockets of variable shape and size. Similar patterns of decay progression have been documented in several species using different equipment and approaches. Larsson et al. (2004) reported cone-shape decayed regions extending up to 2 m along the stem of standing Norway spruce (*Picea abies*) trees. Pockets of decay at the trunk's base (0.3 m) of 36 *Eucalyptus saligna* trees were reported by (Johnstone et al., 2010b). Although the sample size was quite small (five trees), Castello et al. (1999) reported central columns of decayed wood of considerable size in mature (> 75 years old) Scotch elm (*Ulmus glabra*).

Decay affects a wide range of stem tree diameter

Decayed wood is usually associated with ageing trees with poor vitality (Dobbertin, 2005; Koeser et al., 2016). However, our study confirmed that decay occurs across a wide range of tree stem diameters and tree size regardless of their vitality index. Based on our results, it seems that decay is a significant issue for both large mature trees as well as younger trees, and can reduce the carbon storage potential of urban trees. Likewise, Koeser et al. (2016) found that the likelihood of the presence of decay in *Quercus* spp. increased in with tree diameter, however; as tree diameter increased past 75 cm, the probability of incidence of decay declines. In *U procera*, the maximum proportion of the decayed cross-sectional area recorded at the DBH point ranged from 15% to 33%, which based on strength loss assessment, all trees are within the caution zone and must be evaluated with respect to other defects that could contribute to the hazard (Kane et al., 2004). The strength loss due to decayed wood of the other two species do not represent any hazard.

Wood density also has a role to play in limiting the distribution of decay along the trunk of evaluated trees (Cousins et al., 2015). While it is acknowledged that wood decay is not dependant on tree vitality, trees with both very low vitality and low wood density value may be more susceptible to internal decay in urban environments. Moreover, trees with medium vitality and medium wood density may limit the spread of decay with greater rate of success. In contrast, trees with high vitality and high wood density value seem to be successful in isolating decay internally (Harper et al., 2005; Terho et al., 2005). In this regard, *U. procera*, ranked as hardwood with a density of 0.53-0.58 g/cm^3 is expected to be decay resistant. Similarly, *P. acerifolia*, also classified as hardwood but with higher density (0.62-0.67 g/cm^3) was less decayed than *U. procera* and similar to that estimations made for *C. maculata*, a native species with high wood density values (0.57-0.63 g/cm^3) (Lamlom et al., 2003; Miles et al., 2009).

Arboricultural treatments aim to maintain the amenity and safety of trees in public places play a key role in preventing or spreading decay in living trees (Ellison, 2005; Pearce, 2000). In our study, decay was detected at the base, DBH, stem and crown positions of *U. procera* but was less likely to be distributed beyond a height of 2.3 m in *P. aceriolia* and *C. maculata*. In these last two species, decay was only present at the crown position for those individuals that had been severely pruned or had broken branches within their canopy. Branch morphology impacts compartmentalization of pruned or broken branch wounds. For instance, Gilman et al. (2006), claimed that the presence of branch collar in *Acer rubrum* and *Quercus virginiana* was an indicator of strong compartmentalization potential. In addition, branch size seems to affect tree's capacity to compartmentalize pruning wounds, since the removal of large limbs and branches resulted in severe stem discoloration of juvenile *Q. virginiana* and *A. rub*rum (Eisner et al., 2002). *P. acerifolia* evaluated in this study appeared to lack a branch collar and therefore, the species may be unable to generate a branch protection zone (BPZ) when large branches or even limbs are removed.

All *P. acerifolia* trees sampled in this study were situated in parks, however; a large number of street *P. acerifolia* trees in Melbourne city are subject of major pruning and branch removal regime to avoid conflict with infrastructure and power lines, consequently they are more likely to be more affected by internal decayed wood (Ryder et al., 2013) than trees evaluated in our study. In contrast, *C. maculata* trees appeared to have branch collar, hence, the species is capable of create BPZ and limit decay originated from branch removal due to regular tree care.

Visual vitality index as a reliable proxy for stem volume loss calculation

In our study, both decayed area (cm^2) and volume loss (m^3) do not shown any significant association with the vitality index of *U. procera* trees. This finding suggests that, regardless of the tree's vitality status, decay might occur, and can occur at any point along the stem. However, in *U. procera* volume loss was strongly linked with stem diameter, which based on our results the species can be ranked as poor compartmentaliser of decay. The three species evaluated in this study were situated in parks under relatively favourable growing conditions such as regular irrigation, application of mulch and, formative pruning. As such, our 43 sampled trees were restricted to individuals with medium (15 points) to high vitality (more than 25 points). Sampling several trees in different planting sites (streets, car parks, roads, boulevards, etc.), showing low vitality index (≤ 10 points) and including a wider age classes (juvenile, mature, over mature trees) may have allowed us to better test whether the vitality index can be a good predictor of volume loss in stronger compartmentaliser of decay such as *C. maculata* and *P. acerifolia* (Cedro et al., 2006).

The visual vitality index proposed by Johnstone et al. (2012) and used in this study to assess tree vitality does not take account of external signs of decay such as fungi fruiting bodies along the trunk, cranks and wounds, therefore; no association between causal agent and the extent of decayed wood estimated among and within species can be drawn. In contrast, Koeser et al. (2016) found that a visual decay factor that encompassed all the visual indicators of decay was effective (70% of predictability) in in identifying decay presence in *Quercus* spp with diameter range of 45-75 cm.

The exploratory correlation analysis performed for *U. procera* trees suggests that a set of tree and stand attributes (DBH, tree height, crown diameter, vitality index and competition status) can be used as predictors of volume loss calculation in standing trees. The linear model constructed in this study was quite strong (R^2= 0.8006, *P= 0.0046*), however; since the sample size is small (n=15), its predictive power and extrapolation potential are considered limited. A further assessment that includes a greater sample size and different planting sites may assist in the development of a more robust and reliable model.

Scope and limitation of the volume loss calculation approach

Although, the premises assumed in our study to derivate volume loss from decay area were valid and framed in the CODIT model, errors in the calculation of internal volume loss is an entirely reasonable assumption. Our calculations of volume loss using the Smalian equation added the segments of decayed wood at a given point and assumed that decay was distributed as truncated cone from one drilling point to another, regardless of the species' particular pattern of decay registered. A constant drilling distance of 1 m along the trunk until the crown positon is reached might allowed us a more accurate estimation of both the decayed area and the internal volume loss. In addition, In our study we did not take into account changes of wood density along the trunk, limbs and branches which in turn may affect the distribution patter of internal decay in trees (Brazee et al., 2010; Henry et al., 2010; Luley et al., 2009). In order to account for the cross-sectional distribution of decay, each tree's position was micro-drilled at between two to four axes according to the stem diameter, however; since the length of the needle was only 40 cm and, for those trees with diameter ≥ 80 cm, the drilling profiles evaluated for decay may not accurately detect the maximum extent of decay in the cross-sectional area of each drilling point. The extraction and assessment of trunk' discs is the best way to this end (Johnstone et al., 2010b; Terho, 2009). Even though, the vitality index used in this study accounted for dead branches within the tree canopy, we did not tested the occurrence and extend of decay in large branches which may increase the whole tree volume loss (Eisner et al., 2002; Gilman et al., 2006; Heikura et al., 2008). Overall, the methodological approach followed in this study constitutes a significant step in urban forestry science which advances our knowledge on the assessment of decay and stored carbon.

Conclusions

Decay is a significant issue in *Ulmus procera*, *Platanus x acerfolia* and *Corymbia maculta* trees and may occur in a wide range of diameter, tree size and vitality index. The distribution pattern and extent of decay documented in this study was species-dependant and can be aggravated by arboticultural practices. Based on our results, it seems that decay reduces the storage carbon potential of urban trees in the city of Melbourne. The research protocol described in this study may be useful in documenting and quantifying the occurrence and extent of decay in several urban trees. Calculations of stored carbon by urban trees need to be discounted by a species-decay factor rather than a standard factor that account only for differences in biomass yield between natural and urban trees. The detrimental effect of decayed wood on the standing volume of urban trees cannot longer be overlooked and need to be considered to better assess urban tree benefits.

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Appendix 1: Summary statistics of cross-sectional area and the extent of decayed wood along the stem of urban trees (*Ulmus procera*, *Platanus x acerifolia*, *Corymbia maculata*) growing in the city of Melbourne, Australia.

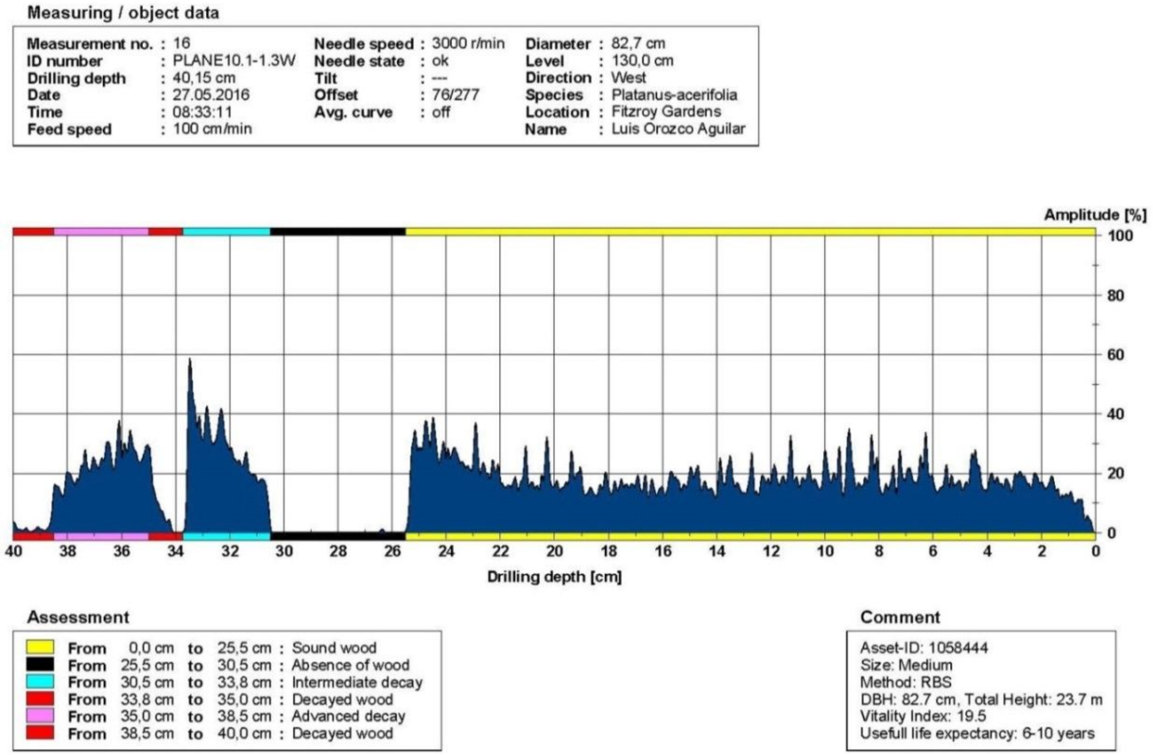
Species	**Drilling Point**	**Mean cross-sectional area (cm^2)***	**Mean cross-sectional extent of decayed wood*(cm^2)**	**Mean proportion of decayed area (%)**	**Maximum extent of decay (% from cross-sectional area)**
U. procera	Base (n=15)	7325.5 (4197.4)	1424.4 (879.2)	19.6 (5.7)	28.6
	DBH (n=15)	5471.3 (3315.2)	982.9 (625.2)	17.6 (5.9)	29.2
	Trunk (n=15)	5582.0 (3448.9)	908.9 (599.3)	15. 8 (6.6)	27.2
	Crown (n=15)	5610.2 (3217.2)	969.8 (426.2)	18. 9 (4.5)	27.4
P. x acerifolia	Base (n=13)	6837.9 (4404.8)	829.0 (1432.9)	8.4 (13.6)	49.3
	DBH (n=13)	4573.0 (3268.8)	359.5 (545.2)	6.2 (9.6)	32.6
	Trunk (n=13)	4551.9 (3433.3)	283.7 (332.2)	5.2 (5.8)	18.2
	Crown (n=5)	4382.7 (2587.7)	473.6 (480.5)	9.5 (10.6)	26.0
C. maculata	Base (n=15)	4589.3 (3590.8)	418. 8 (399.2)	8.6 (3.4)	14.2
	DBH (n=15)	5249.7 (8242.1)	255.6 (234.4)	8.1 (3.0)	15.6
	Trunk (n=15)	2975.0 (2477.7)	227.2 (255.0)	7.5 (3.6)	13.0
	Crown (n=11)	2567.3 (2515.6)	146.8 (193.4)	5.1 (3.4)	10.2

*Values in parenthesis represent the standard deviation of each calculation.

Appendix 2: Detailed description of the process for decay assessment followed in this study.

The process for decay assessment was:

1. Drilling distance as shown in the X axis in the above image is the actual drilling depth across the tree's diameter. The drilling depth of the IML PowerDrill® is 40 cm.
2. The y-axis of the drilling profile describes the drilling resistance in % (amplitude height) and the x-axis describes the actual drilled depth in cm.
3. Each drilling profile was separated into six sections as follow: 1) sound wood, 2) intermediate decay, 3) advanced decay, 4) decayed wood and 5) absence of wood. All sections were color-coded and labelled. The profile distance of each section was recorded in cm (Figure 1).
4. A minimum distance for which variations of wood resistance (either positive or negative) showed in the drilling profile will be set up. In this study, only segments of decayed wood or segments of absence of wood greater than 1 cm were considered relevant within the assessments.



Measuring / object data

Measurement no. : 16
ID number : PLANE10.1-1.3W
Drilling depth : 40,15 cm
Date : 27.05.2016
Time : 08:33:11
Feed speed : 100 cm/min

Needle speed : 3000 r/min
Needle state : ok
Tilt : ---
Offset : 76/277
Avg. curve : off

Diameter : 82,7 cm
Level : 130,0 cm
Direction : West
Species : Platanus-acerifolia
Location : Fitzroy Gardens
Name : Luis Orozco Aguilar

Assessment

🟨	**From**	0,0 cm	**to**	25,5 cm	: Sound wood
⬛	**From**	25,5 cm	**to**	30,5 cm	: Absence of wood
🟦	**From**	30,5 cm	**to**	33,8 cm	: Intermediate decay
🟥	**From**	33,8 cm	**to**	35,0 cm	: Decayed wood
🟪	**From**	35,0 cm	**to**	38,5 cm	: Advanced decay
🟥	**From**	38,5 cm	**to**	40,0 cm	: Decayed wood

Comment

Asset-ID: 1058444
Size: Medium
Method: RBS
DBH: 82.7 cm, Total Height: 23.7 m
Vitality Index: 19.5
Usefull life expectancy: 6-10 years

Figure 1. Drilling profiles from the IML PowerDrill® drill used to assess decayed wood in urban trees.

5. Those sections within the drilling profiles showing absence of "annual rings" were also considered as being decayed wood.

6. In each drilling profile, the "average curve" function in the IML PowerDrill® assessing tools package was activated to capture the overall trend in wood resistance corresponding to the species under study regardless of the drilling point and tree size.

7. Once the average curve was devised, decayed wood assessments were done identifying and labelling segments within the drilling profiles showing “evident” decrease in wood resistance.
8. A segment with amplitude value 5% and 10% below the “average curve” was considered as intermediate and advanced decay, respectively.
9. The drilling amplitude for the tree below which decayed wood will registered was set up. Here we suggested that amplitude below 5% is recorded as decayed wood.
10. An amplitude value of 0% was considered as “absence of wood” within the drilling profile. In order to account for volume loss calculations, both categories (decayed wood + absence of wood) of decayed were labelled and added as DECAYED WOOD in each drilling point.
11. From the drilling profile showed in Figure 8 we can identified the following decay classes: from 0 to 25.5 cm is sound wood, denoted as yellow, from 25.5-30.5 cm is absence of wood, presented as black, from 30.5 to 33.75 cm is intermediate decay labelled as light green, from 33.75 to 35 cm is decayed wood reported as red, from 35 to 38.5 is advanced decay recorded as purple and from 38.5 to 40 cm is mapped again as decayed wood.
12. In this study, “pockets” of decayed wood identified was not considered linear but in fact circular or rounded. Thus, the area of decayed wood (expressed in cm^2) in each drilling point was calculated using the formulae of either a circle or ellipse.
13. All drawings and area calculations were done in AutoCAD 2016. Figure 1 shows the resulting drawings combining four drilling axes (N, S, E, W) taken from a *P x acerifolia* tree.

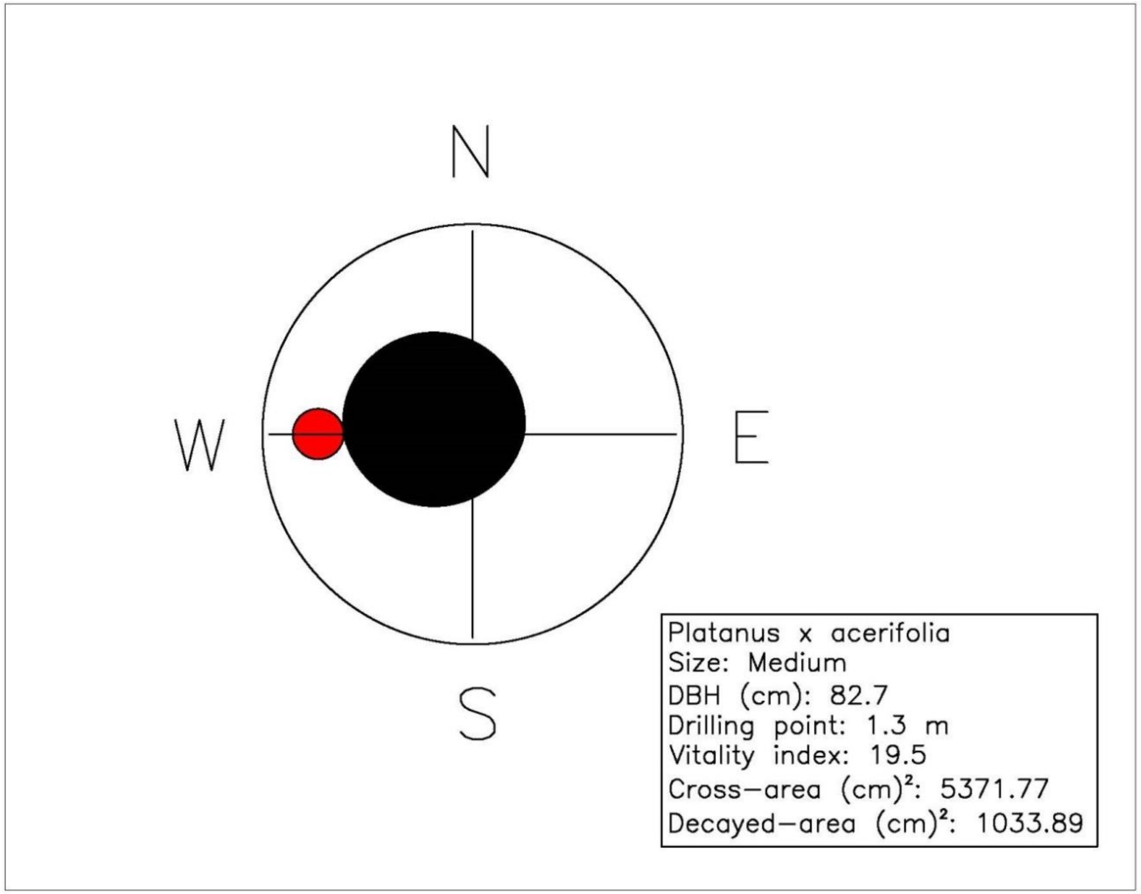
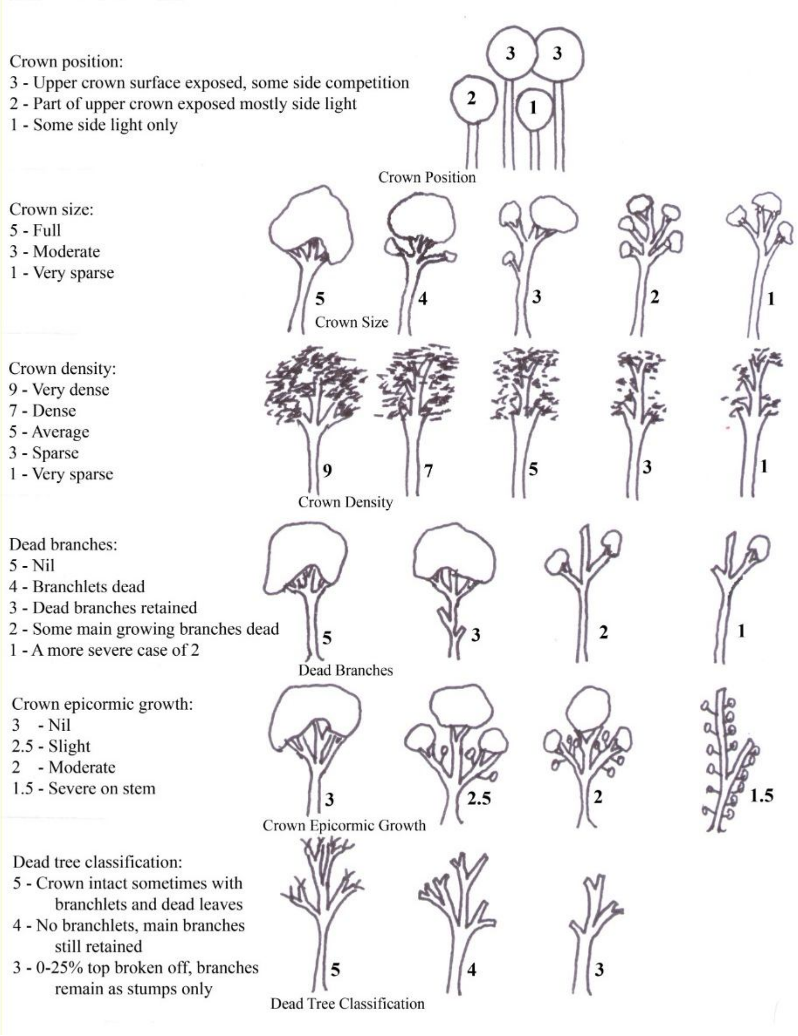


Figure 2. Visual representation of the cross-sectional area and decay area calculated using AutoCAD2016. The drawing correspond to a medium size *P x acerofilia*, with diameter of 82.7 cm and a low vitality index of 19.5. The calculated cross-sectional area was 5371.77 and the resulted decay area was

1033.89 (19.25%) of the cross-sectional area at the DBH (1.3 m) drilling point. The black circle represents absence of wood and the red circule denotes decayed wood.

Appendix 3. Diagrammatic representation of the visual vitality index assessment followed in this study (Johnstone et al., 2012).



Crown position:
3 - Upper crown surface exposed, some side competition
2 - Part of upper crown exposed mostly side light
1 - Some side light only

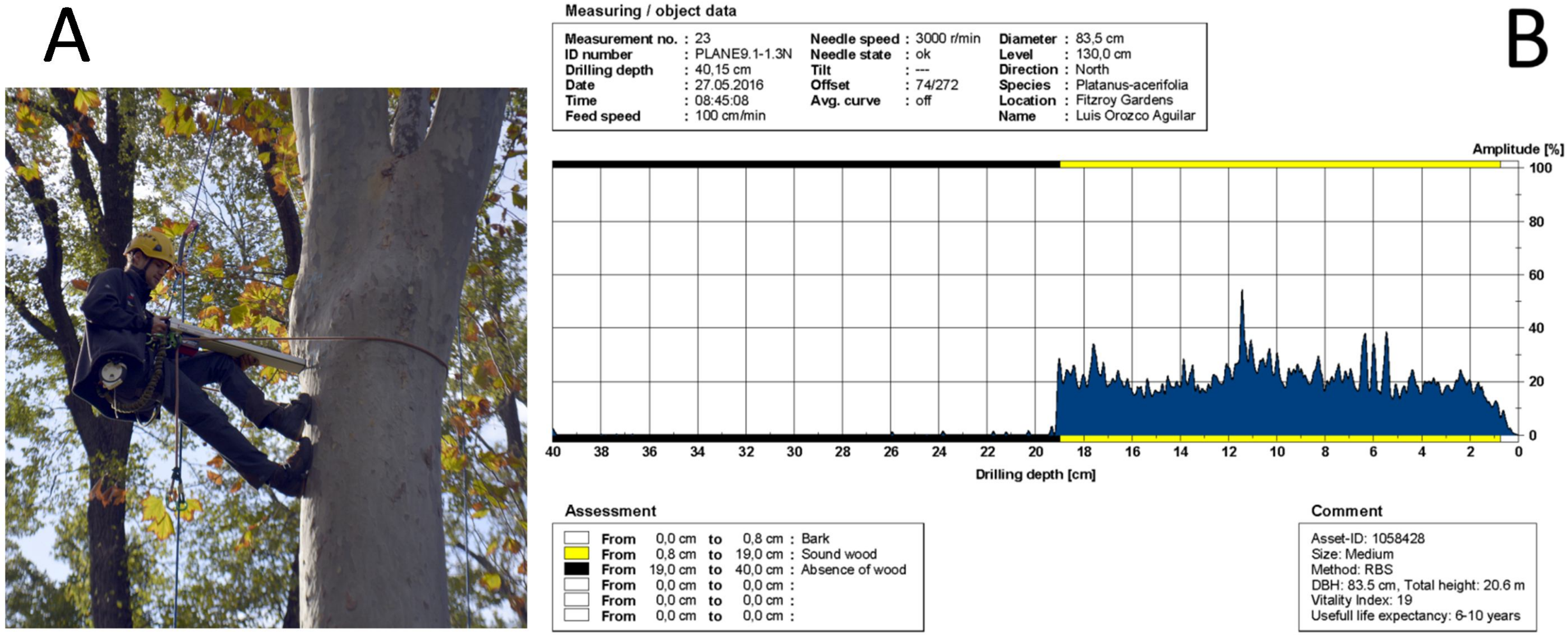
Crown size:
5 - Full
3 - Moderate
1 - Very sparse

Crown density:
9 - Very dense
7 - Dense
5 - Average
3 - Sparse
1 - Very sparse

Dead branches:
5 - Nil
4 - Branchlets dead
3 - Dead branches retained
2 - Some main growing branches dead
1 - A more severe case of 2

Crown epicormic growth:
3 - Nil
2.5 - Slight
2 - Moderate
1.5 - Severe on stem

Dead tree classification:
5 - Crown intact sometimes with branchlets and dead leaves
4 - No branchlets, main branches still retained
3 - 0-25% top broken off, branches remain as stumps only



Measuring / object data

Measurement no. : 23
ID number : PLANE9.1-1.3N
Drilling depth : 40,15 cm
Date : 27.05.2016
Time : 08:45:08
Feed speed : 100 cm/min
Needle speed : 3000 r/min
Needle state : ok
Tilt : ---
Offset : 74/272
Avg. curve : off
Diameter : 83,5 cm
Level : 130,0 cm
Direction : North
Species : Platanus-acerifolia
Location : Fitzroy Gardens
Name : Luis Orozco Aguilar

Assessment

☐	**From**	0,0 cm	**to**	0,8 cm	:	Bark
🟨	**From**	0,8 cm	**to**	19,0 cm	:	Sound wood
⬛	**From**	19,0 cm	**to**	40,0 cm	:	Absence of wood
☐	**From**	0,0 cm	**to**	0,0 cm	:	
☐	**From**	0,0 cm	**to**	0,0 cm	:	
☐	**From**	0,0 cm	**to**	0,0 cm	:	

Comment

Asset-ID: 1058428
Size: Medium
Method: RBS
DBH: 83.5 cm, Total height: 20.6 m
Vitality Index: 19
Usefull life expectancy: 6-10 years

Figure 1. Methodological approach followed in this study to assess the occurrence and calculate the extent of decayed wood along the trunk of *Platanus x acerifolia*. The left picture (A) shows the arborists micro-drilling at the tree's live crown position. The right picture (B) displays the decay assessment done using the IML PowerDrill® tools. The drilling profile shown here has 40 cm in length and corresponds to the live crown position at a north axis. The drilling height and stem diameter at the live crown position were 5.3 m and 83.5 cm, respectively. (Photo taken by Luis Orozco Aguilar).

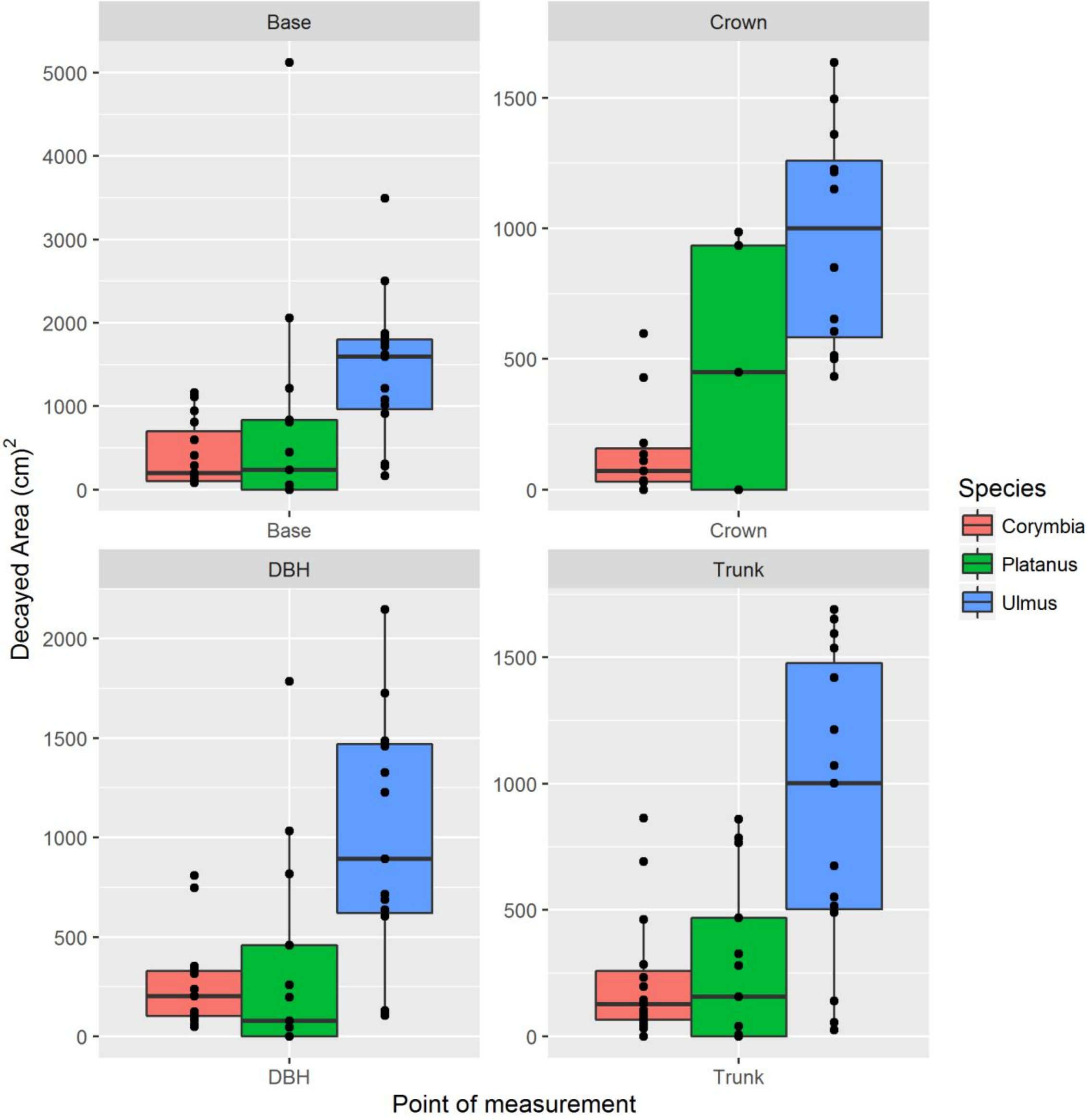


Figure 2. Box plots of the cross-sectional area of decayed wood in urban trees (*Ulmus procera, Platanus x acerifolia, Corymbia maculata*) growing in the city of Melbourne, Australia. Decayed wood was measured at four points up the stem: Base= 0.3 m above ground, DBH= 1.3 m, Trunk= 2.3 m and Crown+ variable mid-crown position (3.3-6.8 m).

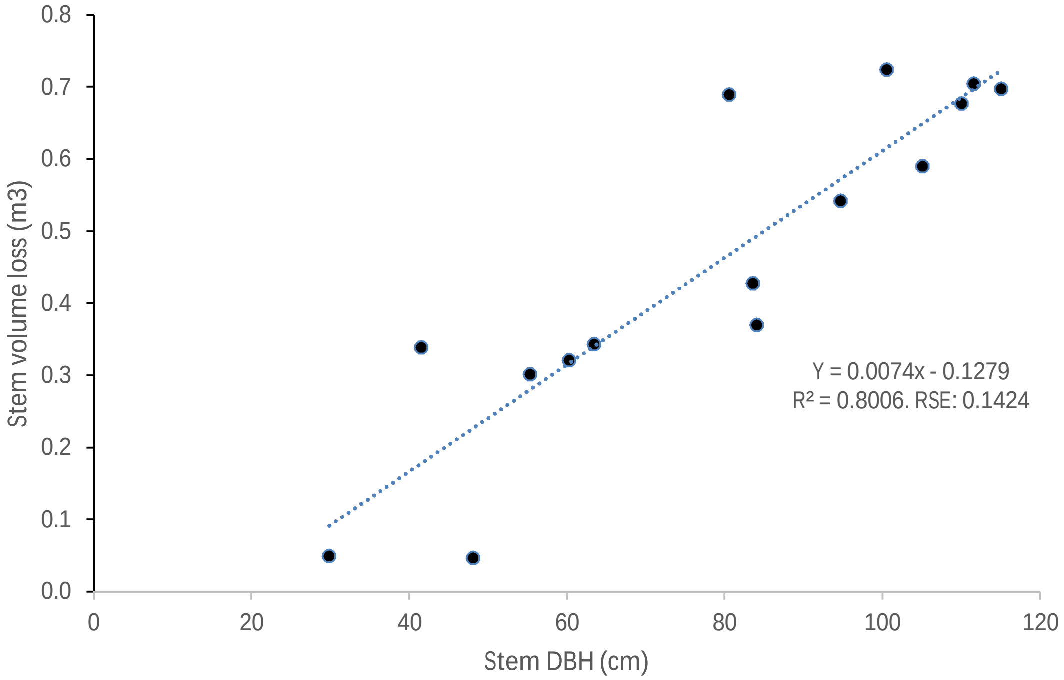


Figure 3. Diameter at breast height (Stem DBH) versus stem volume loss (m^3) for *U. procera* trees growing in parks in the city of Melbourne, Australia. The regression coefficients and related statistical values were as follow: Y = 0.0074x - 0.1279 (R^2= 0.8006, P= 0.0046) where: Y is volume loss (m^3) and X is DBH (cm). RSE: Residual standard error.

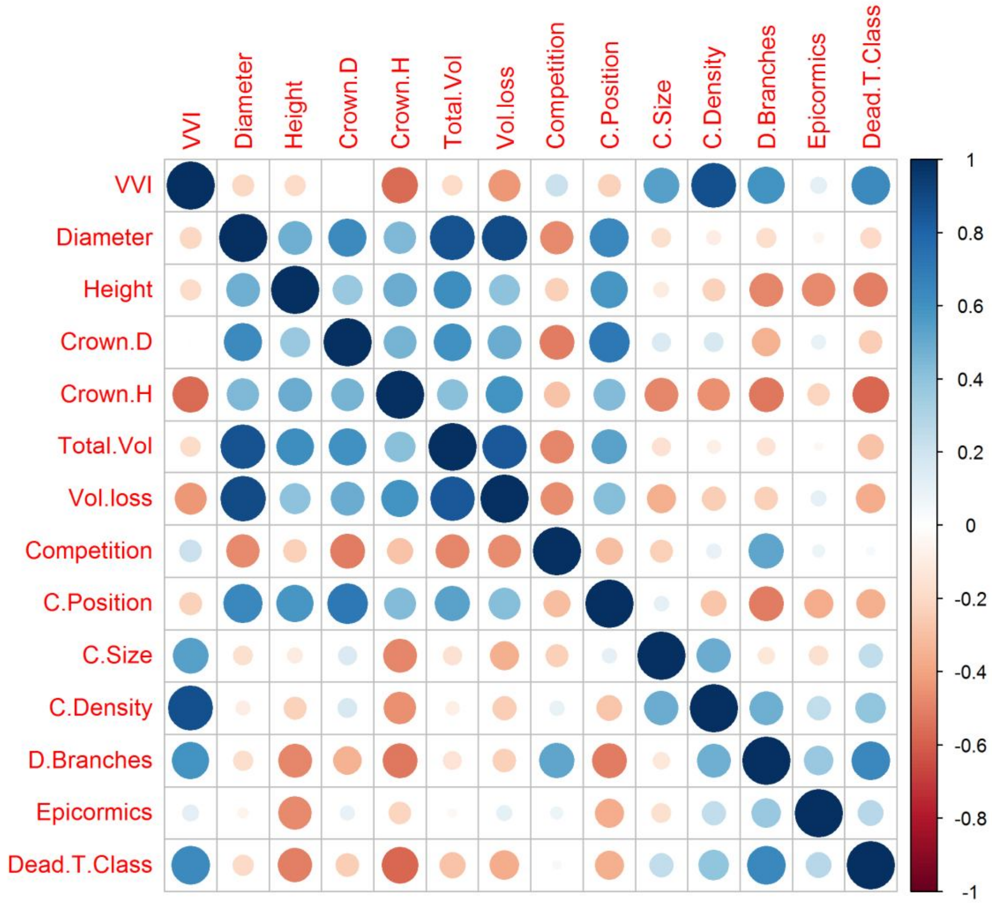


Figure 4. Correlation matrix of stand and tree attributes with potential effect on the predictability of volume loss (m^3) in standing *U. procera* trees growing in the city of Melbourne, Australia. Blue colour represents a positive correlation between paired variables and red colour denotes a negative correlation. The bigger and the darker the colour of the circles, the stronger the correlation between paired variables. Description of the matrix's variables as follows: VVI (visual vitality index), C-Density (crown density), C-size (crown size), Crown-H (crown height), Total.Vol (total stem volume), Vol.loss (volume loss due to decay), C-position (crown position), Competition (number of trees within 10 m radius), D-Branches (retained branches within the canopy), Epicormics (presence of epicormics along the trunk and canopy), Dead-T-class (overall dead tree class).

Table 1: Number of individuals, tree attributes and wood properties of three urban species (*Ulmus procera, Corymbia maculata, Platanus x acerifolia*) included in the study.

	U. procera	***C. maculata***	***P. x acerifolia***
No. of trees	15	15	13
DBH (cm)	80.6 ± 14.8	64.3 ± 24.7	70.2 ± 30.2
Tree height (m)	14.8 ± 3.2	17.3 ± 3.4	17.5 ± 6.5
Stem volume (m^3)	3.6 ± 1.8	5.8 ± 4.7	3.5 ± 2.5
Vitality Index*	20 (17-24)	25 (19-27)	23.5 (20-28)
Age class	Over mature	Mature/Juvenile	Mature/Juvenile
Specific density (g/cm^3)**	0.53	0.62	0.57
Carbon content (%)***	0.4632	0.4963	0.4997

*Values in parenthesis represent the range of vitality index recorded for each species. ** Species-specific wood density values reported for natural stands in the USA (Miles et al., 2009). *** Average value for hardwood species (Lamlom et al., 2003).

Table 2. Summary statistics of internal decayed volume loss in urban trees (*Ulmus procera, Corymbia maculata, Platanus x acerifolia*) growing in parks in the city of Melbourne, Australia.

	U. procera **(n=15)**	***C. maculata*** **(n=15)**	***P x acerifolia*** **(n=13)**
Total stem volume (m^3 $tree^{-1}$)	3.5 (1.8)	6.0 (4.7)	3.52 (2.4)
Average decayed volume loss (m^3 $tree^{-1}$)	0.46 (0.2)	0.30 (0.2)	0.25 (0.15)
Proportion of internal volume loss (%)	13. 8 (4.7)	6.60 (4.8)	5.63 (4.5)
Maximum proportion of internal volume loss (%)	23.9	18.2	12.4
Carbon loss (kg $tree^{-1}$)*	111.8 (56.2)	94.0 (68.5)	69.2 (48.2)

Values in parenthesis represent the standard deviation of each calculation. * Based on the equation: kg of carbon = wood volume × carbon factor; where carbon factor = SG × 1 000 kg (weight of 1 m 3 of water) × ratio of per cent C (Brazee et al., 2010).