Greening Australia

Plant Smart

A VEGETATION MANAGEMENT PARTNERSHIP

ERGON ENERGY

An assessment of tree susceptibility and resistance to cyclones

A study based on Severe Tropical Cyclone Yasi

2nd February 2011

Proudly sponsored by Ergon Energy and Townsville City Council

City of Townsville

our vision

A healthy, diverse and productive environment treasured by the whole community.

our mission

To engage the community in vegetation management to protect and restore the health, diversity and productivity of our unique Australian landscapes.

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Executive Summary

Townsville has a continuous history of cyclonic events, varying considerably in frequency and the interval between events. On average, the 100km long Townsville coastline can expect to get 8-10 cyclone crossings per decade. Since Townsville's first recorded cyclone in 1867, the city itself has experienced at least 18 cyclonic events. The most severe cyclone in living memory was Category 3 Cyclone Althea in December 1971, and there are no records available to suggest a stronger cyclone has hit Townsville since European settlement. Considerable property damage and loss of life has occurred in Townsville during past cyclones, primarily due to the effects of storm surge and flooding.

The landfall of Category 4 Cyclone Yasi on Mission Beach in February 2011 had significant impacts on Townsville, as the exceptionally large diameter of the cyclone resulted in Townsville experiencing winds equivalent to a Category 2 event and an accompanying storm surge. Unconfirmed reports suggested that approximately 65,000 trees were blown over in Townsville, causing widespread power failure and blockage of roads. Following the cyclone, a total of 450,000 cubic metres of green waste was collected, in addition to the 30,000 loads of green waste deposited by residents.

Despite the damage caused by cyclone-affected trees, trees can have significant benefits during cyclones. The benefits may include reducing wind loading on buildings, intercepting potentially lethal flying debris, offering protection to other plants, reducing erosion along flooded rivers or storm-damaged beach fronts, and potentially even preventing the loss of rooves from buildings. Windbreaks are particularly valuable in absorbing the energy from wind gusts as the force of wind increases as a cube of its velocity, so even minor reductions in wind speed can have significant benefits for buildings. Flying debris is one of the most significant causes of death and property damage during cyclones and the role of trees in immobilising this material is widely recognised. The removal of trees from around buildings can leave them exposed to cyclone damage, and increase the likelihood of debris from that structure damaging other structures further downwind. Careful species selection is necessary to ensure that vegetation captures rather than contributes to flying debris.

Trees have been shown to vary significantly in their response to cyclones, and this study aims to evaluate the relative responses of different species to such events. While loss of foliage and branches can be nearly 100% during severe category cyclones, the failure of the trunk and roots is of greatest significance. Susceptibility to trunk snapping varies between species due to differences in wind resistance, trunk flexibility, wood density, crown symmetry and the presence of hollows, often caused by termites. The damage itself can arise from tension (pulling), compression or torsion (twisting). An 'adaptive growth hypothesis' has been developed to explain how trees adapt to the wind loading in their environment, so planting advanced trees or staking trees may deny them the opportunity to develop sufficient strengthening. Most tree species sit on a gradient or spectrum between 'resistance' (ability to withstand disturbance) and 'resilience' (ability to recover from disturbance), and this is strongly correlated with wood density and growth rates. Natural ecosystems tend to have a combination of the two strategies to maximise the options for recovery from disturbance.

Uprooting (wind throw) is a result of failure of the root system. The root / shoot ratio for some trees decreases with maturity, so taller trees become top heavy and more prone to wind throw. Roots may have reduced depth due to either intrinsic or environmental factors and the resulting shallow roots will make them susceptible to waterlogging. The physical extent of the root system is of great importance in preventing windthrow. In urban areas, trees may be increasingly susceptible to windthrow. Trees may have compromised root systems at the time of planting, be planted into an impenetrable substrate or develop shallow roots in response to shallow watering regimes. Planting trees close together provides them advantages from mutual support, but increases their chances of being damaged from adjacent falling trees and debris.

Following Cyclone Yasi, Greening Australia collected tree damage data between Ayr and Mission Beach to capture the effects of different wind speeds, though the majority of data was collected in Townsville. The primary questions examined were to identify which species contributed the most to vegetation damage in Townsville, which species contributed the most to cases of power failure, which trees suffered the highest proportion of damage in parks and roadside corridors, and how different tree species responded along the gradient of increased wind speed.

The most common form of tree damage in Townsville was uprooting, followed by snapped trunks and broken branches. Large trees contributed the most to uprooting and snapped branches. Although the sample of damaged trees in Townsville included 2,584 trees in 151 species, it was shown that damage occurred primarily in a small number of species. After incorporating the influences of tree size and damage type to generate a ‘green waste score’, it was seen that 55.35% of green waste was generated by five species:

- yellow flame tree (*Peltophorum pterocarpum**);
- African mahogany (*Khaya senegalensis**);
- river blue gum (*Eucalyptus tereticornis*);
- weeping fig (*Ficus benjamina*); and
- pink trumpet tree (*Tabebuia impetiginosa ** *(*syn*. T. palmeri)*)

All size classes of trees suffered damage, though the greatest numbers of damaged individuals were large trees but the relationship between tree size and cyclone damage within a particular species cannot be established from this data. While exotic species (not native to Queensland) contributed more than twice as much green waste as non native trees, there are both resistant and susceptible species amongst both native and exotic trees.

Despite the ‘Plant Smart’ Ergon Energy partnership with Greening Australia to assist in vegetation management around powerlines, a survey of power failures in Mundingburra and Aitkenvale showed 95.45% were caused by vegetation, with 42.85% caused by yellow flame trees. While the Plant Smart program has aimed to reduce the height of plants grown under and around powerlines, 85.7% of the offending trees fell from the opposite side of the road, and 81% of the trees were growing on the public nature strip, rather than in private gardens.

Examination of parks and roadside avenues of trees also showed that trees varied considerably in the percentages damaged, but also showed that the proportion of damaged trees varied from one location to another. While the percentage of trees damaged increased with wind speed, there was noticeable variation even between different locations in Townsville. Different explanations for these variations are explored. Damage to the tree species identified as being the biggest contributors to green waste were generally identified as being amongst those suffering the highest proportional losses.

Impacts of cyclonic winds and storm surge were examined at seven locations, including one damaged by Cyclone Ului in 2010. Levels of damage were minimal under Category 1 impacts, but the proportion of undamaged trees generally decreased as wind speed increased. Comparison of the responses of the total vegetation communities showed few clear and identifiable trends, while obvious yet different trends exist in different individual species.

It was also possible, based on observations along the wind profile and from reports on previous cyclones, to generate a description of the indicative effects of different categories of cyclones, to complement the list of typical indicative effects on houses, infrastructure and crops regularly distributed by the Emergency Management Systems and Bureau of Meteorology. These impacts range from Category 1 where impacts are negligible except on highly susceptible species or trees compromised by damage or disease, through to Category 5 events where the majority of mature trees are uprooted or snapped, and remaining upright trees are usually stripped back to their basic framework.

Within a particular cyclone, not all individuals of a species behave the same, and the cyclone resistance of a population of trees, even within an urban environment, appears to fit a bell-shaped curve. Attempts have been made in the past to identify unifying traits of cyclone resistant or susceptible trees to improve our powers of prediction. A range of traits are examined and discussed in detail, including flexibility, root system development, ease of defoliation, leaf size, open branching habits, density of the canopy or crown, termite resistance, growth rates, longevity, natural habitat type and taxonomic relationships. It was concluded that no single trait is effective at identifying resistant species, though several traits are strongly correlated with sensitive species. Resistant species probably must possess a range of traits to achieve their resistance.

The report concluded that the value of trees in cyclones is not apparent at lower wind speeds of Category 1- weak 3 cyclones, but is more graphically demonstrated in the rarer Category high 3-4 events when trees are extremely valuable in catching flying debris and reducing wind loading on buildings. It was also concluded that while Category 1-3 cyclones cause significant damage to urban vegetation, there is clear evidence that the majority of damage can be attributed to a small number of highly susceptible tree species. Basic risk management needs to consider both the likelihood and consequences of an event, so large trees that can cause a lot of damage when they fail and that are susceptible to cyclones and likely to fail should be regarded as high risk. The consequence of tree failure is highest in areas of high potential impact, such as:

- in proximity to overhead electrical lines;
- in proximity to buildings and other built infrastructure; and
- along roadsides where their failure can block road access.

Recommendations of this report include:

- Incorporating a consideration of cyclone resistance into a statute of planning schemes may be the best way to avoid allowing highly susceptible species to proliferate during inter-cyclone periods;
- Reducing the consequences of damage from highly susceptible species by only allowing their use in areas away from essential infrastructure, such as in revegetation sites where the susceptible species is a local native;
- Discouraging the use of all sensitive species (Appendix C) in areas of high potential impact and encouraging the increased use of resistant species (Appendix B);

- Ensure that replacement trees do not have other undesirable traits such as weediness;
- Inappropriate lopping and pruning can increase cyclone susceptibility, so trees should be removed and replaced rather than being made asymmetrical by lopping to achieve powerline clearances;
- Council should have a web site advising residents of best-practice management and pruning of cyclone damaged trees;
- Replacing trees with low growing shrubs is undesirable since these low growing plants are incapable of delivering any benefits such as debris catchers or wind breaks during intense cyclone events;
- Public education projects should be undertaken using a process of thematic-based communication to inform people that the majority of damage is caused by a minority of tree species and that resistant tree species can protect life and property;
- Giveaways of cyclone resistant species may be an effective form of public education;
- The role of highly susceptible tree species in causing power failure should be incorporated into the Ergon Energy / Greening Australia 'Plant Smart' program;
- Placement of electrical supply underground does not necessarily protect them from damage from inappropriate tree species;
- Beach fronts should be planted with broad rooted species resistant to both wind damage and bulk removal of beach sand, in contrast to small rooted species such as coconuts with little ability to either reduce rates of sand loss or to survive its removal; and
- Council should consider a moratorium on planting advanced dicotyledonous plants in areas of high potential impact in pots exceeding 25L.

Appendices include the data set for green waste surveys in Townsville, lists of cyclone resistant and cyclone susceptible trees and a visual representation of the levels of damage that can be expected for many common species under Category 1-4 wind speeds. The profile of tree behaviour recognises that some individuals are stronger or weaker than the average, and that increased levels of damage will occur if:

- subjected to opposing wind directions from the eye of the cyclone,
- higher wind speeds at the top of slopes,
- higher wind speed from funnelling effects of the terrain,
- very high rainfall precedes the cyclone;
- the duration of the damaging winds is prolonged due to the slow speed ; or
- if the tree is suffering a previous injury or deficiency in care and management or the tree.

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introduction

Introduction

Severe tropical cyclones have periodically impacted on the north Queensland coast since time immemorial, and numerous cyclones have devastated north Queensland towns and cities since their establishment. The most cyclone-prone area of Queensland is the stretch of coastline between Cooktown and Mackay (Trollope *et al*. 1972), and Townsville lies almost at the centre of this zone. It was only since the devastating impacts of Cyclone Althea in Townsville in 1971 and Cyclone Tracy in Darwin in 1974, that the *Home Building Code of Queensland* (1975-1984) was implemented as an Appendix to the standard Building By-laws (Henderson *et al.* 2010).

Since the implementation of this cyclone building code, damage to buildings from wind loading is becoming increasingly less common, but cyclone damage bills in north Queensland towns and cities remain high, primarily through failure of trees under dynamic wind loading. Tree damage by winds, often referred to in the general literature as 'windthrow' has received comparatively little interest or research compared to damage to buildings by wind loading, despite it being responsible for millions of dollars of damage during cyclones. A common perception is that all trees will suffer damage during cyclonic events, and accepting damage from windthrow events was the price to pay for living in a green and leafy community. Existing literature relating to the effects of cyclones on trees, and results of the current study suggests that cyclonic impacts on trees are in no way uniform and that definite trends exist (e.g. Bowman & Panton 1994, Bruce *et al*. 2008, Cairns City Council 1986, Calvert 2006, Cameron *et al*. 1981, Curran *et al*. 2008, Donohue 1975, Fox 1980, Jackes 2011, Roach 2006, Saynor *et al*. 2009, Tucker *et al*. 2006, Turton 2008 and Van der Sommen 2002).

Aim of the Project

Greening Australia Queensland was invited by Townsville City Council and Ergon Energy in February 2011 to investigate trends in tree damage following Severe Tropical Cyclone Yasi, with the aim of understanding:

- how trees contributed to instances of power failure,
- which tree species contributed most to the amount of green waste generated;
- trends in urban tree survival and damage along a wind speed gradient from Category 1-4;
- trends in beach front tree survival and damage along a wind speed gradient from Category 1 to 4; and
- comparison of cyclonic tree damage from STC Yasi with previous cyclones and hurricanes.

It is anticipated that these results may be applied to:

- Generating a list of cyclone resistant trees for use in different substrates/soil types; and
- Broadening the existing Ergon 'Plant Smart' program to include identification of tree species that may disrupt power distribution during cyclonic events.

tropical cyclones

Tropical Cyclones

Defining tropical cyclone categories

In Australia, cyclone intensity is described as Categories 1-5, which are in turn defined by the speed of maximum wind gusts at a height of 10 metres over open flat land or water. Wind speeds are generally highest at the southern edge of the eye of the cyclone and are progressively lower with increased distance from the eye. As the cyclone crosses over land, its energy rapidly dissipates and the wind speeds get progressively lower until the cyclones degenerates to a rain depression. This means that wind speed gradients are generated both along the coast away from the cyclone, and inland away from the point at which the cyclone crossed the coast.

It should be noted that the wind speed experienced by a particular tree will be dependant on its position relative to the path of the cyclone, the diameter of the cyclone and its forward speed. Wind speeds also increase up over steep topography (Henderson *et al*. 2010).

The five category system used by the Australian Bureau of Meteorology is shown in Table 1 below. This system should not be used to compare with Hurricanes and Typhoons in the Northern Hemisphere, which have different categories with different definitions (e.g Saffir-Simpson scale for hurricanes).

Table 1 **Australian tropical cyclone category scale (Henderson *et al*. 2010)**

Cyclone Category	Gust wind speed at 10m height in flat open terrain			Central Pressure hPa
	Km/hr	knots	m/s	
1	90-125	49-68	25-35	990
2	125-164	68-89	35-46	970-985
3	165-224	89-121	46-62	950-965
4	225-279	121-151	62-78	930-945
5	>280	>151	>78	<925

Note that the most intense cyclone ever recorded in Australia was Cyclone Mahina that struck Bathurst Bay on Cape York in 1899 with a central pressure of 914hPa (Trollope *et al*. 1972). The wind speed definitions given in Table 1 above are for maximum wind gusts, which are faster than the ten-minute mean winds, or 'sustained winds'. Lourensz (1981) uses a sustained 10-minute wind speed of more than 63 kph as part of his definition of a tropical cyclone.

Although each Cyclone category incorporates a large variation in wind speeds, there are relatively predictable levels of impacts, particularly on infrastructure, that occur in different category cyclones. These predictions are used to inform the general public what to expect from a particularly category cyclonic event (Table 2). Note that most cyclone-rated houses in north Queensland have an ultimate limit state design wind speed of approximately 250 kph (Boughton *et al* 2011).

Table 2 Cyclone Categories (from Emergency Management Systems & Bureau of Meteorology (2007)

Category	Strongest Gust (km/h)	Typical Indicative Effects
1 Tropical Cyclone	<125 Gales	Negligible house damage. Damage to some crops, trees and caravans. Craft may drag moorings.
2 Tropical Cyclone	125-169 Destructive winds	Minor house damage. Significant damage to signs, trees and caravans. Heavy damage to some crops. Risk of power failure. Small craft may break moorings.
3 Severe Tropical Cyclone	170-224 Very destructive winds	Some roof and structural damage. Some caravans destroyed. Power failure likely.
4 Severe Tropical Cyclone	225-279 Very destructive winds	Significant roofing loss and structural damage. Many caravans destroyed and blown away. Dangerous airborne debris. Widespread power failures.
5 Severe Tropical Cyclone	>280 Very destructive winds	Extremely dangerous with widespread destruction.

Variable Characteristics of Tropical Cyclones

Although this report attempts to categorise and predict levels of damage to trees during different category cyclones, there is significant variation in the characteristics of different cyclones within the same category, and impacts cannot be expected to be evenly distributed across the broad zone of cyclonic influence.

Formation: Every year, approximately 80 cyclones form world-wide, with 65% forming between 10^0 and 20^0 of the equator – cyclones don't form between 4-5^0 of the equator (Anthes 1982). Cyclones normally threaten northern Australia during a distinct season extending from November/December to March/April (Lourensz 1981). Historically, Townsville's cyclone season is limited to a shorter season from December through to March (Naval Research Laboratory 2010). The cyclone season is dictated by the interaction between a range of climatic features. Anthes (1982) notes the following variables and features are important for the formation of tropical cyclones:

- Sea surface temperature and depth of warm water – 26.5^0C is the critical minimum temperature;
- Degree of convective instability – cumulus convection;
- Middle troposphere relative humidity – prevents erosion of convective clouds, allows more moisture convergence in a column and release of more latent heat;
- Low-level absolute vorticity - vorticity is the tendency for elements of the fluid to "spin", associated with regions of enhanced upward motion, cumulus convection and release of latent heat; and
- Vertical shear of the horizontal wind – cyclones are more likely to develop when vertical wind shear is small and there is ittle lateral transfer of temperature and moisture.

Cyclones are intense low pressure systems with large rotating masses of wind and rain, revolving clockwise (in the southern hemisphere) around a central 'eye'. The intensity of the cyclone is generally dictated by the central pressure. Cyclones generally form once the central pressure drops below 990 hPa and are considered 'Severe' when the pressure drops below 965 hpa (Henderson *et al*. 2010). In the South Pacific, the average cyclone pressure is 975hPa, with 50% of cyclones ranging from 985 to 955hPa (Terry 2007). Cyclone Tracy which devastated the city of Darwin in 1974 had a central pressure of 950 hPa (Mottram 1977), while the severe category 5 Cyclone Mahina that killed 400 sailors in March 1899 had a central pressure of 914 hPa. However, the most intense cyclone on record was Cyclone Zoe (Dec 2002) which had a central pressure of 890hPa. The sharp difference in atmospheric pressure between the central eye and the outer edge of the cyclone causes strong winds to blow inwards, creating the cyclone's destructive power (Terry 2007).

Movement: The movement of the cyclone, as dictated by the location and progression of the central eye, is generally very slow compared to the speed of the rotating winds. While the most common speed is usually 11.25 –19.3 kph, it is possible for cyclones to move at speeds of up to 64.35kph (Trollope *et al.* 1972). While in its infancy, cyclones tend to move very slow as they intensify over open water, but often gain speed as the cyclone matures (Terry 2007). Cyclones are, however, highly unpredictable and are known to speed up, slow down or even stop completely (Terry 2007).

The 'Eye': The eye is normally 20-40km wide, with the highest rainfall and wind speeds normally recorded in the wall of the eye (Granger *et al*. 1999, Terry 2007). Within the eye itself, the wind and rain die down almost completely, it is often cloudless, temperatures rise and the relative humidity drops (Holmes 1978). As the eye passes, the winds return with an equal strength, but from the opposite direction from that previously experienced. The zone of strongest winds is obviously circular, with a small radius and decrease in strength with increased distance from the eye (Terry 2007). The most significant wind speeds and damage are usually experienced on the left hand side of the forward track of the cyclone, as this zone experiences the addition of the forward movement to the speed of the rotating winds, while on the right hand side, the wind speed is reduced by the same amount (Terry 2007).

Wind: Cyclones are not homogenous in structure, but contain a number of spiralling streamlines of wind, being continuously drawn towards the eye (Terry 2007). This results in changes of wind direction as the cyclone approaches and then passes (Terry 2007), with the degree of change being related to proximity to the eye. Although cyclones can persist for weeks over water, once they cross land, they begin to degrade rapidly (Lourensz 1981). As the cyclone passes over land, the increased roughness and reduced aerodynamics of the land compared with open water increases the frictional drag, and this creates differences in wind velocity that then result in shearing upwards through the vertical wind column (Holmes 1978). Multiple forces, including the Coriolis effect, centrifugal force, and the boundary layer from frictional shearing creates a new gradient of pressure that acts towards the centre of the cyclone (Holmes 1978). This new force can act against the direction of air flow (Holmes 1978), creating turbulent gusty winds with erratic changes in direction (Terry 2007).

As a cyclone moves over the land, it decays as the central pressure rises by 1-4 hPa/ hour due to:

- Inability to continue evaporation from sea surface and thereby losing water vapour available for convection, and reducing condensation and latent heating
- Cooling effects, as the land is cooler than the ocean, and the rising air becomes cooler
- Increase in surface roughness and friction, slowing surface winds, reducing the Coriolis and centrifugal forces, and increasing air movement towards the eye. As the mass convergence and upwards motion increases, this increases moisture convergence causing heavier rain (Anthes 1982).

It should be noted that reduced evaporation has a greater influence than friction in causing cyclone decay (Anthes 1982). Cyclones are often degraded to tropical lows after only a limited amount of inland penetration (50-100km), however Cyclone Audrey in January 1964 still produced gale-force winds after travelling inland more than 2,200km (Lourensz 1981).

Wind speeds vary considerably within the zone of impact, and not just linearly away from the eye, but influenced by the types of terrain over which the cyclone passes. Cyclonic winds do not occur in an even and linear flow, but is turbulent and highly variable in the landscape. Wind speeds increase velocity up the side of hills, so crests of hills can expect as much as a 20-50% increase in wind velocity (Van der Sommen 2002). These variations in wind velocities were demonstrated during Cyclone Agnes in 1951 and Cyclone Winifred in 1986 where the greatest level of damage occurred to buildings and trees closest to sloping ground (Granger *et al*. 1999). After the passage of Winifred, it was noticed that the windward slopes both north and south of the path of the cyclone were significantly impacted, whilst the leeward sides of the hill crests were virtually untouched (Oliver & Wilson 1986). The compression of wind around immovable objects such as hills can also create increased velocities. It is thought that Castle Hill and Mt Stuart influenced patterns of wind speed and damage during Cyclone Althea but more measuring instruments would be required to determine the level of influence of these features (Trollope *et al.* 1972).

Changes in wind direction occur naturally as the eye of the cyclone moves relative to a particular location. For example, during Cyclone Yasi, Townsville was initially experiencing winds from an angle of 134 – 165 degrees, but this shifted to 105 – 92 degrees as the cyclone crossed the coast. The wind direction then shifted to 60-70 degrees as the cyclone moved inland (BoM data 2011).

As the wind encounters changes in terrain, and surface roughness such as buildings and trees, it flows around these obstacles and becomes increasingly turbulent (Van der Sommen 2002). This in turn creates significant variations in the wind loading on any given structure. There is frictional drag over aerodynamically rougher surfaces, and velocity decreases closer to the ground causing shearing of the wind flow above it (Van der Sommen 2002). These shear stresses are transmitted upwards through successive layers (Holmes 1978). A boundary layer forms over the land, influenced by the height and density of the trees, structures and other obstacles (Van der Sommen 2002). Mean wind profiles obey the ‘power law’, which explains the interaction of forces on the wind at different heights above the ground:

$$\bar{U}/ U_{10}=(z/10)^{\alpha}$$

Where:
$\bar{U}$ = the mean friction wind velocity (influenced by surface shear stress and air density)
U_{10}= the frictional velocity at 10m height
z = height above the ground
$^{\alpha}$ = a power function that varies this surface roughness (Van der Sommen (2002)

When measuring wind speed during cyclones, the wind strength is considered to be the ‘sustained wind speed’ measured as an average over 10 minutes above flat ground (Terry 2007). Gusts are much stronger than the sustained wind speeds and it is the speed of these gusts that are used to determine cyclone categories. When wind gusts over a forest canopy, it’s not the same as over bare ground, since the wind can penetrate the canopy to varying depths (Van der Sommen 2002). These downward deflections of wind gusts are known as “Honami gusts” and can cause significant damage to exposed trees (Wood 1995). This may partially explain patchiness of damage in closed forests.

Tornadoes: A little – known phenomenon related to hurricanes and cyclones is the formation of tornadoes. These are well studied in the USA where it is estimated that they cause up to 10% of fatalities and 0.5% of total hurricane damage (Novlan & Gray 1974). Approximately 25% of hurricanes in the USA generate tornadoes, (Anthes 1982), while up to 60% of tropical cyclones in Australia may generate tornadoes (Seargent 1991). When hurricane formations are suitable, an average of 10 tornadoes are created, but Hurricane Beulah in 1967 spawned 373 tornadoes (Novlan & Gray 1974). Although tornado production is positively correlated with hurricane intensity, for tornadoes to develop, the cyclone must be degenerating and undergoing rapid infilling (Novlan & Gray 1974). This creates a sharp rise in central pressure, and a rapid cooling of the core (Seargent 1991). Cyclone – imbedded tornadoes will then form if the following conditions occur:

- The cyclone or hurricane is still intensifying as it makes landfall (Seargent 1991);
- Surface winds are gale force, rather than hurricane force (Seargent 1991);
- The surface pressure is between 1004 and 1012 hPa (Novlan & Gray 1974);
- vertical wind shear exceeds 74 kph from the surface (Novlan & Gray 1974);
- high levels of vertical wind shear in the bottom 1-2 kilometres (Anthes 1982); and
- where tilting creates enough of a vertical element of vorticity or rotation (Anthes 1982).

The tornadoes generally develop within the strong outer rain bands, usually 110 to 460km from the centre of the cyclone (Novlan & Gray 1974). These strongly convective rain bands don't rotate around the eye but remain in the quadrant in which they have formed (Anthes 1982). In the northern hemisphere where hurricanes rotate anti clockwise, tornadoes form in the front right quadrant of the hurricane path (Novlan & Gray 1974), so in the southern hemisphere where rotation is opposite, tornadoes would form in the front left quadrant. The convective cells in which tornadoes form move slower than the mean wind speed (Anthes 1982). The strong convection (vertical movement of hot air) within the rain bands creates strong variable gusts of wind, up to 50% more than the mean wind speed (Anthes 1982).

Tornadoes are not often discussed in the context of Australian cyclones. Townsville was impacted by a tornado during Cyclone Althea in 1971, and another tornado associated with Cyclone Joy cut a swathe through Mackay in December 1990 (Seargent 1991). In February 2011, the town of Karratha in WA was hit by a destructive tornado associated with Cyclone Carlos off the coast. Following Cyclone Yasi, at least some of the damage caused to the coastal town of Cardwell was attributed to a tornado (Anderson 2011b). It is possible that cyclone-spawned tornadoes are far more common than often realised (Seargent 1991), and may help explain some zones of heavier damage in cyclone-affected areas.

Rain: The other more obvious feature of tropical cyclones is torrential rain. The amount of rain received is not necessarily related to the intensity of the cyclone, as even weak systems can produce just as much rain as intense systems (Terry 2007). Rainfall is not evenly distributed, but falls in well defined bands that are easily visible on radar images. The bands of intense rainfall are separated by 'moats' of relatively light cloud and rain (Terry 2007). Some of the heaviest rainfalls have been recorded once the cyclone degenerates into a tropical rain depression, such as the remnants of Cyclone Sid in January 1998, which dumped over 700mm of rain on Townsville in 24 hours.

In summary, every cyclone is different, even cyclones of the same category, and the impact of a cyclone on a particular location has a lot to do with both the characteristics of the cyclone, and the way the cyclonic winds interact with the surrounding landscape. Variable characteristics of cyclones that can influence patterns of tree damage are listed in Table 3 below:

Table 3 **Variable characteristics of cyclone and their potential impacts on trees**

Characteristic	Reduces survival	Increases survival
Proximity to the eye	Close to the eye, wind direction comes from opposite directions	Away from the eye, wind is mostly unidirectional
Speed of the cyclone movement	Slower speed increases the duration of the event	Faster speed decreases the duration of the event
Speed of the cyclone movement	Faster speed increases overall wind speed to the south of the cyclone	Slower speed decreases overall wind speed
Rainfall	Higher rainfall saturates the soil, reducing mechanical strength of the soil	Lower rainfall gives tree roots greater resistance to uprooting

Storm Surge

A significant and highly destructive component of tropical cyclones is the 'storm surge'. A storm surge is an abnormal increase in sea levels, often causing extensive inland flooding. A storm surge is usually the combination of several factors:

- strong winds creating large and erosive waves (wave set-up);
- strong winds that cause water to "pile up" at the shoreline (wind set-up), and
- low barometric air pressure at the centre of the cyclone (Mabin 2000).

The ability for waves to 'pile up' along the shore is often dependant on the bathymetry (submerged topography) of the coastline. Where the sea bed is gradually sloping, there is increased friction between the returning sea water and the sea bed, reducing the opportunity for water brought onto the coast by wave action to return (Terry 2007). The volume of water coming in by wave action begins to exceed the rate of water evacuation, and flooding may occur. Similarly, the tunnelling effect caused by bays and estuaries can also trap water, exacerbating the height of any storm surge rises (Terry 2007). The low central pressure associated with the cyclone causes the surface of the ocean to rise up like dome (Granger *et al*. 1999, Terry 2007). The height of the dome increases by approximately 1cm for every hPa decrease in central pressure (Terry 2007), so the height of the dome is directly proportional to the intensity of the cyclone. While Terry (2007) notes that the domes are generally about 50km in diameter, the size is also dependant on the particular cyclone. This dome should not be confused with a wave, but is a massive movement of sea water, often 2-5 metres in height, that can increase normal sea levels for several hours (Granger *et al*. 1999).

These various components will come together to form the 'storm tide'; which will have its greatest impact on the coast approximately 20-50km on the left of the cyclone path, and not in the actual eye or eye wall (Granger *et al*. 1999, Terry 2007). The overall magnitude of the storm tide may depend on:

- the diameter and central pressure of the 'eye';
- direction and speed of the cyclone;
- the bathymetry and geographical features of the coastline; and
- Timing of landfall in relation to the 'astronomical' tide levels, particularly the 'Highest Astronomical Tide' or HAT (Granger *et al.* 1999, Terry 2007, Trollope *et al.* 1972).

Impacts: As the storm surge comes ashore, normally protective coral reefs are submerged, allowing waves to penetrate further inland (Terry 2007). As salt is generally toxic to most plants, this salt water intrusion and salt spray can have a significant negative impact on vegetation. It is, however, the physical force of the water that creates the most damage to beachfronts, and this damage can be further divided into

Figure 1 Storm surge impacts on Cardwell foreshore, Cyclone Yasi

five different categories:

1. Hydrostatic damage: damage caused by the pressure of a weight of water at rest extends inland as far as the limit of inland penetration of the storm surge;
2. Hydrodynamic Damage: damage caused by the mechanical forces of water, combining hydrostatic pressure with the dynamic pressures of wave action, and velocities of the surge and currents as it moves around obstructions;
3. Scour damage: the abrasive effects of water as it produces swirling vortex flow patterns around obstructions;
4. Wind effects: strong winds creating high waves on top of the storm surge, pushing water on to the coast and raising water levels; and
5. Debris: impacts of debris carried along with flood waters at high velocities (Trollope *et al.* 1972).

Further increases in water levels are also caused by torrential rain, which may cause localised flooding in its own right. In coastal areas, these combined hydraulic impacts are often responsible for at least half the loss of life and a significant amount of property damage (Trollope *et al*. 1972).

Once the storm tide has come ashore to its maximum extent, further damage is caused as this water runs back out to sea. Following passage of the cyclone, sea levels can drop by as much as 3 metres, so the outward run of water can achieve significant velocities (Granger *et al.* 1999). In addition, this backwash of water also carries a significant amount of debris, further damaging structures weakened by the initial incoming waves and volumes of water (Granger *et al.* 1999). One of the biggest impacts on beaches is the scour and removal of unconsolidated beach materials, which can often result in beachfronts migrating backwards (Terry 2007). The survival of trees under these situations therefore depends not only on withstanding wind impacts, but also surviving being bare rooted by the removal of the substrate in which they were anchored.

Historical storm surge impacts: The impacts of storm surge has featured heavily in historic records of cyclones in northern Australia. The highest level storm surge ever recorded worldwide was in Queensland when Category 5 Severe Tropical Cyclone Mahina (central pressure 914hPa) hit Bathurst Bay in 1899, delivering a storm tide between 13.11-14.64 m high. Most cyclonic storm tides have been significantly lower than this.

In Townsville, storm surges were obviously a feature of cyclones Sigma (1896) and Leonta (1903), but since tide gauges were not installed until after the 1940 cyclone, no accurate storm surge heights are available. Cyclone Althea (1971) delivered a storm surge of 3.66 m at Toolakea north of Townsville, and a maximum of 2.9m in Townsville Harbour (Maunsell Australia 2005). Fortunately, the cyclone did not hit at high tide, so the combined storm tide in Townsville was 4.15m, compared to a potential 5.29m if it had hit when the tide was highest (Trollope *et al*. 1972). Even at this lower height, the storm surge still inundated many low lying areas with salt water, causing significant damage (Trollope *et al*. 1972). Category 1 Cyclone Tessi impacted Townsville's foreshore in April 2000 with a storm surge 1m above the tidal level, altering the beach foreshore along Rowes Bay and Pallarenda (Mabin 2000). On the exposed side, foreshore trees had their bark sandblasted to a height of more than 3 m above the ground (Mabin 2000).

Cyclone Yasi in February 2011 delivered a destructive storm surge along an extensive length of the north Queensland coastline. Storm surge values for Cardwell vary from 5 metres (Bureau of Meteorology 2011) to 5.4 m (Boughton *et al* 2011), but fortunately hit on a quarter falling tide, creating a storm tide approximately 2.2-2.3m above

Highest Astronomical Tide (HAT) (Boughton *et al* 2011, Bureau of Meteorology 2011). The height of the storm surge reduced with increased distance from the eye, resulting in a 2.35m storm surge in Townsville and still more than 1 metre in Bowen (Boughton *et al* 2011), which was located further to the south than any damaging winds. Estimates of a 6m storm surge at Palm Island (Anderson 2011b) were obviously mistaken. The fact that the storm surge in Townsville persisted after the peak for more than 12 hours meant that Townsville experienced a second peak of 1.2m on the following high tide, resulting in water levels 0.4 metres above HAT (Boughton *et al* 2011). Impacts of this storm surge were variable. At Tully Heads where the beach is shallow and sloping, the storm tide penetrated approximately 500m inland, but the sharper and steeper beach at Cardwell limited the inland penetration (Boughton *et al* 2011). On the exposed beachfront at Palm Island, the storm tide scoured huge holes in the rock wall on the seafront promenade, significantly damaging between 80-100% of the seawall (Anderson 2011a).

It must be considered likely that the combined hydraulic impacts, including sediment loss by scouring, would have similar levels of significance to beachfront vegetation as wind impacts.

Historical Impacts on Townsville by Tropical Cyclones

Of the tropical cyclones that form off the Australian coastline, 43% occur off the coast of north Queensland, compared to 23% off the Northern Territory and 34% off the Kimberley coast in Western Australia (Lourensz 1981). It is not surprising then, that the recent impact by Severe Tropical Cyclone Yasi is just the latest in a long history of cyclone impacts on north Queensland and Townsville.

A review of past cyclone activity in the Townsville area has been undertaken by the Naval Research Laboratory (2010). They assessed a total of 36 cyclones that came within 180 nautical miles of Townsville between 1958-1997. Based on these records, Townsville has an annual recurrence of 0.9 cyclones per year coming within this proximity of the city (Naval Research Laboratory 2010). There has been considerable variation between years. No cyclones came close to Townsville within the four year period extending from 1991-1992 wet season to the 1994-1995 wet season (Naval Research Laboratory 2010). Lourensz (1981) looked at frequency of cyclones actually crossing the coast. Forty percent of cyclones that form off the coast of North Queensland make landfall (Lourensz 1981). Dividing the tropical Australian coastline into 100km long sections, Townsville sits at the border between coastline section 83 (Townsville to Ingham) and 84 (Townsville to Ayr). From July 1909 to June 1980, six cyclones crossed between Townsville and Ingham, including two ‘water to land’ crossings and four ‘land to water’ crossings (Lourensz 1981). Over the same period, seven cyclones crossed between Townsville and Ayr, including six ‘water to land’ crossings and one ‘land to water’ crossings (Lourensz 1981). Although Lourensz (1981) note the landfall of 6-7 cyclones in the Townsville area over a 71-year period, this report also includes maps indicating an average incidence of 10-12 cyclones per decade for Townsville.

A review of the literature revealed a total of 18 periods when Townsville has experienced cyclonic winds, and these are listed in Table 4 below. Not all of these events involved the eye of the cyclone passing over the city, but included those events where the peripheral winds exceeded cyclone strength. Attempting to correlate historical events with contemporary cyclones is difficult, due to the great differences in monitoring equipment available at the time. Precise measurements of historic cyclones in Townsville are not available for all cyclones, many of which were not even given names. Historical recordings of minimum central pressure were often overestimated, especially at sea (Lourensz 1981). Meteorological Observations commenced in Townsville in 1871 (Bureau of Meteorology 2011a), but tide gauges were not installed until after the 1940 cyclone. Cyclone Agnes in 1956 was the first of Townsville's cyclones to be tracked by radar, but wind and pressure data was only available after 1958 (Naval Research Laboratory 2010). Much of the historic meteorological data associated with the cyclones listed below was provided in imperial measurements and was converted using the BOM converter (http://www.bom.gov.au/lam/calc.shtml), however, no conversion is necessary between millibars (mb) and hectopascals (hpa).

Table 4 **Historical cyclone impacts on Townsville**

Year	Name	Category experienced	Central pressure (hpa)	Max wind gusts (kph)	Storm surge (m)	Fatalities
Mar 1867	NA	NA	NA	NA	NA	NA
Feb 1870	NA	NA	NA	NA	NA	NA
Mar 1890	NA	NA	NA	NA	NA	NA
Jan 1896	Sigma	3?	992	NA	2-3+	18
Mar 1903	Leonta	3?	963	118.5	NA	10
Feb 1926	NA	NA	NA	NA	NA	NA
Feb 1929	NA	NA	NA	NA	NA	NA
Jan 1932	NA	NA	NA	NA	NA	0
Apr 1940	NA	3?	966	NA	NA	0
Feb 1954	NA	1	NA	NA	NA	0
Mar 1956	Agnes	3	968	146.3	3ft	0
Dec 1971	Althea	3	973	197	2.85-3.7m	14
Dec 1973	Una	1<	NA	74.08	NA	4
Jan 1977	Keith	1<	NA	64.82	NA	0
Mar 1988	Charlie	1?	NA	64.82	NA	0
Mar 1997	Justin	1<	NA	130	NA	7
Apr 2000	Tessie	1		130	NA	0
Feb. 2011	Yasi	2	929	144		0

NA = Not Available. Note that '*Category experienced*' is the wind strength experienced in Townsville, not the highest winds at the core of the cyclone.

Earliest Records: Townsville was not quite three years old when it was hit by its first cyclone. Damaging winds “raged for two days and few structures withstood the onslaught” (BoM 2011a). Another three years later the fledgling town was hit again, with nearly every house in the town damaged (BoM 2011a). Cyclone Sigma in 1896 caused massive destruction in Townsville. The associated deluge of rain caused Ross River to break its banks, flooding parts of the town with two metres of water and killing 18 people (BoM 2011a). The comments made by Fawcett (1896) that “Several of the large, fine shade trees on the Strand were literally torn to pieces” are the oldest reference to cyclone damage to trees in Townsville. Cyclone Sigma significantly impacted vegetation on Castle Hill. Every tree was damaged to some extent, many uprooted or with broken branches, but all with stripped foliage (Fawcett 1896). This is indicative of a high Category 3 cyclone, although it is obvious from accounts that the eye did not pass over Townsville itself. Cyclone Leonta in March 1903 is regarded as the most serious of any cyclone to have hit Townsville. Its central pressure was recorded as 963mb (Trollope *et al.* 1972), identifying it as a Category 3 event. It was described as “surpassing Cyclone Sigma in violence” and consequently a greater level of destruction than ever experienced in Townsville (BoM 2011a). Townsville was generally spared significant cyclonic damage over the next 68 years, although the 1940 cyclone did knock down many trees around town.

Althea: Townsville was heavily impacted again when Category 3 cyclone Althea (central pressure 952mb) crossed the coast 50km north of the city at 10am on 24 Dec 1971 (BoM 2011b). Townsville experienced wind gusts up to 197 kph, with severe damage recorded within 80km from the centre. It was noted that local relief obstacles such as Castle Hill created a convergence and eddies of wind, contributing to localized areas of greater damage. The cyclone caused three deaths in Townsville and caused $50 million in damage, including damaging or destroying 90% of the houses on Magnetic Island (BoM 2011b). The Category 3 winds bent

Figure 2 Impacts of Cyclone Althea on Pallarenda and Townsville Strand Dec. 1971. Reproduced with permission from CityLibraries Townsville, Local History Collection

heavy steel poles, lifted houses from stumps and stripped the leaves from trees (BoM 2011a). In addition to the wind damage, a storm surge of 3.66m was recorded at Toolakea Beach, with a smaller surge of 2.9m in Townsville Harbour. This storm surge caused extensive damage along the Strand and at Cape Pallarenda (BoM 2011b).

Tracy: The biggest impact on the way that Australians face cyclones came in the wake of Severe Tropical Cyclone Tracy, a category 4 cyclone that struck Darwin on Christmas Day in 1974. The cyclone itself was relatively small - approximately 100km wide, but had a central pressure of 950 hPa and wind gusts of 217 kph before the anemometer failed (Mottram 1977). One of the most destructive features was its very slow rate of movement – as low as 5kph, so the duration of the cyclone was prolonged (Mottram 1977). The city was devastated by the cyclone - 60% of Darwin's houses were destroyed and unrepairable with only 6% considered immediately habitable. Darwin had to be almost entirely evacuated, 71 people were killed and 650 injured (Mason & Haynes 2009). Although this cyclone did not make landfall in north Queensland, the repercussions are still felt today. Assessments of building damage and causes of death from Tracy and Althea were considered when new cyclone strengthening elements were made compulsory under the new building codes. All new buildings constructed in the 1980s and since have had to comply with these new standards, and this has greatly reduced the extent of damage and fatalities from cyclones.

Recent Cyclones: After Althea, Townsville was spared any significant cyclonic influence for decades, until feeling the impact of peripheral winds from Category 2 Cyclone Justin in March 1997. The cyclone caused significant inconvenience through power loss, when power lines were brought down, mainly by tree branches, palm fronds and other wind-blown debris (Granger *et al*. 1999). After 36 hours without power, the water supply and sewerage systems also failed (Granger *et al*. 1999). Category 1 cyclone Tessi hit Townsville in April 2000. Although this was a relatively weak system (maximum wind gusts to 130 kph), the cyclone unroofed buildings, uprooted trees, and downed power lines from Ingham to Ayr. Most areas of Townsville were without power for up to four days, mostly the result of trees falling on powerlines. The city received 260mm of rain in association with the cyclone, and this was generally thought to have been a significant contributing factor to the widespread uprooting of trees.

The impacts of Cyclone Yasi was perceived as being the biggest cyclonic impact on Townsville since Althea, and this was particularly exacerbated by the much large size of Townsville now than in 1971. The effects of this most recent cyclone are discussed in greater detail in the following section.

Future Cyclones: Our understanding of the patterns of cyclonic impact in north Queensland has been hampered by the relatively short duration of instrumented records of these events. Meteorological observations in Townsville didn't commence until January 1871 (BoM 2011a). It is difficult to draw conclusions relating to trends in increased intensity using this data since there have been significant improvements in the type and quality of data collected, including the use of radar and satellite (Terry 2007). Recently, however, a palaeorecord of cyclonic activity has become available, by looking at the isotopic signature that cyclones leave in rainwater and became incorporated into a limestone stalagmite from Chillagoe caves (Nott 2007). Accuracy of this record was determined by cross-referencing with BoM cyclone data over the last 100 years, and found signatures of all major cyclones and 75% of all other cyclones that came within 300km of the site (Nott 2007). The isotopic record extended back 800 years, from AD 2004 to 1200. It was found that the frequency of cyclone landfall has been highly variable, with very active periods from 1400 to 1500, and 1600 to 1800, but activity since 1800 has been relatively quiet, particularly since European settlement (Nott 2007). Although climate change via global warming is expected to result in fewer cyclones but an increase in average intensity, a return to the natural cycle of cyclone landfall frequency combined with an increase in intensity could have serious consequences, particularly in light of coastal developments that have expanded considerably during the recent lull in cyclone activity (Nott 2007)

Severe Tropical Cyclone Yasi

Interest in increasing the resilience of coastal towns and cities to cyclone impacts has increased considerably following the recent impact by Severe Tropical Cyclone Yasi.

Yasi first developed on the 29th January 2011 as a tropical low northwest of Fiji (Bureau of Meteorology 2011). As it formed into a cyclone, it tracked westwards towards the Queensland coast, intensifying into a Category 2 and 3 system on 31st January 2011 (Bureau of Meteorology 2011). It continued to intensify to a Category 4 on the 1st February and to a marginal Category 5 on the 2nd February (Bureau of Meteorology 2011).

Queensland Premier Anna Bligh urged north Queensland residents to take precautions as Yasi was expected to cross the coast as a Category 5 cyclone, with widespread damage anticipated. Suggestions by Prime Minister Julia Gillard that Yasi was likely to be the worst cyclone in Australian history were mirrored by the Bureau of Meteorology (Carpenter 2011), and this probably assisted in ensuring the general populace was making serious preparations. Severe Tropical Cyclone Yasi came only a week after Tropical Cyclone Anthony had crossed the coast at Bowen, and many people had already taken precautions against that cyclone. High storm surge levels were predicted, and approximately 10,000 residents from low lying areas were evacuated prior to the cyclone crossing the coast (Carpenter 2011). In Townsville, residents were evacuated from coastal areas such as the northern beaches, Pallarenda, South Townsville, Railway Estate and Cungulla.

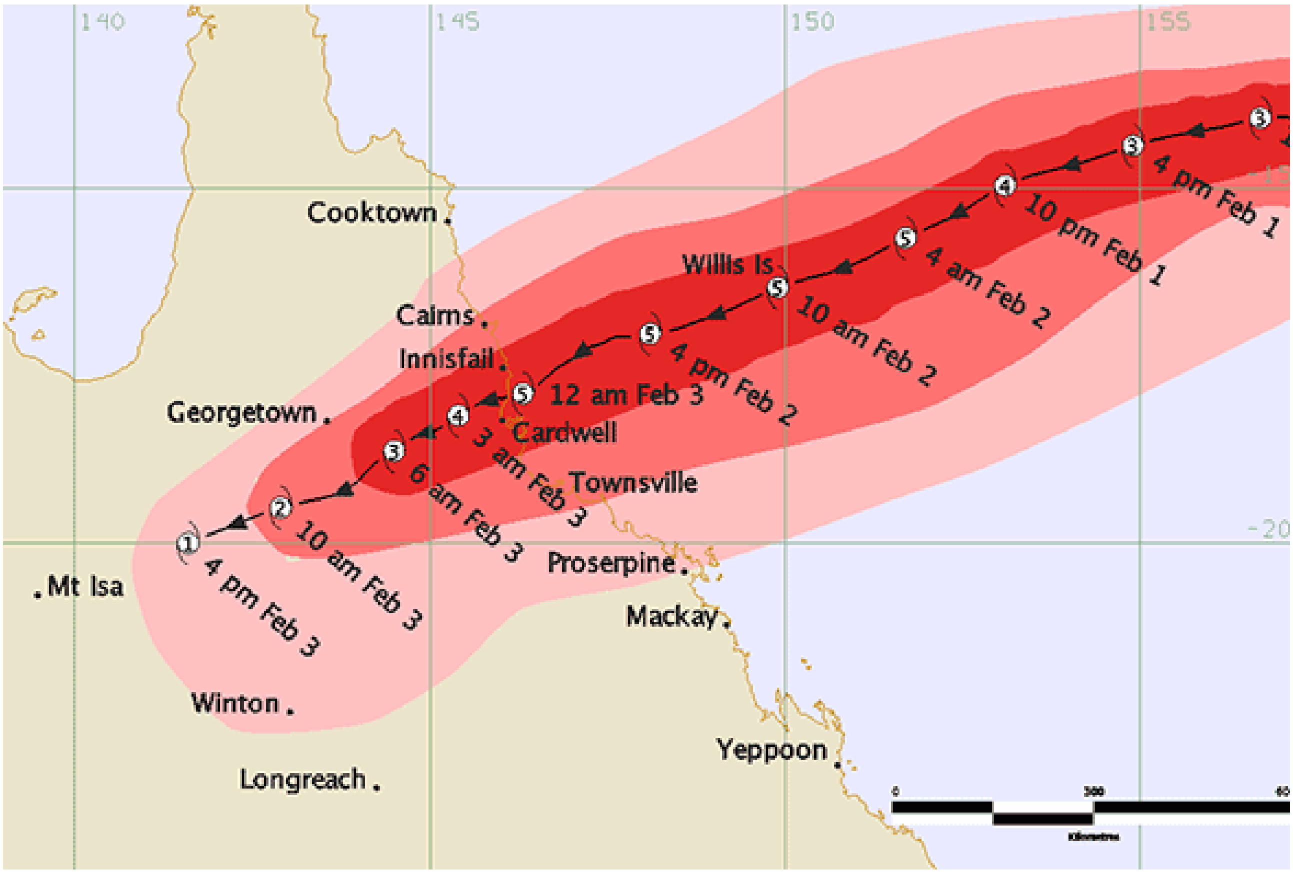
Of particular concern was Cyclone Yasi's very large diameter of more than 500km, so damage was not going to be restricted to a small section of the coastline. Estimates at the time of impact suggested that hurricane-force winds (defined under the Beaufort Scale as winds exceeding 118 kph) extending for around 145 kilometres from its centre and tropical storm-force winds (103–117 kph) extending 400 kilometres (Carpenter 2011).

Just after 9am on 2nd February 2011, as Yasi passed over the Bureau of Meteorology weather station on Willis Island, the radar and anemometer failed after recording a central pressure of 938 hPa and maximum wind speeds of 185kph. By mid afternoon in Townsville, winds were gusting to more than 70 kph, and the first power failures were noted in Annandale at 5pm when wind gusts of 80kph brought down a *Peltophorum* tree over power lines. Gusts had increased to 100 kph by 8.45pm, by which time much of Townsville had lost power. Maximum wind gusts of 135kph were recorded by BoM at 1.22am the following morning.

Landfall and Damage: Severe Tropical Cyclone Yasi crossed the Queensland coast near Mission Beach between midnight and 1am on the 3rd February 2011. In addition to damaging winds, a significant storm surge was experienced as far south as Bowen, though fortunately this did not coincide with the high tide (Boughton *et al* 2011). Although no deaths were recorded, damage to infrastructure, crops and vegetation were extensive, and due to the very large diameter of the cyclone, it extended for a considerable distance along the coast. There was noticeable damage to vegetation from the Daintree area in the north to Ayr and Home Hill in the south.

House damage was widespread in Bingil Bay, Mission Beach, Wongaling Beach, South Mission Beach, Hull Heads, Tully Heads, Tully, Cardwell and Upper Murray (Boughton *et al* 2011). At Port Hinchinbrook in Cardwell, dozens of luxury yachts were left piled on top of each other. More than 200,000 residents were left without power (Carpenter 2011). Yasi degraded as it moved inland, but still had additional strength to impact towns and settlements as far inland as Mt Isa. Due to the very large diameter and intensity of the cyclone, vast areas of the north were impacted. Disaster relief was made available for 24 local government areas: Boulia, Burdekin, Burke, Cairns, Carpentaria, Cassowary, Charters Towers, Cloncurry, Croydon, Doomadgee, Etheridge, Flinders, Hinchinbrook, Kowanyama, Mackay, Mckinlay, Mount Isa, Palm Island, Richmond, Tablelands, Townsville, Whitsunday, Wujal Wujal and Yarrabah (Commonwealth of Australia 2011). The online Daily Weather Observation records from the Bureau of Meteorology show maximum wind speeds of 113 kph in Hughenden, 98 kph in Julia Creek, 69 kph in Richmond and 70 kph in Mt Isa. Maximum wind gust speeds are not available for Charters Towers but reports of the type and extent of the damage suggests it was probably equivalent to a low Category 1 event.

Figure 3 Path of Severe Tropical Cyclone Yasi showing path, categories and extent of destructive winds (© Bureau of Meteorology 2011, reproduced with permission http://www.bom.gov.au/index.shtml)



Damage estimates have varied widely, but by April 2011, $868 million from 59,990 insurance claims had been lodged for damage caused by Cyclone Yasi (Wynne 2011). In addition to private insurance payments, figures released by the Commonwealth of Australia (2011) on 27 May 2011, showed that payouts via Australian Government Disaster Recovery Payment totalled $300,980,200 from 266,050 successful claims. The Australian Government also granted 5,676 claims for the 'Disaster Income Recovery Subsidy', totalling a further $7,960,227 (Commonwealth of Australia 2011). Damage to crops was extensive. It is estimated that 15% of the national sugar and 90% of the national banana supply was damaged by Yasi (Carpenter 2011), leading to fears that banana prices would again increase by 250% as they did after Cyclone Larry in 2006. Impacts on many of the listed communities are expected to last for years to come.

Pressure: Although there was no official anemometer in the path of the eye, the Bureau of Meteorology estimated a central pressure of 929 hPa and suggested that wind speeds of 285 kph would have been possible (Bureau of Meteorology 2011). This would define Yasi as a Category 5 at the time it crossed the coast. Yasi weakened as it moved inland but still maintained enough strength to penetrate as far inland as Mt Isa before it finally weakened to a tropical low around 10pm on 3rd February (Bureau of Meteorology 2011).

Wind Speeds: Attempts to develop a profile of wind speeds along this gradient are hampered by the fact that the Bureau of Meteorology only operate two anemometers within the area – at Townsville and Lucinda (Greg Connor, Bureau of Meteorology pers. Comm.). The anemometer on the Lucinda Jetty recorded a maximum wind gust of 137kph before the unit failed (Greg Connor BOM per. comm.), so it is likely that maximum wind gusts exceeded that value. Wind speeds in Townsville were highest between midnight and 1am on 3rd February 2011. The official BOM anemometer in the Townsville – Magnetic Island channel recorded maximum wind gusts of 135kph, while an unofficial anemometer measured 144 kph (Greg Connor BOM per. comm.), identifying impacts in Townsville as being equivalent to a Category 2 cyclone. BOM anemometer records show the highest wind gusts (>130 kph) were experienced between 1:22am and 1:27am on the 3rd February.

However, recent studies by the Cyclone Testing Station at James Cook University in Townsville suggest that wind speeds were significantly lower than the 285 kph estimate at Yasi's core. Their initial reports suggested that wind speeds would have been similar to that experienced during category 4 Cyclone Larry in 2006 (JCUCTS 2011). They used a combination of anemometer readings with estimates of wind speeds at other locations based on the wind load required to form a plastic hinge in the post holding up a road sign (Boughton *et al* 2011). The conclusion was that a range of wind speeds from 140 to 225 km/h (with a 10% error margin) were experienced in areas between Townsville and Innisfail (Boughton *et al* 2011), making Yasi a low Category 4 cyclone. Based on these results, most severely impacted areas away from the eye of the cyclone would have experienced category 3 wind speeds. Rumours of 360 kph winds at Abergowrie via Ingham are unsupported by the observed level of damage to trees and infrastructure seen in the area.

Rainfall: As is usual with tropical cyclones, a significant amount of rain was experienced close to the eye and to the south. South Mission Beach recorded 471mm while the Tully and Herbert River catchments recorded 373mm (Bureau of Meteorology 2011). No official rainfall records were collected in Townsville on the 2nd February as BoM staff were evacuated due to concerns about storm surge (Greg Conner BoM pers. comm.). The total of 170.4mm for the 4th February incorporates totals collected on the 3rd. One unofficial record from Cranbrook recorded 138 mm for the evening of Cyclone Yasi, however, it is possible that this is an underestimate due to the horizontal nature of the rain during the cyclone (Malcolm Calvert pers. comm.). Another rain gauge in Alligator Creek measured over 250mm before the funnel blew off the gauge (Jaymie Rains pers. comm.). It can be concluded that there was significant variation in rainfall totals in the Townsville area but that most areas would have received in excess of 130mm during the cyclone event.

cyclones and trees

Cyclones and Trees

Damage to Townsville and other tropical cities by Tree impact

The most immediately noticeable impact of Yasi and most other tropical cyclones is damage to vegetation. Where wind speeds are less than the design standard for buildings, fallen and broken trees are one of the biggest contributors to cyclone damage, the other being storm surge impacts. Trees may fall on houses and cars, block roads, and tear up underground services such as water mains, if the tree roots are extensive (Granger *et al*. 1999). The huge bulk of broken and fallen material can represent a major challenge for Council's waste managers, while fallen vegetation in natural areas can significantly increase fuel loads and fire risk in the following dry season.

Damage by trees: Inspections of building damage by the Cyclone Testing Station at James Cook University noted many cases of damage to buildings by fallen trees (Boughton *et al* 2011). In many cases, damage to roofs caused by trees led to subsequent significant water damage. Damage to buildings by falling trees and flying branches was also noted after Cyclone Tracy in Darwin in 1974, but this was considered insignificant compared to damage caused by flying debris such as roof cladding and other building parts (Cameron *et al*. 1981). As previously mentioned, great inconvenience was caused by Cyclones Justin and Tessi as a result of trees bringing down power lines, and these impacts were repeated again during Cyclone Yasi.

Damage to trees: Following Cyclone Yasi, one estimate suggested that 65,000 trees had been blown over in Townsville (Wallace 2011). There were numerous power outages caused by trees having pulled down powerlines or snapped powerpoles, while roads were blocked by fallen trees. There was widespread damage to fences and sheds, but damage to houses from trees was relatively uncommon. The first priorities were the clearing of trees from major arterial roads and the restoration

Figure 4 Greenwaste generated by Cyclone Yasi in Ayr, North Queensland

of power supply (Wallace 2011). Clean-up crews from the Department of Defence were used in the first couple of days in Townsville (Tyrell 2011), but they remained involved in the worst impacted communities for some time to follow. Most householders undertook tree clearing on their own properties and stacked piles of green waste by the roadside for collection. Townsville City Council engaged all available teams and employed contractors to assist with the clean-up and street-by-street collection of bulk green waste. At the height of the clean-up, the council was utilising 190 trucks, nearly 100 bobcats, loaders and backhoes, in addition to chippers and specialist stump grinders (Wallace 2011). In total, there were more than 70 clean up crews, including 300 council staff, with more than 100 chainsaws (Tyrell 2011). A total of 450,000 cubic metres of bulk tree waste was collected. This was stored and processed at nine bulk disposal sites around the city to create 260,000 cubic metres of mulch (Wallace 2011). Many residents took advantage of the free green-waste dumping at the two rubbish dumps with more than 30,000 loads of green waste delivered (Tyrell 2011). Removal of green waste from suburban gardens was finally completed on 10th April 2011 (Tyrell 2011). Details of total quantities of green waste removed from other impacted towns is not available, but one local council collected an equivalent amount of green waste as is normally generated over a 14 year period (Wallace 2011). Even as far south as Ayr, Cyclone Yasi still generated massive amounts of green waste.

There have been attempts to limit the impacts of cyclones and increase community resilience. Following Cyclone Justin, the ‘Far North Queensland Electricity Board’ (FNQEB) undertook a major tree management program to reduce the risk of tree impacts on power supply in future cyclones (Granger *et al*. 1999). These efforts were apparently useful in reducing power interruptions during Category 2 Cyclone Rona, however Granger *et al*. (1999) questioned whether these efforts would be useful during severe cyclones where whole trees are likely to be uprooted rather than having the odd branch broken off.

How do trees protect life and property?

In spite of the predictable recurrence of cyclones in Townsville and other towns and cities in north Queensland, and in spite of the long history of trees damaging infrastructure and interrupting power supply, residents still insist on having trees throughout the city.

The suggestion that tree cover is of value in protecting life and property during tropical cyclones is a recurring theme in much of the cyclone literature. In the aftermath of the devastation wrought by Severe Tropical Cyclone Tracy on Darwin in 1974, it was seen that trees contributed to damage to houses by falling on them, as well as protecting houses from flying debris (Van der Sommen 2002). Assessments of housing damage and vegetation cover in the wake of Tracy, Van der Sommen (2002) notes that “It provides a strong indication that maintaining high tree cover around susceptible houses may have been beneficial”.

Jackes (2011) lists many of the benefits provided by trees and shrubs during cyclones in addition to the obvious benefits of providing shade and attracting wildlife:

- Well-chosen healthy trees can protect buildings and people.
- Trees can intercept debris, which may otherwise become a flying missile.
- Well-chosen plants offer protection for other plants and objects.
- Well-chosen trees or plantings will protect stream banks in times of floods.
- Well-chosen trees reduce shoreline and

landscape damage.
- Even if a tree falls on a house it may help to hold the roof on and belongings inside may be salvageable (Jackes 2011)

The most common themes for the protection of buildings by vegetation are by reducing wind velocities and wind loading on structures, and by collecting of flying debris. These aspects are discussed in detail below.

Wind Break

Most of the damage caused to buildings during Cyclones is caused by wind, and this damage can start once wind speeds exceed 75 km/hr (Granger *et al*. 1999). The highest wind speeds are in the wall of the eye of the cyclone, particularly in the front left quadrant of the axis of movement, as here the speed of forward movement of the cyclone are added to the rotational wind speeds. The force of wind increases at the square of its speed, so wind speeds of 250km/hr are four times as great as 125km/hr winds (pers. comm. Cam Leitch Manager JCU Cyclone Testing Station), so any reduction in wind speed velocities can have a significant impact on wind energy and damage.

Wind velocities within the boundary layer represent the greatest cyclone hazard, but this can be significantly influenced at the small scale by increased surface roughness. Barriers such as buildings and trees create a boundary surface of separation at a height roughly the same as the height of the barrier (Van der Sommen 2002). These barriers then create both turbulence and shelter, with wind protection mostly on the leeward side, but some sheltering also occurs on the windward side (Van der Sommen 2002). The level of protection depends on the height, shape and porosity of the barriers (Van der Sommen 2002). These barriers offer mutual support and protection depending greatly on the ratio of object: inter-space gaps (Vickery 1976). With buildings, reducing the ration to less than 1/4 reduced the wind loading on buildings by 75%, but if the ratio is widened from 1/6 to 1/12, then the sheltering effect is reduced from 65% to 35% (Vickery 1976). In addition, if there are gaps, this causes the wind to increase in velocity via the Venturi Effect, unless the gap is the same width as the height of the building (Vickery 1976).

Figure 5 Windbreak of cyclone resistant vine thicket species

Unlike buildings, trees are flexible and are able to bend and absorb energy. Trees behave like ‘damped

force harmonic oscillators' and bypass the normal process of turbulent energy dissipation by effectively absorbing energy at their resonant frequencies (Van der Sommen 2002). The swaying of trees absorb momentum from the wind, but they always return to their natural resting position due to the damping influence of the tree's structure (Van der Sommen 2002). A belt of trees increases resistance to wind, resulting in a loss of momentum, but in a closed forest, the wind travels over the canopy with occasional downbursts of turbulent wind and locally increased wind velocities (Van der Sommen 2002). For this reason, you get a higher rate of tree movement and energy transfer on the edge of a forest than within it (Van der Sommen 2002).

Experiments with porous windbreaks have shown that a single row, high density windbreak reduced air infiltration by about 60% when planted approximately four tree heights away from the building (Visser & Cleijne 1994). On the leeward side of a windbreak, a partial vacuum is created, with a resulting suction effect acting in the same direction as the wind pressure on the windward side (Terry 2007). A degree of porosity in the windbreak can reduce this suction effect. The degree of porosity influences the degree of protection, but Van der Sommen (2002) notes that a porosity of 40-50% is adequate to achieve protection. The efficiency of the windbreak is also dependant on its orientation relative to the direction of dominant winds (Visser & Cleijne 1994). Trees shelter and protect each other from damaging winds, forming wind resistant structures (Van der Sommen 2002). This 'shielding effect' from the tree canopies will extend to houses within the zone, as long as the tree cover is stable (Van der Sommen 2002), and this can alter the extent of predicted uplift on house roofs (Visser & Cleijne 1994). Buildings surrounded by vegetation of similar dimensions can receive a considerable amount of shielding from that vegetation, and similarly, vegetation also receives shelter from the buildings (Reardon 1978).

Unfortunately, prior to Cyclone Tracy, the influence of vegetation buffering was overstated. The wind speed design for houses in heavily wooded areas was reduced, but due to the long duration of destructive winds experienced, the trees became progressively more defoliated and thinned out, substantially reducing the shielding characteristics (Mason & Haynes 2009).

Debris

During the high wind velocities experienced during cyclones, one of the more damaging impacts is the ability for objects to become airborne and act as missiles, smashing and cutting through anything in their path. In the wake of Cyclone Tracy in 1974, some of the significant technical lessons learnt were that flying debris can be significant and that house design must consider its impact (Mason & Haynes 2009). It was also determined that expecting vegetation to make up for deficiencies in structural design should not be relied upon (Mason & Haynes 2009).

Impacts on Buildings: Of significant importance during cyclones is the issue of internal pressurisation. As wind flows over the roof of a house, it creates suction forces that attempt to pull the roof off. While the building envelope remains intact, internal pressures counteract this suction. However, if internal pressures become positive, they act in unison with external suction forces, and the roof may be torn off. Failure of roller doors are a common cause of internal pressurisation leading to significant damage to the house, but pressurisation from the impact of flying debris is also very common. During Cyclone Tracy, a number of eyewitnesses reported flying debris smashing windows, leading to the immediate failure of a part of or the entire roof as a consequence of these internal pressurisation forces (Mason & Haynes 2009).

Generally, residents in cyclone prone areas are aware of the danger of flying debris, and in the lead up to cyclone season there is often a reminder to residents to clean their gardens of loose objects, particularly if a cyclone threat exists. However, during a cyclone event, failed elements from damaged buildings become significant windborne debris. During Cyclone Yasi, this windborne debris included roofing tiles, awnings, guttering, flashing and roller doors (Boughton *et al* 2011). Extreme cases involved large assemblies of roofing and battens, significant portions of the roof structure, whole sheds and even an entire shipping container (Boughton *et al* 2011). These objects can travel for hundreds of metres, causing significant damage to anything they hit. A building impacted by a large piece of debris during an extreme event is likely to have the building envelope breached. This can cause the cycle of windborne debris to 'snowball', whereby the impacted building will release even more debris into the air stream, causing more impact on downwind buildings (Boughton *et al* 2011). During Cyclone Yasi, numerous pre-1980's houses lost substantial parts of their roofs, and in 20% of these cases, this debris caused damage to other houses (Boughton *et al* 2011). When post-1980's houses lost sections of their roofs, 40% of them damaged other buildings (Boughton *et al* 2011). Some of these differences can be explained by newer houses being closer spaced and with fewer and smaller trees (Boughton *et al* 2011).

Figure 6 Building envelope breached by flying debris, Cardwell (Cyclone Yasi)

Impacts on Health: Of course, this flying debris can have extreme impacts on human health. Of the 71 people killed during Cyclone Tracy, 50 of these were killed on land and 21 at sea. Of the 50 killed on land, laceration or spearing by flying debris (especially roof sheeting and glass) was a contributing cause to the death of 15 people (Mason & Haynes 2009). Crush asphyxia was the main cause of death in 31 cases, from falling masonry (Mason & Haynes 2009). In addition to these fatalities, there were significant injuries from flying debris. Approximately 500 people suffered superficial lacerations from roof sheeting and glass, another 64 had severe lacerations and 74 suffered blunt injury trauma (Mason & Haynes 2009). A surgical specialist Dr A.F. Bromwich also suggested that fibro-asbestos sheeting may have caused many of the severe lacerations (Mason & Haynes 2009). While improved building codes have both reduced the levels of flying debris and improved buildings ability to withstand impact (Mason & Haynes 2009), debris still continues to pose a very real danger to life and property during cyclones. One of the three people killed by Cyclone Winifred in 1986 was killed by flying debris (Oliver & Wilson 1986). During Cyclone Yasi, flying debris impacting houses punctured external cladding and sometimes entered the building's interior, posing a significant danger to its occupants (Boughton *et al* (2011).

Trees and Debris: One of the greatest benefits of having trees around a property is its ability to intercept flying debris. During Cyclone Tracy, it was noted that trees acted as a debris screen "..immobilising a significant proportion of the flying debris" (Cameron *et al*. 1981). Even the spreading canopies of fallen trees captured a lot of flying debris (Cameron *et al*. 1981). It was also noted in the wake of Tracy that recently established treeless suburbs sustained a greater level of damage than older suburbs, but noted it was unlikely that trees were the sole cause of difference (Cameron *et al*. 1981). Prior to the cyclone, trees were removed from around many houses and this left them susceptible to 'debris attack' (Cameron *et al*. 1981).

One of the best illustrations of the role of trees in reducing 'debris attack' comes from an assessment of three caravan parks during cyclone Tracy. While the practice of parking caravans under trees made them susceptible to falling trees and branches, the presence of numerous young trees in one caravan park substantially reduced damage levels compared to a nearby caravan park with no trees. A comparison of damage at the two caravan parks is provided in Table 5 below

Table 5 Damage to caravans at two caravan parks in Darwin during Cyclone Tracy (Cameron *et al*. 1981):

Damage Type	No Trees	Numerous young trees
undamaged	0	2
Minor damaged	27	46
Severely damaged	25	0
Destroyed	5	4
Total caravans	57	52
Permanent buildings	Most unroofed	Minor damage only

A third caravan park was bombarded by flying sheet iron from upwind buildings, but a line of trees captured a mass of tangled iron up to 2 metres high in places (Cameron *et al*. 1981). Many photographs taken after Cyclone Tracy show debris wrapped or caught up by vegetation.

Figure 7 Examples of flying debris intercepted by trees at Cardwell, Cyclone Yasi

The ability to capture flying debris has been noted with other cyclones since. During Cyclone Winifred, it was noted that vegetation catching debris contributed to reduced extent of damage from wind-borne debris (Oliver & Wilson 1986). Photographs were published after this cyclone of a coconut tree at Silkwood with a wooden paling speared through the trunk. After Cyclone Yasi, numerous examples of debris captures by vegetation could be seen in Cardwell, including sheets of corrugated iron caught by trees more than 20 metres off the ground. A corrugated iron roof that had peeled off a holiday villa was found wrapped around a golden cane palm only metres away, preventing that debris from gathering momentum and causing significant downwind damage. While Mason & Haynes (2009) note that trees can also be a significant source of flying debris themselves, the potential for trees to capture or create flying debris is highly species dependent.

In conclusion, windborne (and water-borne) debris is a significant threat to life and property during

Figure 8 Debris attack can be caused by storm surge - A fallen tree trunk carried by storm surge is prevented from impacting the building by a row of palms (Cardwell – Cyclone Yasi)

cyclones and vegetation plays a role in capturing this flying debris. Removal of trees from around properties can leave them exposed to debris attack and increase the likelihood of debris from that structure damaging structures further downwind. Although fallen trees can also capture fallen debris, careful species selection may be necessary to ensure that vegetation captures rather than contributes to flying debris.

How do cyclones damage trees

Cyclones can be quite damaging to the environment. In addition to the impacts on coral reefs and coastal erosion, the cyclonic winds strip foliage, uproot trees and flatten crops, while the salt spray blown off the oceans is driven inland where it burns and poisons coastal vegetation (Terry 2007).

Considering the significant impact of cyclones on the environment, infrastructure and human lives, surprisingly little published research is available, and even less of this literature relates to impacts on vegetation. For example, Terry (2007) examined the impact of cyclones on coral reefs, landslides, river hydrology, and fluvial geomorphology, but made no comment relating to vegetation impacts. In many technical reports on cyclones, 'trees' is a term used generically, with no attempt to distinguish between species or any discussion regarding differences in patterns of damage. It is a view widespread throughout the community that it is bad to have trees during cyclones, and numerous trees are often removed needlessly when a cyclone threat is issued.

In contrast to earlier cyclones such as Leonta and Sigma, there is a much broader range of plant species now being grown in Townsville urban areas. Many of these are native plants of various provenance, and many others introduced, originating from a broad range of countries. The plants have enormously variable traits including, but not limited to:

- height;
- plant form and structure;
- growth rates;
- ecological niche and regeneration pattern;
- wood density and strength;

- leaf size, shape, arrangement and strength of attachment;
- wind resistance (ie aerodynamic drag or 'sail');
- root morphology, structure and penetration depth;
- rates of water uptake and transpiration;
- evolutionary exposure to extreme wind events; and
- resistance to drought, flood, fire, frost and insect damage

In consideration of these fundamental differences between trees, it would be unreasonable to assume that these differences did not cause significant differences in resistance to wind impacts. The generic use of the term 'tree' when describing impacts of cyclones completely fails to recognise that a broad spectrum of responses to cyclonic winds exists amongst different tree species.

Available Literature: The majority of research undertaken on the impacts of wind on trees is from temperate zones, particularly North America and Europe, and particularly on a small number of commercial forest species. The majority of Australian work on the impacts of cyclones on trees was done in the wake of Cyclone Tracy (eg. Cameron *et al.* 1981, Fox 1980, Stocker 1976, Van der Sommen 2002) and Cyclone Larry (e.g. Bruce *et al*. 2008, Curran *et al*. 2008, Kanowski *et al* 2008, Kupsch 2006, Pohlman *et al.* 2008, Turton (2008, 2008a). In most cases of reports on cyclone damage, the data recorded is observational with no pre-cyclonic baseline survey available to assess impacts. Some of the most extensive research ever undertaken into the impacts of cyclones on trees was undertaken by the Environmental Research Institute of the Supervising Scientist (ERISS) following the impacts of Cyclone Monica on Arnhem Land and Kakadu National Park in 2006 (Saynor *et al*. 2009), but sadly this extensive data set has not yet been analysed and published.

Types of Damage: The key to understanding why different species might show different levels of susceptibility to cyclones and different patterns of damage, is an understanding of how and why trees are damaged during cyclones. Tree damage following Cyclone Tracy was divided into the following categories by Stocker (1976):

- Windthrow (uprooted);
- Crown damage – a) leaves and twigs removed, b) branches torn off;
- Bole (trunk) broken or severely fractured;
- Bole leaning; and
- Tree standing but dead

Most research into the impacts of cyclones on trees uses a variation on these categories, though most studies do not consider the loss of leaves and twigs as noteworthy damage. Following Cyclones Winifred, Larry and Yasi, loss of foliage was nearly 100% for rainforest trees in proximity to the eye of the cyclone. It should be noted however, that trees may eventually die due to excessive loss of branches or leaves (Asner & Goldsten 1997). Other damage can be caused by the twisting or whipping of the trunk, slapping of branches, exposed existing points of weakness, bark stripped by flying debris and sand blasting (Stocker 1976). Following examination of beach fronts damaged by Cyclones Ului and Yasi, it is possible to add collapse due to undermining of substrate by wave action, and bark stripped by abrasion and wave action.

It should be noted that during a cyclone, all of these impacts may occur to different trees. It follows logically, that since trees do not all show the same patterns of damage during cyclones, that trees possess different characteristics that make them more or less susceptible to different types of damage. In many cases, these differences are not necessarily environmental but are species-specific. This section will explore the main types of severe tree damage – failure of the trunk, or failure of the roots (windthrow), which may or may not be related to each other, depending on the tree species.

Trunk failure

Examination of the damage characteristically experienced by particular species shows that a number of species are more likely to suffer failure of the trunk than other damage types. Failure of the trunk is usually a consequence of excessive bending (Wood 1995), or more precisely, where the wind loading on the tree exceeds the stem strength, but is not powerful enough to dislodge the roots (Asner & Goldsten 1997). As soil strength diminishes with degree of saturation, lower rates of wind loading are required to cause uprooting. Logically, root strength will be greater in drier soils and the trunk becomes increasingly likely to reach its failure threshold before the root system does. Trunk failure is a more noticeable feature of tree damage when the soil is relatively dry prior to the cyclonic impacts (Jackes 2011). In addition to the damage caused by excessive bending it has been shown that torsion (rotational bending) is just as important in some species (Skatter & Kucera 2000). Bending only occurs as an isolated force if the wind has no small-scale variation or gradients, and the canopy has perfect rotational symmetry, which is rarely the situation in the real world (Skatter & Kucera 2000).

Notwithstanding climatic influences such as rainfall and wind profile, the likelihood of a tree suffering trunk failure is dependant on a range of other factors that vary between individuals and species, including.

- wind resistance: Trees vary in terms of aerodynamic drag, also known as the 'sail' or wind resistance (Wood 1995);
- flexibility: Measured by Elastic modulus - trees with a lower elastic moduli bend more easily when subjected to lateral wind loading, allowing the tree to shed the wind and remain upright (Asner & Goldsten 1997);
- wood density: Measured as the mass per unit volume, wood density is related to the ability of wood to resist torsional forces (Asner & Goldsten 1997);
- crown symmetry: the likelihood of the tree being subjected to torsional forces (Skatter & Kucera 2000); and
- presence of hollows (Stocker 1976) or other trunk defects.

There have been numerous mathematical equations and computer models generated to explore the physics of tree mechanics. Understanding the likely influences on a tree may require calculation of the trees mass, wood density, bending stiffness, sway frequency (natural resonant sway), and damping (rate at which oscillations of tree sway decay after a disturbance to return to normal position) (Wood 1995). While the behaviour of trees has been tested in wind tunnels as long ago as 1963, detailed studies into the physics of tree movement and physics has never been done with Australian trees, and the research is limited to a small number of commercial tree species from the northern hemisphere. Modelling tree behaviour in wind becomes increasingly complex when you understand that wind stresses on a tree are not static, but dynamic, due to the gusting effects, which vary in both intensity and frequency (Wood 1995). The interactive forces of the biomechanics of the tree and the highly variable forces at work during wind gusts are highly complex. While various components are well understood, physicists have yet to perfect a mathematical equation to integrate all the variables that explain tree responses to wind.

Stresses from wind loading often cause failure

Figure 9 Failure of large branches (e.g. Terminalia) and trunks (e.g. Khaya)

of the trunk, in contrast to instances where vibration loading (oscillation) is the primary stress, causing root failure (Wood 1995). Within the trunk, wood failure can be seen to be related to damage to the wood cells. These may experience damage from:

- tension (pulling):
- compression (pushing / pressing); or
- torsion (twisting) (Van der Sommen 2002).

Generally, the windward side of the trunk is under tension, while the leeward side is under compression, particularly in the outer sapwood and base of the stem (Van der Sommen 2002). Cells may buckle and bend if subjected to extreme compression, and this is the mostly likely damage to occur, but the tree may not fail if cells under tension don't snap (Van der Sommen 2002). Changes in wind direction commonly experienced near the eye of the cyclone may cause twisting of the trunk, leading to failure (Jackes 2011). Additionally, trees with very asymmetrical crowns will also have asymmetrical wind loading, which may also lead to twisting and spiral fractures of the trunk. Height may play a significant contributing factor to trunk failure. In an open situation, the tree may experience relatively uniform wind loading along the length of the trunk, but in reality, taller trees will usually have maximum loading, creating excessive stresses near the top (Wood 1995).

As trees, particularly conifers and dicots, are subjected to strong winds, the trees respond with changes to their wood anatomy, developing compression and tension cells (Van der

Sommen 2002). This observation gives weight to the "adaptive growth hypothesis", which suggests that trees will only grow strong enough wood to resist the stresses that it has experienced during its life, so in an extreme event, trees will be susceptible to forces beyond those it has previously experienced (Wood 1995). This may explain why trees are more susceptible to wind damage after removal of shelter (Wood 1995). Trees may not have the opportunity to respond to wind by adaptive growth if the trees are over 1 m tall when planted, and then are staked for too long (Jackes 2011): Interestingly, monocots such as palms don't have secondary xylem tissue and don't develop reactionary compression or tension cells, which may partially explain their flexibility in strong winds (Wood 1995). Increased trunk flexibility is of advantage during extreme wind events as this allows the tree to shed the lateral wind force and prevent snapping (Asner & Goldsten 1997).

The correlation between wood density and cyclone resistance is common in the cyclone literature, since increased density generally correlates with increased mechanical strength (Van der Sommen 2002). There have been a number of reports suggesting that increased wood density results in lower rates of stem breakage (e.g. Curran *et al* 2008, Putz *et al*. 1983, Van der Sommen 2002, Van Gelder *et al*. 2006), while others have found no correlation (e.g. Asner & Goldstein 1997). Different tree species show a significant variation in wood density, and this is often related to the life history of the plant. At either end of this spectrum are two negatively correlated traits:

- resistance – the ability to withstand disturbance
- resilience – the ability to recover from disturbance (Curran *et al* 2008).

Resistant species generally have increased wood density, leading to increased strength and stiffness (Van Gelder *et al*. 2006), but this comes at a cost. As trees allocate greater resources and biomass towards dense timber, this results in slower growth rates (Curran *et al* 2008). Many of these species tend to be shade-tolerant as juveniles or 'k strategists'. At the other end of the spectrum are the faster growing light-demanding pioneers or 'r strategists'. These species have low wood density, and are more susceptible to trunk failure but have the highest rates of resprouting and fastest resprouting response times post-cyclone (Curran *et al* 2008). It has been suggested that the ability of a tree to snap and resprout rapidly allows these trees to maintain a competitive advantage over species regenerating from seed (Asner & Goldsten 1997). This spectrum from slow growing shade tolerant species with high wood density to fast growing light-demanding species with low wood density and high resprouting rates, is therefore also a spectrum for the likelihood of trees to suffer significant trunk and limb damage during cyclones. While Roach (2000) suggests that taking any particular species and growing it too fast with the aid of water and fertiliser will result in short fibres and weaker wood, Van der Sommen (2002) states that increasing growth rates does not necessarily result in lower wood density.

In north Queensland, and across northern Australia in general, trunk failure is often related to the hollowing of the tree trunk by termites. Following Cyclone Tracy in 1974, it was found that the level of crown damage in eucalypt forests was proportional to the degree of termite damage (Stocker 1976). Although termites attack a range of species, Acacias and Eucalypts are most susceptible to termites (Jackes 2011), particularly the *Coptotermes* and *Mastotermes* timber feeding species. As a hollow trunk bends, lateral forces increase the curvature of the hollow, causing 'hoop' stresses, and when these stresses exceed the circumferential strength, splitting will occur (Mattheck *et al* 1995). Susceptibility to termite attack may therefore be seen as a surrogate for susceptibility to trunk failure during cyclones. Termite damage to trees is widespread, even in urban areas, but can be difficult to diagnose. The presence of termites can be confirmed by drilling a hole into the centre of the trunk, or looking for tell-tale dead outer branches and twigs (Jackes 2011).

Generally speaking, tree trunks fail when the wind loading on them exceeds the mechanical strength of the wood, and this is often a function of the level of wind resistance of the tree canopy (Yuruga Nursery 2009). Increasing the crown size by applying fertilisers and irrigation can increase the degree of wind damage (Van der Sommen 2002). During cyclones, the wind loading on a trunk will often reduce dramatically as the plant loses leaves and branches, and the sacrifice of this material can often save the main trunk from snapping (Jackes 2011, Stocker 1976). Similarly, arborists suggest that wind loading can be reduced on the plant prior to cyclones by opening the canopy to allow wind to pass through it (Roach 2000, Yuruga Nursery 2009). The Australian Standards for Pruning Amenity Trees (Standards Australia 2007) suggests that lopping is not a good practice as the resulting regrowth has poor connections and attachments and is more likely to fail in the future (Standards Australia 2007). Some trees have inherent weaknesses in their structure, such as poor branch attachment, existing injuries, bark inclusions or termite damage, and these weaknesses will manifest themselves during wind loading. These limbs or points of weakness are generally targeted by arborists who avoid allowing too much weight to develop on a poor attachment (Roach 2000). Yuruga Nursery (2009) suggests that young saplings are more likely to be top heavy, however, this is in contrast to empirical results provided by Werner & Murphy (2001) that suggests that trees become increasingly top heavy with age (see Section 5.3.2 below).

Root Failure (Windthrow)

The other primary cause of tree failure is uprooting, generally known in the literature as ‘wind throw’. Roots fail when the lateral stresses on the tree exceeds the lateral strength of the roots (Mattheck *et al* 1995), which, as previously discussed, may be related to low rates of trunk failure (Van der Sommen 2002). Therefore, uprooting may be more commonly associated with trees with high wood density, compared to higher rates of trunk snapping associated with lower wood density (Asner & Goldsten 1997). Although some studies (e.g. Coutts 1983) have used static tension via winches to measure root stability, wind throw is actually a interactive process that combines wind, tree crown, stem deflection, tree vibration, their oscillating forces and their associated moments (Watson 1995). Note that ‘moment’ is a physics term used to denote the tendency of a force to twist or rotate an object, where the distance of the applied force from the fulcum (pivotal point) is critical.

In keeping with the theme of the “adaptive growth hypothesis”, trees will grow adaptively to increases in lateral stress by increasing the size and weight of their root systems (Mattheck *et al* 1995, Wood 1995). However, although the root system may expand, the mechanical strength of the soil in which the tree is anchored does not, which is one of the reasons why bigger trees become more susceptible to uprooting (Wood 1995). Another reason why taller trees may be more susceptible to uprooting may be due to changes in the proportion of the plant’s biomass that is allocated to the roots. Studies in Kakadu showed that as trees grew and their trunk diameter (DBH) increased, there was a decreasing proportion of total biomass below ground (Werner & Murphy 2001). The root / shoot ratio for Darwin stringybark (*Eucalyptus tetrodonta*) varies from 0.5 for small trees <10cm DBH to 0.4 for trees with 20cm DBH and 0.25 for larger trees 40–55 cm DBH (Werner & Murphy 2001). Put simply, it indicates these trees become increasingly top-heavy with increased size, which would also help explain why larger trees were

Figure 10 Root ball failure in yellow flame tree (Peltophorum pterocarpum)

more susceptible to uprooting. The perception that trees are increasingly susceptible to cyclone damage with increased size is reflected in results from Cyclone Tracy, which showed that 43% had increased rate of root failure with size, 23% had same rates of root failure at different size classes, and 34% had no clear trend (Van der Sommen (2002). Observations in following Cyclones Monica and Yasi indicates that yellow flame tree and African mahogany show marked increases in uprooting and trunk snapping with increased size, with only low levels of damage recorded on trees less than 3.5-4m in height. One avenue of yellow flame tree in Annandale, Townsville with an average height of 4 metres suffered very little damage, while another nearby avenue of the same species 6-8 metres in height suffered 100% damage, with 53% uprooted (see Table 28).

The strength of the root system and its resistance to failure may be related to a range of factors. In the Kakadu area, where much of the area is characterised by a shallow and largely impervious ferricrete layer, the unpublished results of Saynor *et al*. (2009) suggests that soil type and depth play a significant role. Examination of eucalypt root systems in these shallow soils showed 70% of the root biomass was at less than 20-cm soil depth (Werner & Murphy (2001).

Root penetration may also be limited by an excess of soil water levels, as high water tables tend to lead to shallow root systems that are more susceptible to uprooting (Rodgers *et al*. 1995). Where high soil moisture is not a permanent feature, short-term increases in soil moisture from excessive rainfall may also reduce soil strength. Soil strength is a function of the cohesive forces between particles and the friction between those particles. When soil becomes waterlogged, the cohesive forces between particles decreases, clay particles separate and the friction between the particles decreases, allowing easier slippage. As a tree sways with increased wind loading in saturated soils, pressures on the root system creates high pore water pressures in the soil, leading to hydraulic fracturing in the root plate (Rodgers *et al*. 1995). Once this hydraulic fracturing has occurred, the tree is able to sway with greater movements at lower wind speeds, increasing the bending moments that eventually cause the tree to uproot (Rodgers *et al*. 1995). In terms of the sequence of events leading to uprooting, soil resistance is therefore of highest importance in the early stages, but least in the later stages once the tree movements are increasing (Van der Sommen (2002). It is interesting to note that following Cyclone Yasi, many otherwise susceptible trees showed a reduced rate of windthrow when growing in car parks. It is hypothesised that the soil is more likely to retain its high mechanic strength under the impervious asphalt, and that tree roots may be more likely to be deeper in these relatively dry soils. Anecdotally, most people associate high levels of windthrow with saturated or waterlogged soils, and Stocker (1976) also noted that after Cyclone Tracy windthrow was worse in poorly drained sites where soil moisture was highest. In the USA, hurricanes that were preceded by significant rainfall generated lots of uprooted trees, compared to those with relatively low rainfall where many trees snapped (Van der Sommen (2002). However, although cyclones do vary considerably in terms of associated rainfall, they do generally bring abnormal rates of rainfall. Even Cyclone Yasi, considered by many people to be a relatively 'dry' cyclone, still delivered more than 130mm of rain to Townsville, and considerably more in some areas. It should be noted that rainfall in cyclones is not evenly distributed but falls in the well-defined spiral rain bands, so rainfall amounts can vary widely across an area (Terry 2007). The ability of a tree to withstand root failure in saturated soils should be considered alongside resistance to stem breakage as part of a trees resistance to cyclonic impacts.

In resisting the influence of reduced soil strength, the shape and size of the root system is also of great importance. An increase in extent and size of the root system provides stability through the increased weight of the root soil plate (Van der Sommen 2002). Greater stability also occurs where the roots were growing in the direction of rocking movement than those growing at right angle, so trees with a more even and uniform root spread are generally more stable (Rodgers *et al*. 1995). On the leeward side of the rocking tree, lateral roots act as a cantilevered beam, which in turn determines the location of the fulcum for the tree as a whole (Coutts 1983).

Root Failure in Urban Gardens

In urban areas, failure of the root system may often be a consequence of the management regime of that tree. The role of maintenance regimes is highlighted by the analysis of tree fall during Cyclone Tracy where it was found that although there was no significant difference in cyclone damage between native and exotic garden plants (in contrast to observations by Oliver & Wilson (1986) following Cyclone Winifred), there was a significant difference between cultivated and naturally grown native trees (Van der Sommen 2002). Management techniques that may alter a plants resistance uprooting during cyclones includes:

- planting;
- maintenance;
- fertilising;
- watering and irrigation; and
- mulching (Van der Sommen 2002).

The ability to withstand cyclonic events may depend on the condition of the tree at the time of planting. Root-bound (also known as 'pot bound') trees will have a compromised root system, so it is preferable to plant smaller trees less than 1 metre high (Jackes 2011, Roach 2000). When advanced trees are planted and staked for too long, this denies them the early exposure to wind stresses that would normally cause the release of hormones to stimulate growth of the cambium (Jackes 2011). Examples of this could be seen in Townsville following Cyclone Yasi where recently planted lilly pillys (*Syzygium* spp) were uprooted or developed a lean because the crown was too heavy and the plants had not had the opportunity to develop a compensatory root system (Jackes 2011).

Similarly, site preparation is also vital for the development of a healthy root system. Regardless of the natural species-specific shape of the root mass, most trees will develop shallow root systems of reduced stature if planted into small holes in a hard substrate (Yuruga Nursery 2009). Development of a healthy root system commonly requires that the soil surrounding the seedling be loosened to allow the root system easy penetration (Yuruga Nursery 2009). In soils with hard clay, gypsum may need to be applied at rates of 0.5-1kg/m or higher to aid penetration of the clay (Roach 2000) To ensure that trees integrate with the surrounding soils, Roach (2000) also suggests that the hole not be backfilled with a different soil type. An example may be the failure of Hill's weeping fig (*Ficus microcarpa* var. *hillii*) in Ayr following Cyclone Yasi, which was attributed to the liquefaction of soil within large holes dug for advanced specimens (Tano Buono Burdekin Shire Council pers. comm.). The shape of the tree should also be considered – the tree should be well-balanced with no co-dominant leaders (Roach 2000).

Inappropriate watering regimes have frequently been implicated in causing shallow rooting, leading to increased rates of windthrow. Regular shallow watering ensures the shallow surface of the soil remains moist, and removes any incentive for deeper roots to develop. Shallow roots will then develop with increased susceptibility to cyclone damage (Yuruga Nursery 2009). By contrast, plants that are watered thoroughly only every few weeks tend to develop deeper and stronger root systems as the roots will need to go deeper into the soil to seek water (Yuruga Nursery 2009). One suggested technique is to insert a pipe beside the tree at the time of planting, and to fill it with water weekly to encourage deeper root growth (Jackes 2011). It is considered desirable to extend the intervals between watering to as long as possible without the garden suffering (Yuruga Nursery 2009). An example of how watering may influence root development is provided by Deborah Bisa; a resident of Maningrida during Cyclone Monica in 2006. Her observation were that a stand of cypress pine (*Callitris intratropica*) growing on the outskirts of town and never watered suffered almost no damage, while another stand subjected to regular watering sustained a high proportion of loss due to uprooting.

Following planting, it is also desirable to keep the plant healthy and free of injury and disease, particularly *Ganoderma* fungus that attacks damaged trees (Roach 2000). It is therefore important to minimise root damage from trenching, digging or pipe works as this may lead to infection and disease (Roach 2000).

Influence of Clump Planting

It is considered preferable to plant trees in clumps rather than as isolated individuals, as clusters of trees will support each other (Roach 2000). In groups and clusters of trees, the root systems of different trees may graft together to form unions, that allow sharing of nutrients and water, and subsequently increase wind resistance (Van der Sommen 2002). Following Cyclone Tracy, it was found that decreased cyclone damage to trees occurs with increased stand density (Van der Sommen 2002). Following an inspection of the Ross River Bush Garden in Townsville after Cyclone Yasi, it was obvious that some species normally cyclone prone had received protective buffering from the surrounding vegetation. Further evidence of buffering and mutual support was evident where stands of trees running at right angles to the direction of wind were extensively windthrown, but rows of trees running in the axis of wind direction suffered damage only to those most exposed individuals (Jackes 2011).

In urban areas where vegetation is quite patchy, gaps of lawn between trees are critical in reducing stand stability. As the gaps are increased, trees develop weaker wood but are less reliant on mutual support from other trees (Van der Sommen 2002).

While vegetation growing in dense stands obviously has a buffering benefit, the disadvantage is the increased likelihood of being struck by another falling tree or branch. At the Ross River Bush Garden, 4% of all trees had been struck by another tree or branch, making up 14% of all tree damage. In a study of damage to Alexandra palms following Cyclone Larry, Dowe *et al*. (2007) found the highest rate of mortality (18.4%) was in young sub-canopy plants being crushed by falling debris. In addition to the crushing impact of falling branches and trees, the uprooting of some sensitive species (eg *Acacia*s) was seen to have contributed directly to the root failure of adjacent trees. This was also evident after Cyclone Monica in Jabiru where normally highly resistant species were uprooted after a highly sensitive species immediately adjacent was uprooted. It would appear then, that from the perspective of uprooting, a stand of trees may only be as strong as its weakest link and that weak trees undermine the strength of strong trees, rather than strong trees protecting the weaker trees.

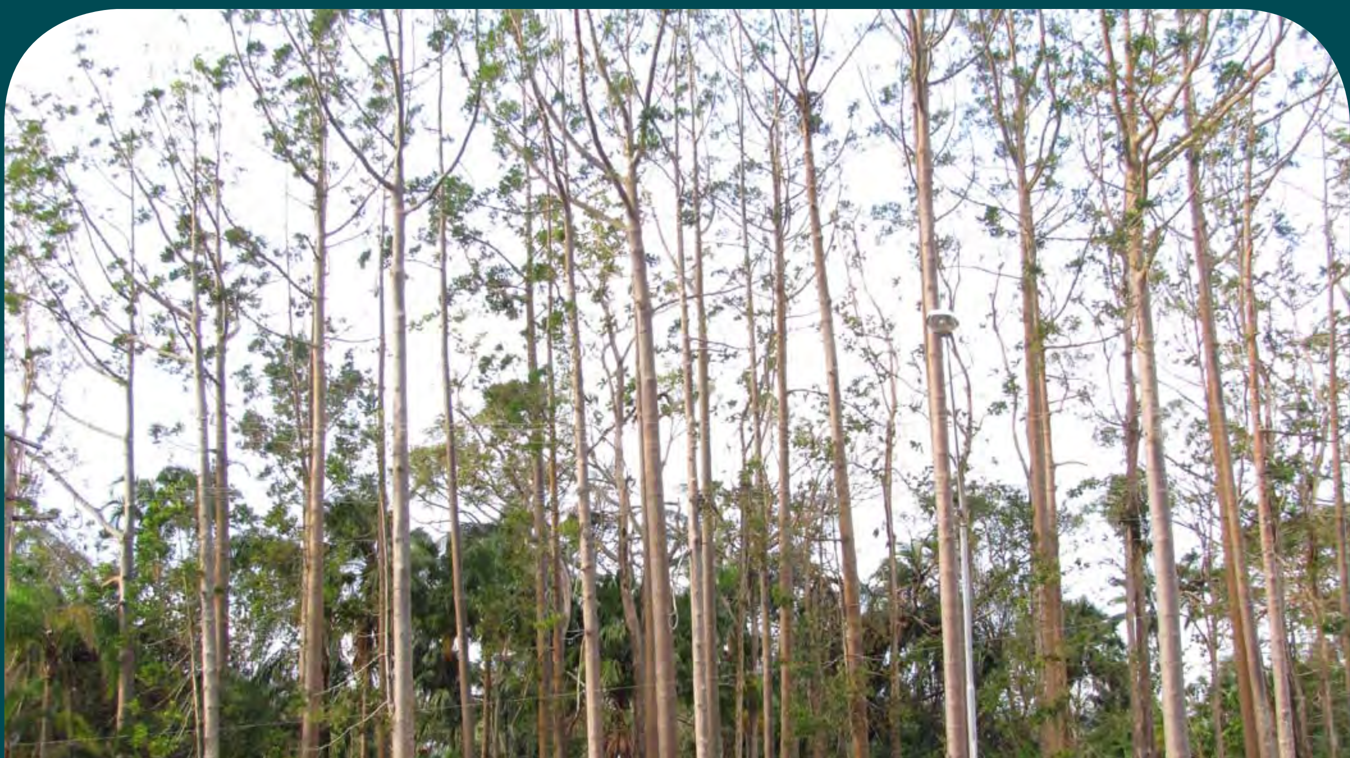
The influence of mutual support can, in many cases, mask the individual cyclone resistance or susceptibility of individual tree species, with height and stature becoming a more noticeable influence (Williams & Douglas 1995). In particular, the taller trees have increased exposure to damaging winds, making them more susceptible, and where trees are grown too close together, trees become relatively taller compared to the trunk diameter, which also increases their susceptibility to breakage (Williams & Douglas 1995). In a forest canopy, over-storey dominants that are also fast-growing pioneer species are particularly likely to be damaged (Foster 1988). For example, at the Ross River Bush Garden, it was obvious that wind speeds were significantly higher above than below the average canopy height, evidenced by many emergent trees having their trunks sheared off at the average canopy height. In contrast, isolated trees, though denied the mutual support of trees in clusters, have a more even taper and are relatively more stable (Van der Sommen 2002).

In summary, a high level of variation can be expected when examining the response of trees to cyclonic winds, even when comparing between cyclones of the same category (strength), or between different locations subjected to the same cyclonic event. A summary of the influence of these varied impacts on tree stability are shown below in Table 6:

Table 6 Influence of variable characteristics of tree susceptibility to cyclone damage

Characteristic	Reduces survival	Increases survival
Proximity to other trees / buildings	Isolated trees don't have mutual support from other trees, but trees in stands may suffer impact from other trees falling	Clump plantings provide mutual support but isolated trees have a more even taper and are more stable
Position in landscape	Exposed positions such as beachfronts and hilltops receive strongest unbuffered winds	Trees in valleys and on leeward sides of hills may escape damaging winds
Size at planting	Trees planted out as advanced specimens (eg 25 or 100L bags) are very top heavy with little anchoring root support	Trees planted out when very young have a greater opportunity to establish anchoring tap roots.
Overall height	Taller trees have a decreased root / above ground ratio, are more exposed to damaging winds and are subjected to increased leverage	Younger plants have a more even root / shoot ratio, gain protection from taller surrounding vegetation, have less thickening of the woody tissue making them more flexible
Crown symmetry	Asymmetrical crowns can lead to torsion or twisting of the trunk, causing spiral fractures	Symmetrical crowns lead to more even wind loading along the trunk
Root depth	Shallow roots are less stable and are less able to withstand the bending moments of the root mass	Deeper roots provide deeper anchorage and are more likely to be anchored in soil that is drier with increased mechanical strength

methodology



Methodology

Limitations

This report is based on observational, rather than experimental data, and as such is limited by what statistical analyses can be applied. Areas subjected to different wind speeds had different soil types and topography, were subjected to differing amounts of rainfall and impacts by storm surge. Trees varied considerably in terms of size, health, shape, damage by termites, conditions at the time of planting and post-planting maintenance such as watering and pruning. One advantage relating to this study has been the very large sample sizes available. It is assumed that all species are subject to the same degree of variability in terms of cyclonic condition and tree husbandry, and only by merging the large sample sizes from the various areas, can we expect to see general trends and patterns emerging.

Sampling was dictated by several overriding considerations:

- Sampling should in no way interfere with the operations of emergency services and clean-up crews;
- Personal health and safety was to remain paramount at all times; and
- Private property boundaries were to be respected at all times

While future analysis of aerial photography (before and after Cyclone Yasi) may overcome some of these limitations, the observations included in this report are primarily restricted to trees readily observable and identifiable from public roads and areas.

The species of all individual trees were identified. The identification of *Tabebuia* species is complex, and its possible that several of these species may have been grouped as one. Similarly, *Eucalyptus tereticornis* and *E. camaldulensis* look very similar without leaves, and it's possible that these two species have been combined in some instances.

Species Contribution to damage and green waste

Only damaged trees were counted, and trees were assigned to one of the following mutually-exclusive damage classes:

- Branches broken (one or more significant branch not including the main leader, its loss noticeably altering the plant shape and /or generating a large amount of green waste)
- Trunk snapped (loss of the main trunk or leader)
- Uprooted (plant is laying over but roots are not necessarily exposed)

Leaning plants were only considered 'uprooted' if the author thought that the plant would need to be removed or straightened as a result. Damage was only recorded where it was caused by the cyclone. In contrast to post-Tracy studies by Fox (1980), trees that were damaged by being struck by another falling tree or debris were not included. Including trees damaged by other trees masks their actual resilience to cyclonic winds. All records were collected within three weeks of the cyclone, so no assessment is made as to the long-term survival of the trees.

Simple counts of damaged trees is not truly reflective of the contributionof each tree species to the total mass of green waste. A formula was applied to take into account the difference in green waste generated depending on the size of the plant, and also the level of green waste generated by different types of damage:

Total Green Waste per species = Tree size x ((Number uprooted x 5) + (Number with trunk snapped x 2) + (Number with broken branches x 1))

The values assigned for tree size are 5 for large trees, 2 for medium trees, and 1 for small trees and shrubs. No allowance is made for age of the individual, so it is assumed that the formula is applicable for the average size value for that species. Generally, young plants suffered little damage, so the vast majority of trees recorded were sexually mature. This approach does not take into account:

- numbers of branches broken;
- whether trees with broken branches or trunks were later completely removed; or
- whether some uprooted trees were later recovered by straightening rather than sent to green waste

Species contribution to power failure

Ergon Energy identified the locations of individual power failures throughout Townsville following Severe Tropical Cyclone Yasi. An assessment was undertaken of trees responsible for power failure in the Townsville suburbs of Aitkenvale and Mundingburra, as high resolution LIDAR aerial imagery was available for these areas. A total of 25 locations were identified from Ergon and Townsville City Council data, and subsequently assessed through on-site inspections.

Site inspections were undertaken approximately one month after the cyclone, and in all instances the tree responsible for the power failure had been removed from the powerline and broken parts removed. In some sites, only a crater remained. In many instances the precise locations of fallen powerlines were provided by local residents. Tree species responsible for individual power outages were identified using the following techniques:

- identification from aerial photographs and comparison with reference trees;
- distinctive bark and regrowth;
- fallen foliage and seed pods around craters; or
- photographs provided by nearby residents

At each location, the following data was collected:

- street address;
- tree species;
- damage type (uprooted, trunk/leader snapped, significant branch broken);
- side of road relative to overhead powerline damaged; and
- land tenure (street tree or tree on private land)

At several locations, no evidence of tree impact on power supply was evident, and cross referencing to information collected by Ergon showed that at least four of the mapped sites were not locations of power failure.

Proportions of individual tree species

Estimating the proportions of individual tree species damaged was generally difficult in suburban areas, since the author generally didn't have access to private property where the majority of the trees were growing. Therefore the proportions of trees damaged for each species, were calculated opportunistically where avenues of single species were encountered. In tree avenues where damage levels were estimated as a proportion of the total, additional categories of tree health were used. The trees were placed into the following categories:

- good (no visible damage to the tree apart from loss of foliage);
- small branches (subjective, but generally a branch comprising only a small proportion of the tree and generating a minimal amount of green waste);
- large branch (subjective, but a significant branch not including the main leader, its loss noticeably altering the plant shape and generating a larger amount of green waste);
- trunk snapped (loss of the main trunk or leader); and
- uprooted (plant is laying over but roots are not necessarily exposed)

Tree species response to different cyclone categories

Tree species responses to cyclonic winds were assessed at different locations along the Cyclone Yasi wind speed gradient. Information relating to tree response to different cyclonic winds was supplemented by literature specifically relating to tree responses to particular category cyclonic events. The following literature and data sources (Table 7), were incorporated into the data set:

Table 7 Available literature providing as assessment of cyclone impacts on trees in different cyclone categories

Cyclone Category	Relevant Literature
1	Bowman & Panton (1994), Calvert (2000)
2	Calvert (2006),
3	Oliver & Wilson (1986)
4	Bruce *et al* (2008), Cameron *et al.* (1981), Curran *et al* (2008), Donohue (1975), Fox (1980), Kupsch (2006), Pohlman *et al* (2008), Stocker (1976), Tucker *et al.* (2006), Turton (2008),

Tree damage data was also collected by the author following Cyclones Justin (March 1997 – Category 1), Cyclone Tessie (March 2000 – Category 1), Cyclone Monica (April 2006 – Category 3) and Cyclone Ului (March 2010 – Category 2).

The likely response of trees to a particular category of cyclonic event is mapped for 143 species and is provided in Appendix D. Wind damage is separated into the several categories ('Uprooted', 'Trunk broken' and 'Branches broken '), since there is no reason to believe that one of these events will naturally follow another. It is acknowledged that many other factors apart from species identity can influence the response of an individual tree to cyclonic winds. Cyclone response profiles assume that the plant is mature and in average health for that species, since old and senescent trees are likely to be more susceptible to damage. The predicted response also assumes that the plant is in an average location for that species, and is neither unusually exposed or protected from damaging winds.

results and discussion

Results and Discussion

Species Contribution to damage and green waste

The street surveys conducted around Townsville following Cyclone Yasi resulted identified 2,584 individual trees in 151 species that exhibited some degree of significant damage, including 54 species introduced to Queensland. This figure represents only a sample of the total population, and does not imply that all damaged trees were seen and counted. If the unverified account of 65,000 trees being damaged across Townsville was accurate, then this sample amounts to only 4%., However as no such records were collected it is unlikely that this estimate of total number of damaged trees is accurate. Damaged trees surveyed in this study included:

- 1,014 trees uprooted or with a significant lean (39.24%)
- 811 with a broken trunk or main leader (31.38%)
- 763 with large broken branches (29.52 %)

A complete list of these damaged trees in provided in Appendix A. There is a considerable likelihood that at least a proportion of tree failures may be due to confounding factors, such as those previously described including poor site preparation, and inappropriate pruning and watering regimes. Therefore plant species that are represented by only a small number of individuals may be disregarded for now, as not being able to provide any clear insights into the role of species in cyclone resistance. Species that have large numbers of individuals damaged would be likely to include individual trees that were properly planted, pruned and managed, but had inherent weaknesses that contributed to their level of cyclone damage.

Using a simple measure of number of individuals recorded, the 20 most commonly damaged trees in Townsville following Cyclone Yasi are shown in Table 8 below:

Table 7 Most frequently damaged trees in Townsville following Cyclone Yasi (* - denotes species introduced to Queensland) (Tree size : L= Large, M = Medium, S = Small)

Scientific name	Common name	Tree size	Uprooted	Broken trunk	Broken branches	Total plants
*Peltophorum pterocarpum**	yellow flame tree	L	169	178	193	540
*Tabebuia impetiginosa ** (syn. *T. palmeri*)	pink trumpet tree	M	55	175	3	233
*Khaya senegalensis**	African mahogany	L	116	21	17	154
Eucalyptus tereticornis	river blue gum	L	53	65	30	148
*Tabebuia heterophylla** (syn. *T. pallida)*	pink trumpet tree	M	5	39	61	105
*Albizia lebbeck**	Indian siris	L	24	9	27	60
Corymbia tessellaris	Moreton Bay ash	L	29	10	17	56
Ficus benjamina	weeping fig	L	38	6	10	54
*Syzygium cumini**	Javan plum	M	9	25	15	49
*Roystonea regia**	Cuban royal palm	L	5	1	41	47
*Duranta erecta**	duranta	S	39	4		43
Eucalyptus crebra	narrow-leaved ironbark	M	8	12	22	42
*Samanea saman**	rain tree	L	2	4	36	42
*Ficus benghalensis**	banyan fig	L		2	36	38
*Pterocarpus indicus**	Burmese rosewood	L	17	12	8	37
*Citharexylum quadrangu-lare**	fiddlewood	M	22	12	2	36
Eucalyptus platyphylla	poplar gum	L	13	11	10	34
*Caesalpinia ferrea**	leopard tree	M	28		4	32
Corymbia citriodora	lemon scented gum	L	16	11	5	32
Melaleuca viminalis	weeping bottlebrush	S	6	9	15	30

Since plants vary considerably in size, some species make a larger contribution to green waste than species with a smaller stature, and uprooted plants generate more green waste than those that simply drop branches. Therefore the survey results were corrected to allow for differences in tree size and contribution of damage type to generate a 'Green Waste Score' using the following formula:

Green Waste Score = Tree size x (Number uprooted x 5) + (Number with broken trunk x 2) + (Number with broken branches x 1)

These results are presented in Table 9 below. It should be noted that the 'Green Waste Score' is a relative scoring and does not have any units, though would be proportional to the volume of green waste generated.

Table 9 Plant species contribution to total green waste, based on 'Total Green Waste' Score (* Denotes species introduced to Queensland)

Scientific name	Common name	Tree size	Uprooted	Trunk broken	Branches broken	Total plants	'Green Was Score'
*Peltophorum pterocarpum**	yellow flame tree	5	169	178	193	540	4774
*Khaya senegalensis**	African mahogany	5	116	21	17	154	2959
Eucalyptus tereticornis	river blue gum	5	53	65	30	148	1485
Ficus benjamina	weeping fig	5	38	6	10	54	972
*Tabebuia impetiginosa ** (syn. *T. palmeri*)	Pink trumpet tree	2	55	175	3	233	903
Corymbia tessellaris	Moreton Bay ash	5	29	10	17	56	762
*Albizia lebbeck**	Indian siris	5	24	9	27	60	645
*Pterocarpus indicus**	Burmese rosewood	5	17	12	8	37	457
Corymbia citriodora	lemon scented gum	5	16	11	5	32	427
Eucalyptus platyphylla	poplar gum	5	13	11	10	34	357

Scientific name	Common name	Tree size	Uprooted	Trunk broken	Branches broken	Total plants	'Green Waste Score'
*Caesalpinia ferrea**	leopard tree	2	28		4	32	284
*Spathodea campanulata**	African tulip	5	10	3	2	15	258
*Syagrus romanzoffiana**	queen palm	2	25	1		26	252
*Citharexylum quadrangulare **	fiddlewood	2	22	12	2	36	246
*Cocos nucifera**	coconut	2	24	3		27	246
Terminalia microcarpa	brown damson	5	9	4	11	24	244
*Delonix regia**	poinciana	5	9	3	5	17	236
Melaleuca nervosa	paperbark	5	8	2	2	12	206
*Duranta erecta**	duranta	1	39	4		43	203
*Tabebuia heterophylla** (syn. *T. pallida*)	pink trumpet tree	2	5	39	61	105	189

Examination of the individual species contribution to green waste, shows that five species contributed more than half (55.35%) of all the green waste generated. These species are (in descending order of contribution):

- yellow flame tree (*Peltophorum pterocarpum**);
- African mahogany (*Khaya senegalensis**);
- river blue gum (*Eucalyptus tereticornis*);
- weeping fig (*Ficus benjamina*); and
- pink trumpet tree (*Tabebuia impetiginosa* * (syn. *T. palmeri*))

All five of these species are extensively cultivated throughout Townsville, and while it is not possible to provide an estimate of the percentage of individuals damaged, in each case their contribution to the total green waste is disproportionate to their abundance. For example, while yellow flame trees contributed 23.8% of green waste and 20.89% of individual damaged trees, their abundance in Townsville would comprise less than 5% of Townsville's urban trees, and less than 1% in newer suburbs. Four of these five worst trees are large trees, while the pink trumpet tree is considered a medium sized tree.

It is widely believed in the general community that large trees are more susceptible to cyclone damage than smaller trees and shrubs. The contribution of the different size classes to the overall cyclone damage to trees in Townsville is examined in Table 10 below.

Table 10 Trends in cyclone damage to tree based on tree size

Tree size	Uprooted	Trunk broken	Branches broken	Total species	Total individuals	Green waste
Large trees	545 (53.75%)	378 (46.61%)	519 (68.02%)	44 (19.3%)	1441 (55.77%)	14,900 (74.35%)
Medium trees	337 (33.23%)	396 (48.83%)	199 (26.08%)	80 (35.09%)	929 (35.95%)	4,361 (21.76%)
Small trees / large shrubs	132 (13.02%)	37 (4.56%)	45 (5.9%)	27 (11.84%)	214 (8.28%)	779 (3.88%)
TOTAL	1014	811	763	151	2584	20040

From the data provided in Table 10 above, it can be concluded that:

- the greatest diversity (number of species) impacted by the cyclone was amongst the medium sized trees, but the greatest number of individuals impacted by Cyclone Yasi were large trees
- large trees were the biggest contributors to each of the damage classes (uprooted, broken trunk and broken branches); and
- large trees contributed significantly more green waste than the other two size classes combined.

Not only does the fall of a large tree have greater consequences than that of a smaller tree, but this data shows that the likelihood of a tall tree failing is also higher. It should be noted, however, that all size classes had species that suffered minimal damage, and all size classes had species that were highly susceptible to cyclone damage. Data collected in Kakadu following Cyclone Monica (Saynor *et al*. 2009) will be able to shed light on how increases in height change cyclone susceptibility within a single species, however, this data has not yet been analysed.

It has also been suggested that introduced species tend to perform worse than native plants during cyclones. The contributions of tree species native to Queensland compared to those species introduced to Queensland, are shown in Table 11 below:

Table 11 Trends in cyclone damage to tree based on tree origin

Tree origin	Uprooted	Trunk broken	Branches broken	Total species	Total individuals	Green waste
Native to Qld	309 (30.47%)	269 (33.17%)	265 (34.73%)	91 (59.87%)	839 (32.47%)	6493 (32.4%)
Introduced to Qld	705 (69.53%)	542 (66.83%	498 (65.27%)	61 (40.13%)	1745 (67.53%)	13547 (67.6%)
TOTAL	1014	811	763	152	2584	20040

From Table 11 above, it can be seen that there is generally a greater diversity of native trees being grown in Townsville than exotic species, even accounting for the fact that some species were never recorded because they were never seen damaged. Very few species represented by more than 10 individuals did not suffer some level of damage. It should be noted that species diversity is independent of abundance, and large trees in some Townsville suburbs are dominated by only a handful of species. From the perspective of green waste collection and level of damage sustained by Townsville trees as a result of Cyclone Yasi, exotic species (not native to Queensland) contributed more than twice as much green waste as native trees. There was more than twice the likelihood of a damaged tree being exotic than native, and this was roughly true for each of the categories of damage, especially for uprooted trees. This information, however, does not infer that an exotic tree is more likely to suffer cyclone damage than a native tree because:

- no measure of the relative abundances of native vs exotic trees is available; and
- the full spectrum of cyclone resistance and susceptibility exists for both native and exotic species.

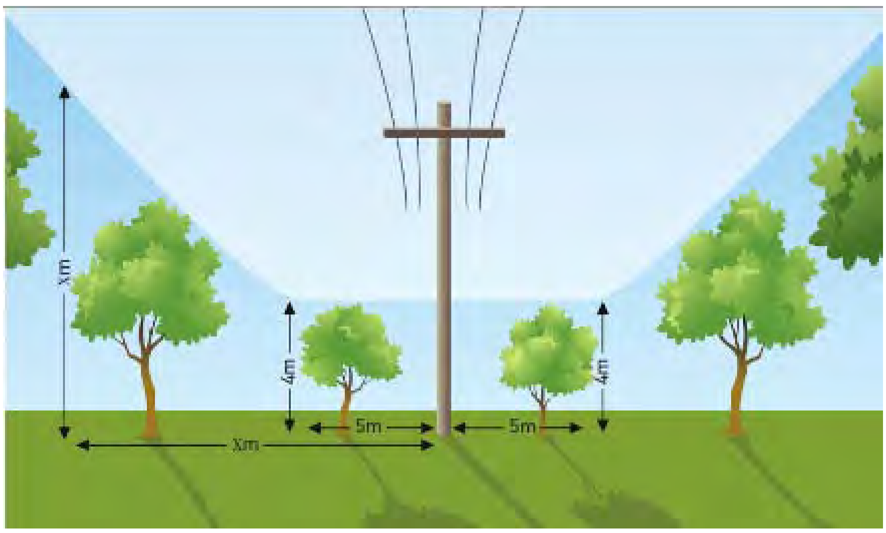
While this data is not as robust as if all undamaged trees had also been counted, this data does provide compelling evidence that the majority of damage caused in Townsville by Cyclone Yasi was not evenly distributed amongst trees, but that a small minority of species contributed an overwhelming majority of the damage.

Species contribution to power failure

Outages from falling trees are a common occurrence during cyclones, and Ergon invest significant time and finances in maintaining vegetation near powerlines. In particular, Ergon have developed a relationship with Greening Australia through the 'Plant Smart' program to assist in educating the planting of appropriate vegetation under and around powerlines. Some of the recommendations for planting trees around powerlines are provided by Ergon (2011).

- carefully choose a powerline-friendly plant;
- plants must be at least three metres from Ergon Energy poles;
- shrubs or small trees can be planted one metre inside the kerb where the council footway is a minimum of four metres wide;
- allow for at least a two metre gap between the service wires to your home and the height of mature trees;
- plants under powerlines must not grow to a height of more than four metres high; and
- trees should be planted the same distance away from the powerline as their expected height, so, if a tree will grow to 5m, it should be planted 5m away from the power pole, or if it will grow to 10m, it should be 10m away.

Figure 11 Tree clearance zones around power lines (Ergon Energy 2009)



Another important component of the ‘Plant Smart’ program is research into vegetation management. Ergon Energy had previously commissioned Brad Jeffers through Greening Australia to investigate damage to powerlines in Innisfail from fallen trees after Cyclone Larry in 2006. He found that most of the vegetation in the heavily impacted zone had lost branches and were covered in new shoots, but commented generally that the ‘Plant Smart’ program was improving vegetation issues in urban areas (Jeffers 2006). A number of problems were identified where vegetation was encroaching into Ergon’s clearance space as defined in Ergon Energy’s Code of Practice Powerline Clearance (Vegetation) 2005. This code specifies that trees be trimmed and pruned to form a 45°angle with the clearance space. One of the biggest issue identified by Jeffers (2006) was the habit of rainforest trees to shed their branches to reduce wind resistance made them a major hazard near powerlines, and that these branches could be carried by wind to create hazards some distance from the parent tree (Jeffers 2006).

To investigate the influence of trees on power outages in Townsville following Cyclone Yasi, a sample of 26 power outage locations were examined in the suburbs of Aitkenvale and Mundingburra, Townsville. Both suburbs have been established for more than 40 years, and are characterised by established gardens with numerous large, mature trees.

Figure 12 Survey locations for reported power outages (red dots = road blocked by tree)

Of the 26 locations, three locations were found not to be the location of a power failure, and one site had a power failure that was due to equipment malfunction. The remaining 22 locations showed that power failure was due to trees coming into contact with the power lines (Table 12). Two reported power failure locations were impacted by the same tree and will be analysed as being the same location hereafter. Therefore, it can be stated that of 22 locations of power failure, 21 of these failures (95.45%) were caused by trees.

Table 12 Contribution of trees to power failure in Aitkenvale and Mundingburra during Cyclone Yasi (* - introduced to Queensland)

Address	Species	Pole side	Opposite side	Uprooted	Trunk broken	Branch	Street Tree	Private
96 Charlotte St	*Albizia lebbeck**		1	1			1	
45 Brownill St.	*Caesalpinia ferrea**		1	1			1	
8 Mays Crt.	*Citharexylum quadrangulare **		1		1		1	
23 Barcroft St	*Corymbia tessellaris*		1		1		1	
29 Beatrice St	*Erythrina variegata*	1				1	1	
20 O'Reilley St.	*Eucalyptus raveretiana*		1		1		1	
67 Love Lane	*Grevillea robusta*		1	1				1
10 Trott St.	*Khaya senegalensis**		1			1		1
9 Kelly St.	not tree related							
2 Baldwin St	*Peltophorum pterocarpum**	1			1			1
4 Brock St.	*Peltophorum pterocarpum**		1		1		1	
4 Wentworth Ave	*Peltophorum pterocarpum**		1	1			1	
39 Wentworth Ave	*Peltophorum pterocarpum**		1		1		1	
48 Wentworth Ave	*Peltophorum pterocarpum**		1	1			1	
5 Kane St.	*Peltophorum pterocarpum**		1	1			1	
9 Warili St	*Peltophorum pterocarpum**	1		1				1
3 Aster St	*Peltophorum pterocarpum**		1	1			1	
8 Barnard St,	*Peltophorum pterocarpum**		1		1		1	
33 Kelso St.	*Spathodea campanulata**		1	1			1	
17 Kelly St.	*Tabebuia heterophylla**		1	1			1	
18 Wentworth Ave	*Tabebuia impetiginosa**		1		1		1	
2 Gena Crt.	*Tabebuia impetiginosa**		1		1		1	
TOTAL		**3**	**18**	**10**	**9**	**2**	**17**	**4**

In 17 of the 21 tree related power failures, the tree responsible was not native to Queensland. The most common tree species was the yellow flame tree (*Peltophorum pterocarpum*), which caused nine (42.85%) of the power failures. The tree responsible was growing on the same side of the road in only 14.3 % of the cases. All other power failures were the result of trees falling onto power lines from the opposite side of the road. There were nearly equal numbers of offending trees uprooted and snapped, but broken branches were only responsible for two (9.5%) of the power failures. Only one of these was from a branch from the opposite side of the road. The majority of trees (81%) were growing as street trees on the public nature strip, with trees in private gardens only causing 19% of power failures. The most significant damage was caused by the uprooting of a large Indian siris (*Albizia lebbeck**). This tree fell from the opposite side of the road, snapping off two power poles, pulling down the power lines and blocking the road for more than a week. As the root system uplifted, it tore up underground services including telephone and ADSL broadband.

Figure 13 Damage to underground services by an uprooted Indian siris

The fact that 95.45% of the power failures in this survey were caused by trees should be ample evidence to give priority to the issue of vegetation management around power lines. The results of this survey indicate that very few of the power outages were caused by trees growing beneath power lines, and from that perspective the ‘Plant Smart’ message has undoubtedly been valuable. That the majority of power outages were caused by street trees growing on the opposite side of the road on council verges suggests that the future direction for expanding the ‘Plant Smart’ message should be in liaison with council to manage problematic street trees. The general perception that the problem of cyclone damage to power lines lies with trees *per se* is not borne out by the present survey. The results of the power failure survey, and the broader cyclone Yasi tree damage survey strongly indicates that a small minority of tree species are responsible for the majority of the damage, and this would be an obvious target for discussion. In Category 2 winds at least, wind-borne branches are responsible for a small minority of cases, so ensuring that identified cyclone sensitive tree species are planted more than their height's distance from powerlines will effectively have a significant reduction in power outages during future cyclonic events. A list of these sensitive species is provided in Appendix C, and profiles of these species should be made available to tree trimming contractors.

Proportions of individual tree species

Although the broader assessment of tree damage throughout Townsville and other affected centres concentrated solely of cyclone-damaged trees, a number of parks were assessed where all trees were examined. This allows the relative proportions of tree damage to be assessed. While general green waste data doesn't answer the question of whether a tree's contribution to cyclone damage is directly proportional to their abundance, the data presented in this section looks at trends of tree damage in situations that are relatively homogenous, and highlights those species that are causing damage out of proportion to their abundance.

Two parks were examined that were subjected to Category 1 winds, while an additional six sites were examined in Townsville, where trees were subjected to category 2 winds. These sites represent a variety of situations, including different soil types, revegetation versus traditional parks, and areas subjected to different management and watering regimes.

Lloyd Mann Gardens (Category 1 – Home Hill)

A total of 95 trees were assessed at Lloyd Mann Gardens, Home Hill with Tano Buono, manager of Parks Services, Burdekin Shire Council. This park is small and compact, and the trees form a nearly closed canopy over the park. The park is entirely exposed by road and rail corridors to the east and west. A minority of trees were original, and some apparently pre-date the settlement of Home Hill. All trees examined were mature, but individuals varied in height and contribution to the canopy or mid storey. The density of the plantings would have provided many individuals with the benefit of mutual protection, although this protection would have been limited for trees growing along the roadside. It is presumed that soil characteristics are uniform across the site, and that management and watering for the same for all trees. A total of 44 species were recorded, including 11 species not native to Queensland. Of these, 15 species were represented by five or less individuals. Table 13 below shows trends in types of damage sustained by trees at the Ayr Showgrounds

Table 13 Types and extent of cyclone damage to trees at Lloyd Mann Gardens, Home Hill

	Undamaged	Small branches	Large branches	Trunk broken	Uprooted	Total
Total	72	4	3	2	14	95
Percentage	75.79%	4.21%	3.16%	2.1%	14.74%	100%

The Lloyd Mann Gardens in Home Hill is characterised by having numerous species with limited representation of each species. Most (93%) of species are represented by less than five individuals, and only one species (Moreton bay ash – *Corymbia tessellaris*) was represented by more than 10 individuals, making it difficult to identify species trends. Ten species represented by only one or two individuals were 100% damaged. Of the six Alexandra palms (*Archontophoenix alexandrae*), none were damaged, while four of the seven Pride of Barbados (*Caesalpinia pulcherrima*) were uprooted. Of the 19 Moreton bay ash, one tree had broken small branches while another had broken large branches.

Ayr Showgrounds (Category 1 – Ayr)

A total of 221 trees were assessed at Ayr Showgrounds with Tano Buono, manager of Parks Services, Burdekin Shire Council. A large majority of these were located on the eastern side, including an avenue of trees along Craig Street. To the east of Craig Street is an open cane field which provides very limited surface roughness and buffering from cyclonic winds. It was apparent that trees varied in age, but all trees examined were mature. Nearly all trees were grown as individual specimens, without the benefit of mutual protection from growing in a clump or stand. Trees were mostly separated by areas of mown lawn or occasional low buildings. It is presumed that soil characteristics are uniform across the site, and that management and watering was the same for all trees. A total of 25 species were recorded, including 11 species not native to Queensland. Of these, 15 species were represented by five or less individuals. Table 14 below shows trends in types of damage sustained by trees at the Ayr Showgrounds

Table 14 Types and extent of cyclone damage on Ayr Showgrounds trees

	Undamaged	Hit by other	Small branches	Large branches	Trunk broken	Uprooted	Total
Total	183	0	9	12	9	8	221
Percentage	82.8%	0	4.07%	5.43%	4.07%	3.62%	100%

The category ‘hit by others’ was absent at this site, presumably due to the distance between trees. It can be seen that the vast majority of trees at this site were undamaged. Examination of the data showed that damage to trees was by no means uniform. Excluding tree species represented by less than 10 individuals, it can be seen that damage was entirely absent in some species, but extensive in other species (Table 15).

Table 15 Types and extent of cyclone damage on the seven most common trees at the Ayr Showgrounds

Scientific name	Common name	Un-damaged	small branches	large branches	Trunk broken	uprooted	total	% damaged
*Calliandra haematocephala**	red powder puff	15					15	0
Casuarina cunninghamiana	river she oak	29					29	0
Eucalyptus tereticornis X *platyphylla*	hybrid gum	25	3	3		2	33	24.24242
Melaleuca fluviatilis	paperbark	28					28	0
*Peltophorum pterocarpum**	yellow flame tree	2	2	7	4	5	20	90
*Tabebuia heterophylla**	pink trumpet tree	12			2		14	14.28571
Terminalia microcarpa	brown damson	27					27	0

All common tree species were represented by at least two undamaged specimens, but the yellow flame tree (*Peltophorum pterocarpum*) sustained the highest percentage of damage, including the highest number and proportion of trees uprooted. The only other species uprooted was a hybrid gum, which also dropped a lot of branches. Of the total number of trees, 31.25% of introduced trees were damaged, compared to 11.46% of native trees. Both native and introduced categories included trees that were entirely undamaged, and trees that were extensively damaged.

Belgian Gardens Cemetery (Category 2 – Townsville)

The Belgian Gardens Cemetery is situated on an old beach ridge (land zone 2 under the Regional Ecosystem mapping definitions), so the substrate is comprised almost entirely of sand and shell grit. To conform with the shape of the old beach ridge, the cemetery is relatively long and narrow in shape. Mid-way along the cemetery on the southern side is a low outcrop of igneous rock known as 'Jimmy's Lookout'. On the northern side, the beach ridge dips into a swale with an ephemeral *Melaleuca*-dominated wetland. Trees are mostly planted alongside the main access roads running through the cemetery, with the exception of *Melaleucas* and eucalypts on the edge of the mown area, which are mostly naturally occurring trees. The survey did not include low growing shrubs planted at the north-western end near the airport. Very few trees were located in the central portion of the cemetery where the majority of headstones are located. It is presumed that soil characteristics are uniform across the site, and that management and watering are the same for all trees. There was no evidence of irrigation and it is presumed that the trees derive most of their moisture through rainfall and natural levels of ground moisture.

A total of 46 species were recorded, including 16 species not native to Queensland. Of these, 15 species were represented by five or less individuals. Table 16 below shows trends in types of damage sustained by trees at the Belgian Gardens Cemetery.

Table 16 Types and extent of cyclone damage on trees at Belgian Gardens Cemetery

	Undamaged	Small branches	Large branches	Trunk broken	Uprooted	Total
Total	288	31	19	17	12	367
Percentage	78.47%	8.45%	5.18%	4.63%	3.27%	100

It can be seen that the vast majority of trees at this site were undamaged and the most common type of damage was loss of small branches. Tree plantings at the cemetery were surprisingly diverse, with most species only represented by a few individuals. A total of 28 species were represented by five or less individuals, and only nine species had more than 10 individuals. These nine species are examined in further detail in Table 17 below:

Table 17 Types and extent of cyclone damage on the nine most common trees at Belgian Garden Cemetery

Scientific name	Common name	Un-damaged	small branches	large branches	Trunk broken	uprooted	total	% damaged
Pleiogynium timorense	Burdekin plum	11					11	0
Alstonia actinophylla	milkwood	9		2	1		12	25
Wodyetia bifurcata	foxtail palm	13					13	0
Mimusops elengi	red coondoo	15					15	0
Eucalyptus sp.	ironbark	8	5		2		15	46.67
Eucalyptus tereticornis	river blue gum	5	1	5	1	3	15	66.67
Melaleuca leucadendra	weeping paperbark	32					32	0
Eucalyptus raveretiana	black ironbox	22	13	4			39	43.59
Melaleuca dealbata	cloudy tea tree	80		1	1		82	2.44

From Table 17 above, it can be seen that different species showed a distinct difference in levels of damage. Four of the common species showed no damage at all, while one (*Melaleuca dealbata*) showed very low rates of damage (2.44%). The highest levels of damage were sustained by the eucalypts, however, it can be seen that *Eucalyptus raveretiana* sustained only relatively minor damage compared to *Eucalyptus tereticornis*.

The damage from Cyclone Yasi to the trees at Belgian Gardens Cemetery was extensive. Not only were significantly damaged trees removed, but it was also noted that the large lateral roots of some trees (eg. African mahogany) were causing damage to graves, so more than 30 trees were eventually removed from the cemetery (Matheson 2011).

Belmont Park, Kirwan (Category 2 – Townsville)

Belmont Park is a small suburban park immediately adjacent to the “Avenues Plaza Shopping Centre” on Kern Brothers Drive, Kirwan. Monteray Way Curves its way around the majority of the park. The park is mostly open space, with planted trees around its periphery and along several pathways within the park. Soils in the area are generally heavy clays that can become quite hard when dry. The park had a lush surfacing of grass, and it is likely that the park had been top-dressed with top soil and was watered frequently.

A total of 80 trees were recorded in 11 species, seven of which were introduced. Most trees were undamaged (66.25%), with 33.75% suffering some sort of damage (27 trees). Introduced trees made up 72.5% of the trees in the park, and comprised 70.37% of the damaged trees, so their contribution to the damage was in proportion to their abundance. Damage to trees was generally severe – the most common form of damage was uprooting, followed by snapped trunks. Table 18 below shows trends in types of damage sustained by trees at the Belmont Park.

Table 18 Types and extent of cyclone damage on Belmont Park trees

	Undamaged	Small branches	Large branches	Trunk broken	Uprooted	Total
Total	53	1	4	12	10	80
Percentage	66.25%	1.25%	5%	15%	12.5%	100%

Of the 11 species growing in Belmont Park, each species had at least one individual that was completely undamaged. Only two species had less than five individuals; most trees had between two and nine individuals. Only two species had more than 10 individuals. Of the 13 star gooseberry (*Phyllanthus acidus*), 15.38% were damaged including seven with snapped trunks. Of the 13 African mahogany (*Khaya senegalensis*), 46.15% were damaged, entirely by uprooting (6 individuals).

Henrietta St Park, Aitkenvale (Category 2 – Townsville)

This suburban park is bordered by Arthur St to the north, Charlotte St to the east, Leopold St to the south, and Henrietta St to the west. The trees are mostly grown in rows around the periphery of the park, with a circular planting towards the north. The soils are heavy clays and are poorly drained. The area was wet and boggy and inaccessible to vehicles at the time of survey.

A total of 160 trees were assessed, in 18 species, eight of which are introduced to Queensland. More than half of the trees were entirely undamaged, with small branches and snapped trunks being the most common forms of damage. Introduced trees made up 26.87% of the trees and contributed 31.34% to the overall damage, so their contribution to damage is roughly proportional to their abundance. Table 19 below shows trends in types of damage sustained by trees at the Henrietta Street Park.

Table 19 Types and extent of cyclone damage on Henrietta St. Park trees

	Undamaged	Small branches	Large branches	Trunk broken	Uprooted	Total
Total	93	23	18	22	4	160
Percentage	58.13%	14.37%	11.25%	13.75%	2.5%	100

Of the 18 species present, 14 were represented by less than 10 individuals. Four species had more than 10 individuals and these are examined in further detail in Table 20 below:

Table 20 Types and extent of cyclone damage on the four most common trees at Henrietta St Park

Scientific name	Common name	Un-damaged	small branches	large branches	Trunk broken	uprooted	total	% damaged
Casuarina cunninghamiana	river she oak	13	1		1		15	13.33%
*Peltophorum pterocarpum**	yellow flame tree	8	6	6	4	1	25	68%
Eucalyptus tereticornis	river blue gum	9	6	6	12		33	72.73%
Eucalyptus raveretiana	black ironbox	40	8	2	2		52	23.08%

From Table 20 above, it can be seen that the river she-oak sustained the lowest amount of damage, with only one tree snapping its trunk. Black ironbox sustained the next highest level of damage (23.07%), though 40 of the 52 trees were entirely undamaged and most of the damage was broken branches. Yellow flame trees sustained 68% damage with significantly higher levels of damage in all categories. River blue gums had the highest level of damage. As many of these gums had snapped their trunk as had sustained branch damage. Both yellow flame trees and river blue gums had more trees damaged than undamaged, while the opposite was true for river she oaks and black ironbox trees.

Dalrymple Drive corridor (Category 2 – Townsville)

The Dalrymple Drive corridor was an extensive planting, mostly of eucalypts, along the service road for Dalrymple Road, and particularly along the edge of the high voltage powerline easement. The plantings originated from the “100,000 Trees for Townsville” campaign in 1988, so were 23 years old at the time of Cyclone Yasi. The area is generally characterised by heavy clays. There was no evidence of irrigation, so it likely that the trees rely on natural rainfall, though they were probably irrigated when young. Near Coora St, adjacent residents had adopted a portion of the planted corridor, planting a greater diversity of trees including many palms. The area was irrigated and being managed very differently from the remainder of the corridor, so was excluded from this analysis. The area assessed for the present study extended from the southwest point at Nathan St, along the southern edge of Dalrymple Road and terminating in the north east at a point midway between Dee St and Coora St.

A total of 187 trees were assessed, in only four species, all of which are native to Queensland. Less than half of the trees were entirely undamaged, with snapped trunks being the most common form of damage. Table 21 below shows trends in types of damage sustained by trees at the Henrietta Street Park.

Table 21 Types and extent of cyclone damage on Dalrymple Drive corridor trees

	Undamaged	Small branches	Large branches	Trunk broken	Uprooted	Total
Total	81	25	17	58	6	187
Percentage	43.31%	13.37%	9.09%	31.02%	3.21%	100%

Of the four species present, only *Corymbia tessellaris* had fewer than 10 individuals. Three species had more than 10 individuals and these are examined in further detail in Table 22 below:

Table 22 Types and extent of cyclone damage on the three most common trees at Dalrymple Drive corridor

Scientific name	Common name	Un-damaged	small branche	large branche	Trunk broken	Tree uprootec	total	% damaged
Casuarina cunninghamiana	river she oak	14	10		1		25	44
Eucalyptus raveretiana	black ironbox	13		2			15	13.33
Eucalyptus tereticornis	river blue gum	48	15	15	57	6	141	65.96

From Table 22 above it can be seen that both the river she-oak and black ironbox sustained relatively low levels of damage, primarily branch damage. In contrast, the river blue gums sustained nearly 66% damage, with more trees having snapped trunks than being undamaged.

Progress Rd, Rupertswood (Category 2 – Townsville)

The Progress Road site is an amenity-planting site on two large, crescent-shaped mounds at the end of progress road, Rupertswood. The mounds are more than 2 metres high in the centre, and trees are planted at different locations over the mounds. Some of these trees would have a large depth of mound material under their roots, while other trees at the toe of the slope are more dependant on the basement material for their root support.

A total of 77 trees in 26 species were recorded at Progress Road, including eight introduced species. Nearly three quarters of all trees were undamaged. Snapped trunks were the most common form of damage, with uprooting and loss of large branches being of equal frequency. Table 23 below shows trends in types of damage sustained by trees at the Progress Road plantings.

Table 23 T**ypes and extent of cyclone damage on Progress Road trees**

	Undamaged	Small branches	Large branches	Trunk broken	Uprooted	Total
Total	57	1	5	9	5	77
Percentage	74.03%	1.3%	6.49%	11.69%	6.49%	100%

Only one plant had more than 10 individuals. One third of the 15 rain trees (*Samanea saman*) were damaged – four had snapped trunks and one had large broken branches, while the other 10 plants were entirely undamaged.

Ross River Bush Garden (Category 2 – Townsville)

A total of 874 individual trees were assessed at the Ross River Bush Garden; a community revegetation project on the banks of Ross River in Mundingburra. Less than a dozen of these are original trees, most having been planted over the years. The oldest parts of the revegetation date back to 1989. Trees on the adjacent Bazza Island were not counted or included in this survey.

A total of 96 species were recorded, including five introduced species. Several of the native species are not native to the Townsville floodplain. Records kept by the site manager shows that at the time of the cyclone, the revegetation site was essentially self-maintaining, as the vegetation had matured and was functioning as a riparian community. Without regular watering, weed control and maintaining the trees, the site had evolved and a total or 42 species have been lost between 1999 and 2011. Remaining trees subjected to Cyclone Yasi were those surviving trees and their watering and maintenance regime resembles that of wild plants.

Table 24 Types and extent of cyclone damage on Ross River Bush Garden trees

	Undamaged	Hit by other	Small branches	Large branches	Trunk snapped	Severe lean	Up-rooted	Total
Total	656	31	32	36	74	14	32	874
Percentage	75%	4%	4%	4%	8%	2%	4%	100%

Of the 96 species identified at the Ross River Bush Garden, the majority were represented by less than 10 individuals. After excluding trees that were hit by others, 19 species had 10 or more individuals, and these are examined in further detail in Table 25 below, excluding trees hit by others.

Table 25 Types and extent of cyclone damage on the 20 most common trees at Ross River Bush Garden (leaning and uprooted merged into the same category)

Scientific name	Common name	Un-damaged	small branches	large branches	trunk snapped	up-rooted	Total	% Damaged
Acacia crassicarpa	thick podded salwood	12		1	5	7	25	52%
Casuarina cunninghamiana	river she oak	5	2		4	1	12	58%
Cordia dichotoma	glue berry	3	1	1	3	4	12	75%
Corymbia tessellaris	Moreton Bay ash	41	2		1		44	7%
Eucalyptus camaldulensis	river red gum	3	2	10	10	3	28	89%
Eucalyptus platyphylla	poplar gum	19	2	1	1		23	17%
Eucalyptus tereticornis	river blue gum	60	5	1	7	5	78	23%
Ficus opposita	sandpaper fig	8		6	1		15	47%
Ficus racemosa	cluster fig	23	1	3	7	2	36	36%
Livistona decora	cabbage palm	10					10	0%
Lophostemon grandiflorus	northern swamp box	28	2				30	7%
Macaranga tanarius	heart leaf	35		2	6	5	48	27%
Mallotus philippensis	red kamala	11					11	0%
Melaleuca leucadendra	weeping paperbark	102		2	3		107	5%
Millettia pinnata	pongamia	9	1				10	10%
Nauclea orientalis	Leichhardt tree	59	2		3	1	65	9%
Pandanus cookii	screw pine	15			1	1	17	12%
Pleiogynium timorense	Burdekin plum	12				1	13	8%
Terminalia microcarpa	brown damson	8	1	1	2	1	13	38%

Extent of damage was disproportional amongst species. Of these 19 species, it can be seen that two species (cabbage palm and red kamala) suffered no damage at all. Another five species suffered less than 10% damage - Moreton Bay ash, northern swamp box, weeping paperbark, Leichhardt tree and Burdekin plum. The highest rate of damage suffered was the river red gum (89%) and glue berry (75%). Uprooting and trunk snapping were the most common injuries sustained by glue berry trees, while trunk snapping and losing large branches was the most common damage for river red gums.

Considering the large numbers of species and individuals present at the Ross River Bush Garden, further trends in resistance and susceptibility to cyclones was explored. Excluding trees that were hit by other trees, and minor damage (small broken branches), a total of 20 tree species are shown in Table 26 that were represented by more than five individuals and suffered less than 10% severe damage:

Table 26 Trees showing consistently low rates of cyclone damage at Ross River Bush Garden

Scientific name	Common name	Number undamaged	Total plants	% badly damaged
Brachychiton australis	bottle tree	7	8	0%
Corymbia clarksoniana	bloodwood	6	6	0%
Corymbia tessellaris	Moreton Bay ash	41	44	2%
Dysoxylum gaudichaudianum	ivory mahogany	9	12	0%
Eucalyptus platyphylla	poplar gum	19	23	9%
Flindersia bourjotiana	northern silver ash	6	6	0%
Livistona decora	cabbage palm	10	10	0%
Lophostemon grandiflorus	northern swamp box	28	33	0%
Lysiphyllum hookeri	native bauhinia	4	5	0%
Mallotus philippensis	red kamala	11	11	0%
Melaleuca fluviatilis	paperbark	8	9	0%
Melaleuca leucadendra	weeping paperbark	102	107	5%
Melaluca sp. (narrow leaf)	bottlebrush	6	6	0%
Millettia pinnata	pongamia	9	11	0%
Morinda citrifolia	cheese fruit	5	5	0%
Nauclea orientalis	Leichhardt tree	59	70	6%
Pleiogynium timorense	Burdekin plum	12	15	7%
Samanea saman	rain tree*	7	8	0%
Sterculia quadrifida	peanut tree	8	9	0%
Terminalia melanocarpa	black damson	5	5	0%

It should be noted that this includes the most common tree at the Bush Garden – *Melaleuca leucadendra* with 107 individuals.

Conversely, 10 species were identified that were represented by more than five individuals and suffered more than 50% damage (Table 27). The highest percentage of severe damage suffered by a single species was river red gum (*Eucalyptus camaldulensis),* which does not occur naturally in the Townsville region.

Table 27 Trees showing consistently high rates of cyclone damage at Ross River Bush Garden

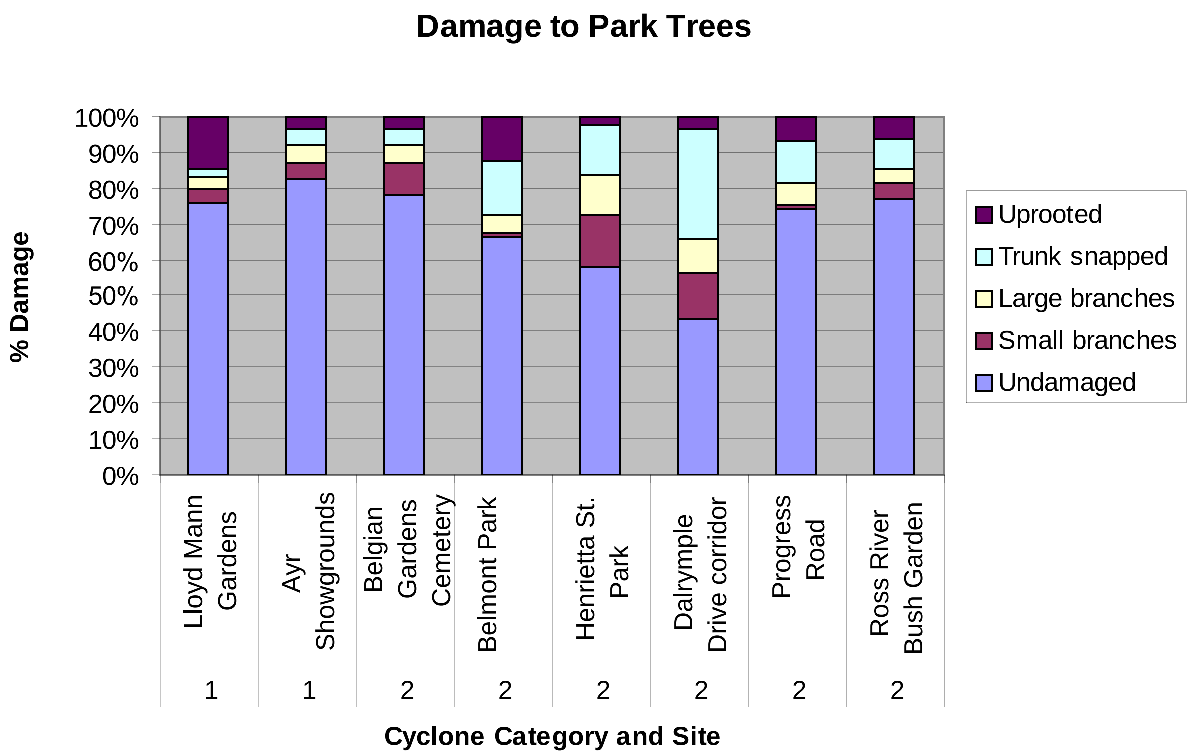
Scientific name	Common name	Number undamaged	Total plants	% badly damaged
Acacia auriculiformis	earpod wattle	1	9	67%
Acacia crassicarpa	thick podded salwood	12	25	52%
Acacia mangium	black wattle	1	5	60%
Casuarina cunninghamiana	river she oak	5	12	42%
Cochlospermum gillivraei	kapok		8	75%
Cordia dichotoma	glue berry	3	12	67%
Eucalyptus camaldulensis	river red gum	3	28	82%
Ficus opposita	sandpaper fig	8	15	47%
Melia azedarach	white cedar	1	5	40%
Terminalia muelleri	Mueller's damson	3	7	57%

All Park Sites

Trends in tree damage were examined for all eight parks surveyed. The different proportions of trees undamaged, compared to the various categories of tree damage are illustrated in Figure 14.

If a significant difference was expected between the sites impacted by category 1 equivalent cyclonic winds, and the sites impacted by category 2 equivalent cyclonic winds, then these differences are not apparent in this graph. Neither is there clear and obvious trends identifying similar patterns of damage on similar soil types. It should be noted, however, that the highest rates of uprooting were on sites that receive watering and/or irrigation – Lloyd Mann Gardens and Belmont Park. The lowest rates of tree emerging completely undamaged come from Henrietta St Park and the Dalrymple Road corridor, where the high rates of failure of a couple of species were by far the most influencing factor. These species – *Eucalyptus tereticornis* and *Peltophorum pterocarpum* have been identified at other parks, in the street surveys and in the literature as being susceptible to cyclones. It is proposed then that the selection of tree species is more likely to influence patterns of damage in trees than other potentially influencing factors such as mutual support, soil types and modes of watering and irrigation.

Figure 14 Percentage damage to trees in parks impacted by Cyclone Yasi



Tree Avenues

Greenwaste surveys did not include counts of all trees due to a majority of cultivated trees being on private property and inaccessible to surveyors. Throughout Ayr, Townsville and Ingham, however, avenues of a single species are common in urban areas, and where these presented themselves, total counts of all individuals were made. A total of 28 locations were assessed for tree avenues, and 47 avenues of 27 species were recorded. This included assessing the proportions of damage of 1,660 trees. Some species were represented by only one avenue, while some (ie. African mahogany) was represented by seven avenues. Numbers of trees in individual avenues also varied. One stand had only six trees (e.g. rain tree in Ingham), while one avenue had 158 trees (pink trumpet tree on River Blvd, Fairfield Waters).

The results of these surveys are shown in Table 28 below:

Table 28 Types and extent of cyclone damage on the avenues and stands of trees at various locations

Scientific name	Common name	Location	good	small branches	large branches	snapped trunk	uprooted	total	% damaged
Agathis robusta	kauri pine (juv)	Anderson Park	33		1		17	51	35.29
Agathis robusta	kauri pine (adult)	Ingham CBD	5	20	8			33	84.85
Agathis robusta	kauri pine (adult)	Mission Beach		6	4	2		12	100
Alstonia scholaris	milky pine	Nathan St	28	5	2			35	20
Bombax ceiba	silk cotton tree	Nathan St	31					31	0
Caesalpinia ferrea	leopard tree	Castlemaine St car park	5	1	1		9	16	68.75
Castanospermum australe	black bean	Queens Gardens	9	12	5			26	65.38
Casuarina cunninghamiana	river she oak	Adelaide St., Ayr	20	2		1	1	24	16.67
Corymbia tessellaris	Moreton Bay ash	Belgian Gardens Cemetery	5				4	9	44.44
Corymbia tessellaris	Moreton Bay ash	Ingham					7	7	100
Eucalyptus raveretiana	black ironbox	Belgian Gardens Cemetery	22	13	4			39	43.59
Eucalyptus tereticornis	river blue gum	Anderson Park	55	2	2	2	19	80	31.25
Eucalyptus tereticornis	river blue gum	Belgian Gardens Cemetery	5	1	5	1	3	15	66.67
Ficus benjamina	weeping fig	Ingham	8	6			3	17	52.94
Ficus benjamina	weeping fig	Kelso Drive	9	1	1	1	1	13	30.77
Ficus microcarpa var. hillii	Hill's weeping fig	Ayr CBD	18			1	7	26	30.77
Khaya senegalensis	African mahogany	Belmont Park, Tville	7		1		6	14	50
Khaya senegalensis	African mahogany	City carpark	10				2	12	16.67
Khaya senegalensis	African mahogany	Dalrymple Rd (Bayswater - Thuringowa Drve	33	1	5	1	22	62	46.77

Scientific name	Common name	Location	good	small branches	large branches	snapped trunk	uprooted	total	% damage
Khaya senegalensis	African mahogany	Ingham	1		1		3	5	80
Khaya senegalensis	African mahogany	Palmetum carpark	22				2	24	8.33
Khaya senegalensis	African mahogany	Sanctuary Drive	8	2	1		6	17	52.94
Khaya senegalensis	African mahogany	Stagpole St	23				16	39	41.02
Khaya senegalensis	African mahogany	William Angus Drive	4	1	1		26	32	87.5
Melaleuca dealbata	cloudy tea tree	Belgian Gardens Cemetery	80		1	1		82	2.44
Melaleuca fluviatilis	paperbark	Riverside Gardens	56	3	1			60	6.67
Melaleuca leucadendra	weeping paperbark	Belgian Gardens Cemetery	32					32	0
Melaleuca leucadendra	weeping paperbark	Fairfield Waters Drive	153	2		1		156	1.92
Mimusops elengi	red coondoo	City carpark	11					11	0
Mimusops elengi	red coondoo	Evans St, Belgian Gardens	10			1		11	9.09
Peltophorum pterocarpum	yellow flame tree	Ingham			5	2	5	12	100
Peltophorum pterocarpum	yellow flame tree	Riverside Gardens	33	16	19	22	22	112	70.54
Peltophorum pterocarpum	yellow flame tree	TAFE carpark	9	5	1	6	16	37	75.68
Peltophorum pterocarpum	yellow flame tree	William Angus		1	5	1	8	15	100
Plumeria obtusa	frangipani	City carpark	13	1				14	7.14
Roystonea regia	Cuban royal palm	Woolcock St	49		21			70	30
Samanea saman	rain tree	Ingham	2	3	1			6	66.67

Scientific name	Common name	Location	good	small branches	large branches	snapped trunk	uprooted	total	% damaged
Schinus terebinthifolius	Brazilian pepper tree	James Cook University				11	6	17	100
Senna siamea	Siamese cassia	Bel Air Ave, Tville	14		7	4	7	32	56.25
Syzygium cumini	Javan plum	Riverside Gardens	23	4	8	20	8	63	63.49
Tabebuia aurea	yellow tabebuia	Bowen Rd					25	25	100
Tabebuia heterophylla (syn. *T. pallida)*	pink trumpet tree	Abbott St, Oonoomba	20	6	6	26		58	65.52
Tabebuia heterophylla	pink trumpet tree	Belmont Park, Tville	1		1	7		9	88.89
Tabebuia heterophylla	pink trumpet tree	Kern Bros Drive				26		26	100
Tabebuia heterophylla	pink trumpet tree	River Blvd, Fairfield Waters	42	22	5	85	4	158	73.42
Tabebuia impetiginosa (syn. *T. palmeri*)	Pink trumpet tree	Duckworth St	4		4		8	16	75
Tabebuia impetiginosa	Pink trumpet tree	Murray Sporting Complex	5			1	17	23	78.26
Terminalia microcarpa	brown damson	Nathan st	9				6	15	40

From Table 28 above, it can be seen that three avenues sustained 0% damage, while six avenues sustained 100% damage. Most avenues sustained between 10-70% damage, and this information is valuable in predicting likely levels of damage to different tree species. While some species suffered consistently low damage (eg *Melaleuca leucadendra, Mimusops elengi*), and other species had consistently high damage (eg. *Peltophorum pterocarpum, Tabebuia* spp), some species showed considerable variation even in locations subjected to similar wind speeds. In Townsville, the seven stands of African mahogany varied from 8.33% to 87.5% damage, though in every location, uprooting was the primary form of damage. This variation is evidence that while the intrinsic cyclone resistant attributes of individual species is important, other influences must also play a role to determining the resistance of an individual tree.

Differences in the impacts of a particular tree species under different cyclone categories were contrasted between five species (*Agathis robusta, Corymbia tessellaris, Ficus benjamina, Khaya senegalensis**, and *Peltophorum pterocarpum**. In most of these cases, a significantly higher level of damage was recorded under the higher wind speed. In most cases, there was an increased rate of uprooting.

Figure 15 Damage to Peltophorum (100%) and Khaya (87.5%) on William Anglis Drive, Annandale (before and after)

Figure 16 Low levels of damage to Melaleuca leucadendra (1.92%) on Fairfield Waters Drive (before and after)

Although kauri pine (*Agathis robusta*) suffered a higher rate of damage with increased wind speed, mature adult trees in Ingham and Mission Beach suffered only branch damage, compared to a third of trees uprooted in Anderson Park. While Tucker *et al*. (2006) note that juvenile kauri pines are more susceptible to cyclone damage than adults, it is also possible that much of this uprooting was caused by the trees being planted as advanced trees where the young trees had significant wind resistance but little corresponding root development.

The high level of variation in damage to African mahogany (*Khaya senegalensis**) deserves comment. The highest level of damage recorded in Townsville was on William Angus Drive in Annandale where 87.5% of trees were damaged, primarily by uprooting. Examination of the root system of a number of these trees showed that the outline of a 200mm pot (~25L) could still be seen in the shape of the root system, and that all lateral roots were emerging from the top, rather than the bottom of the pot. In contrast, the lowest rates of damage were recorded in the city carpark and Palmetum carpark. Low rates of uprooting were noted but not recorded in the Queensland Nickel carpark at Yabulu. A similar phenomena was noted with leopard trees (*Caesalpinia ferrea*) at the Castlemaine St carpark in Kirwan, where trees in garden beds were uprooted while those in the asphalt carpark largely remained upright. Several explanations are possible to explain the higher survival rate of cyclone prone trees in carparks, all relating to water. One is that the asphalt is preventing water from reducing the mechanical strength of the soil, allowing them to remain firmly rooted in dry ground while surrounding plants struggle to remain upright in waterlogged soils. The other possibility is that because of the limited water infiltration below the asphalt, the trees produce less shallow lateral roots as these would not be assisting in maintaining the trees water budget, but instead follow the flow path of the water infiltration closer to the trunk possibly leading to deeper roots. Excavation of trees surrounded by asphalt would be required to determine if the shape of the root system is significantly different from trees in open garden bed situations, however, it can be seen in both the inner city carpark and Queensland Nickel carpark that African mahogany is still producing very large shallow lateral roots as these are uplifting and damaging the asphalt.

Impacts on beach front communities

In addition to the parks described in the previous section, proportions of trees were also assessed in beach front communities; a vegetation community comparable at different locations along the wind speed gradient. Assessments of different cyclone-impacted beach fronts were undertaken at the locations shown in Table 29 below:

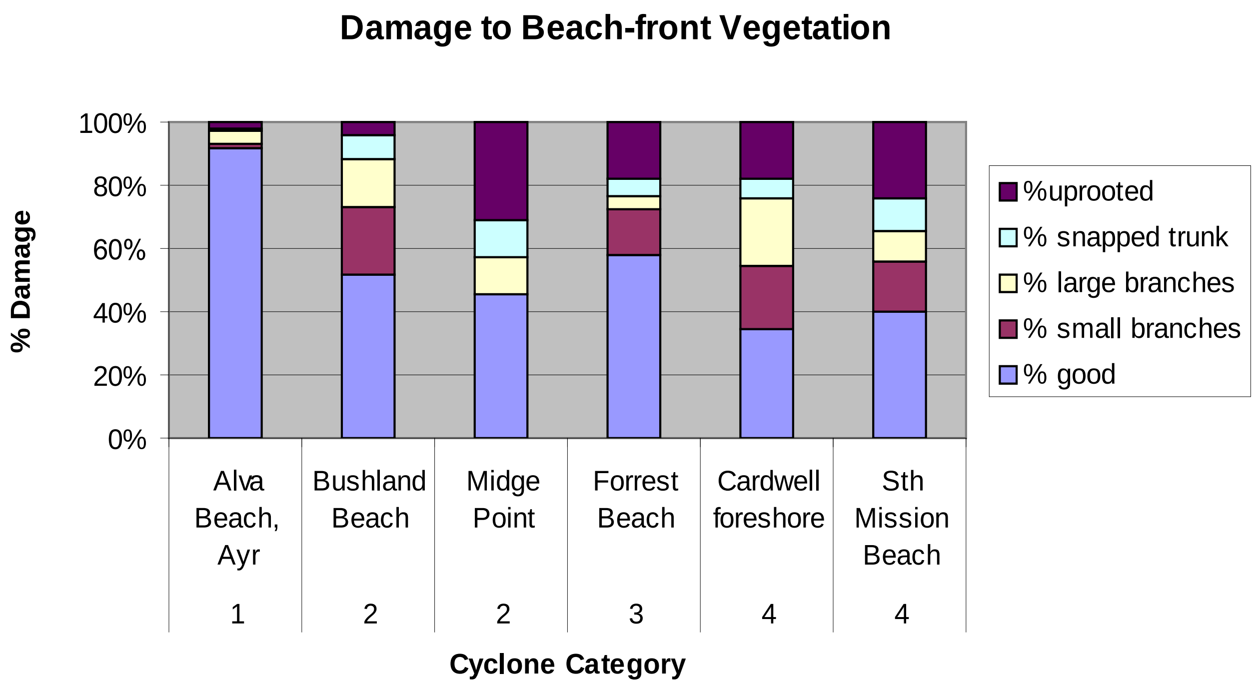
Table 29 Location of beach front vegetation surveys

Location	Estimated Cyclone Category
Alva Beach via Ayr	1 – Cyclone Yasi
Midge Point via Proserpine	2 – Cyclone Ului
Bushland Beach via Townsville	2 – Cyclone Yasi
Forrest Beach via Ingham	3 – Cyclone Yasi
Lucinda	3 – Cyclone Yasi
Cardwell	4 – Cyclone Yasi
South Mission Beach	4 – Cyclone Yasi

Wind speeds are not available for all sites to confirm the level of impacts. Wind speeds at Midge Point as a result of Cyclone Ului were determined to be 45m/s or 160 kph (Henderson *et al* 2010), making this a representative of a high Category 2 cyclone. Wind speeds at Townsville were likely to have reached 144kph (Greg Connor BoM pers. comm.), so it is likely that Bushland Beach may have exceeded that. Wind speeds at Lucinda were recorded at 137kph before the unit failed, but it is likely that wind speeds were significantly higher than in Townsville, as it is located nearly 100km closer to the point of landfall than Townsville. It is likely that much of the damage seen at these sites was caused as much from storm surge and wave action as by the wind itself, and this is discussed in greater detail in the relevant section

Numbers of trees present at each site varied so counts were converted to percentages for a more accurate comparison.

Figure 17 Percentage damage to trees on beachfronts impacted by Cyclone Yasi

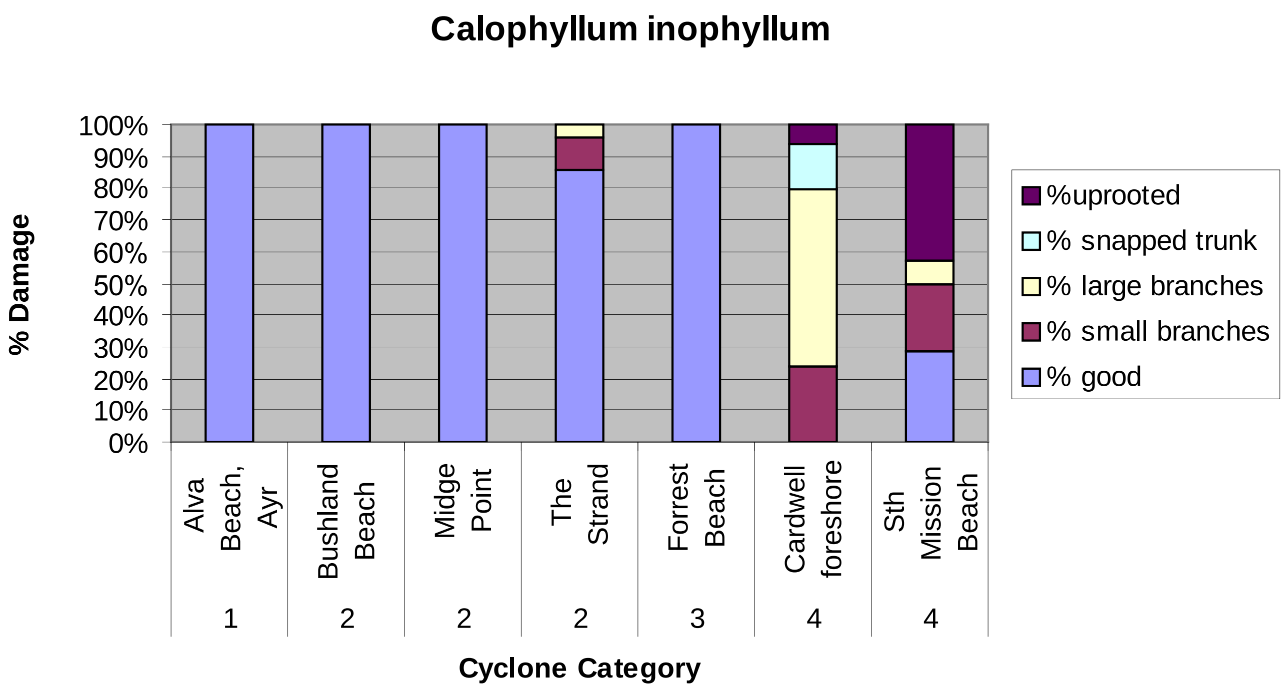


Levels of damage were minimal under Category 1 impacts, and the proportion of undamaged trees generally decreased as wind speed increases. The percentage of trees suffering from the different classes of damage showed no clear and obvious trend, with large variations even between sites subjected to the same category winds. It is likely that this is due to the different floristic composition of the different beach fronts, highlighting the role of species composition in altering the levels of tree damage experienced.

If this theory is correct, then there would be expected to be far clearer trends within single species along the wind speed gradient. A total of 40 plant species were recorded on beachfronts at different locations. Many of these were recorded at only one or two locations, so it is difficult to make comparisons between impacts at different sites. A total of five species were located in sufficient numbers along a gradient of cyclone damage for further comparison of differences in response. These species were:

- Alexandrian laurel (*Calophyllum inophyllum*);
- beach she oak (*Casuarina equisetifolia*);
- coconut (*Cocos nucifera*);
- coastal screw pine (*Pandanus tectorius*); and
- sea almond (*Terminalia catappa*)

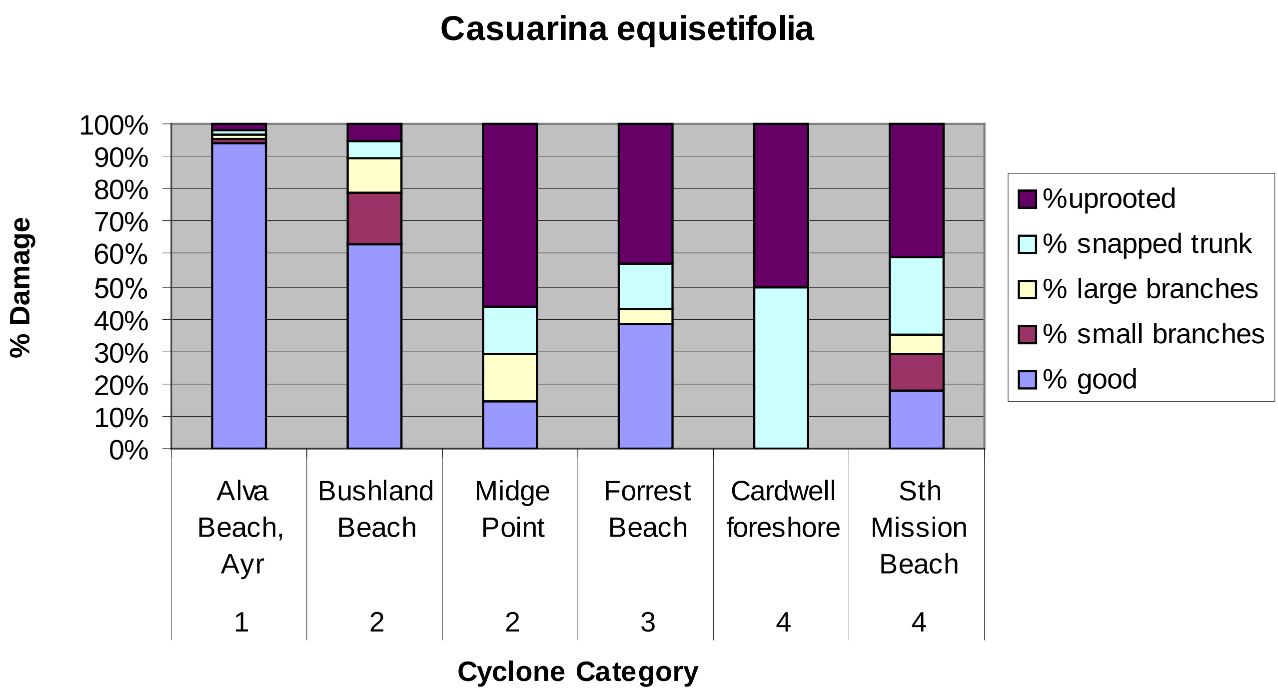
Figure 18 Changes in levels of cyclonic damage to Alexandrian laurel (Calophyllum inophyllum)



Alexandrian laurel has been widely described as being a cyclone resistant tree (Cairns City Council 1986, Calvert 2006, Cameron *et al* 1982, Donahue 1975, Kupsch 2006, Roach 2006, Tucker *et al*. 2006, Stocker 1976, and Van der Sommen 2002). Alexandrian laurel trees were almost entirely undamaged by category 1-3 cyclones, but showed a marked tendency for broken branches in Category 4 winds. Only on the Cardwell foreshore were there no undamaged plants. At this location, many of the Calophyllum trees had been bare-rooted by sand removal, and the bark of many trees had been torn off. This was presumably due to the hammering of the storm surge and wind driven rains pounding on their trunks. Many of the Alexandrian laurels had long limbs reaching out towards the ocean that were torn off during the cyclone, accounting for the large proportion with large broken limbs. At South Mission Beach, where the eye of Yasi actually crossed, 42.85% of the Alexandrian laurels were uprooted, as a consequence of the beach being eroded out from under them. Without the supporting sand, the bare rooted trees had no support and fell over. In many individual circumstances, the broad spreading root systems allowed trees to remain upright, even when bare rooted, allowing an opportunity to save the trees through sand replenishment programs.

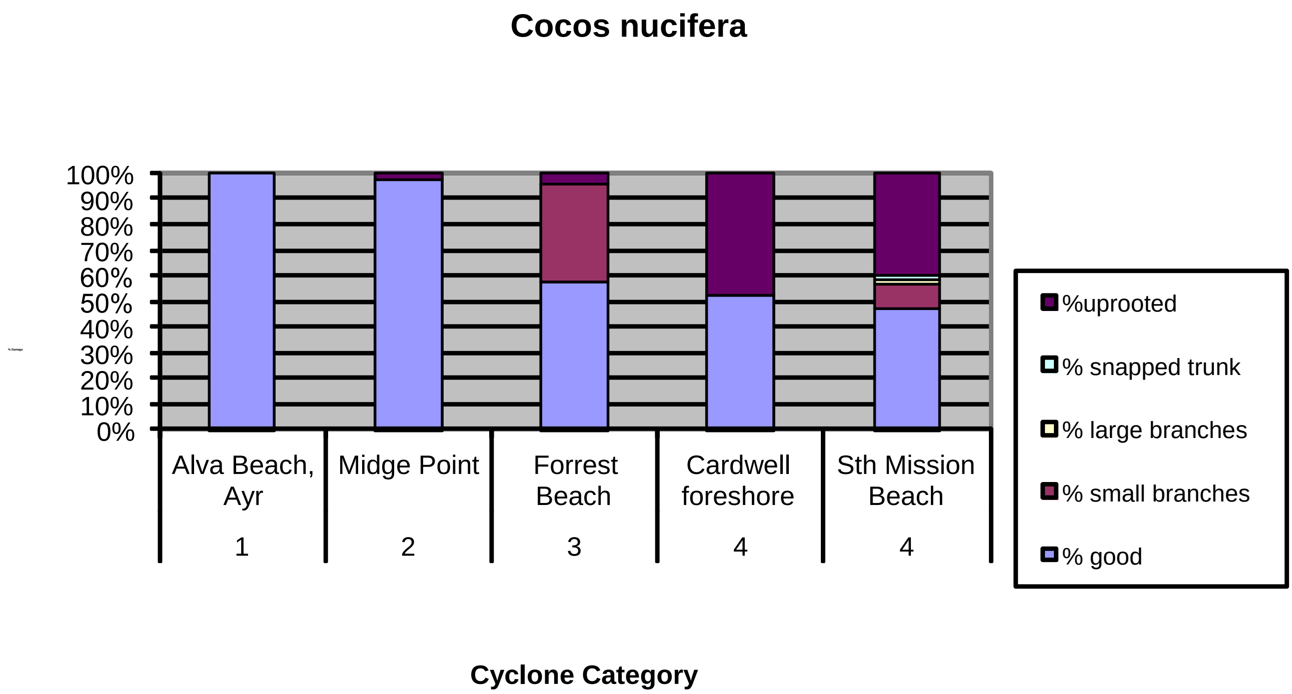
It is worth noting that the Alexandrian laurels at Cardwell that were bare rooted, with broken limbs and stripped of bark during Cyclone Yasi were noted to be recovering when examined four months later (Betsy Jackes pers. Comm.).

Figure 19 Changes in levels of cyclonic damage to beach she-oak (Casuarina equisetifolia)



Beach she-oak is a naturally dominant beachfront species throughout north Queensland, and is described by Jackes (2011) as having medium resistance, showing mixed results but noted for having flexible foliage and branchlets. It is, however, noted for being prone to stem and branch breakages (Cameron *et al* 1981, Stocker 1976). During the present study, they suffered only very minimal damage during Category 1 and low Category 2 winds, but at the upper end of Category 2 wind speeds (Midge Point), they dramatically increase the rate of uprooting and snapped trunks. Some variation of these results should be expected in Category 3 and 4 cyclones as even at South Mission Beach, three of the 17 trees were entirely undamaged.

Figure 20 Changes in levels of cyclonic damage to coconut (Cocos nucifera)

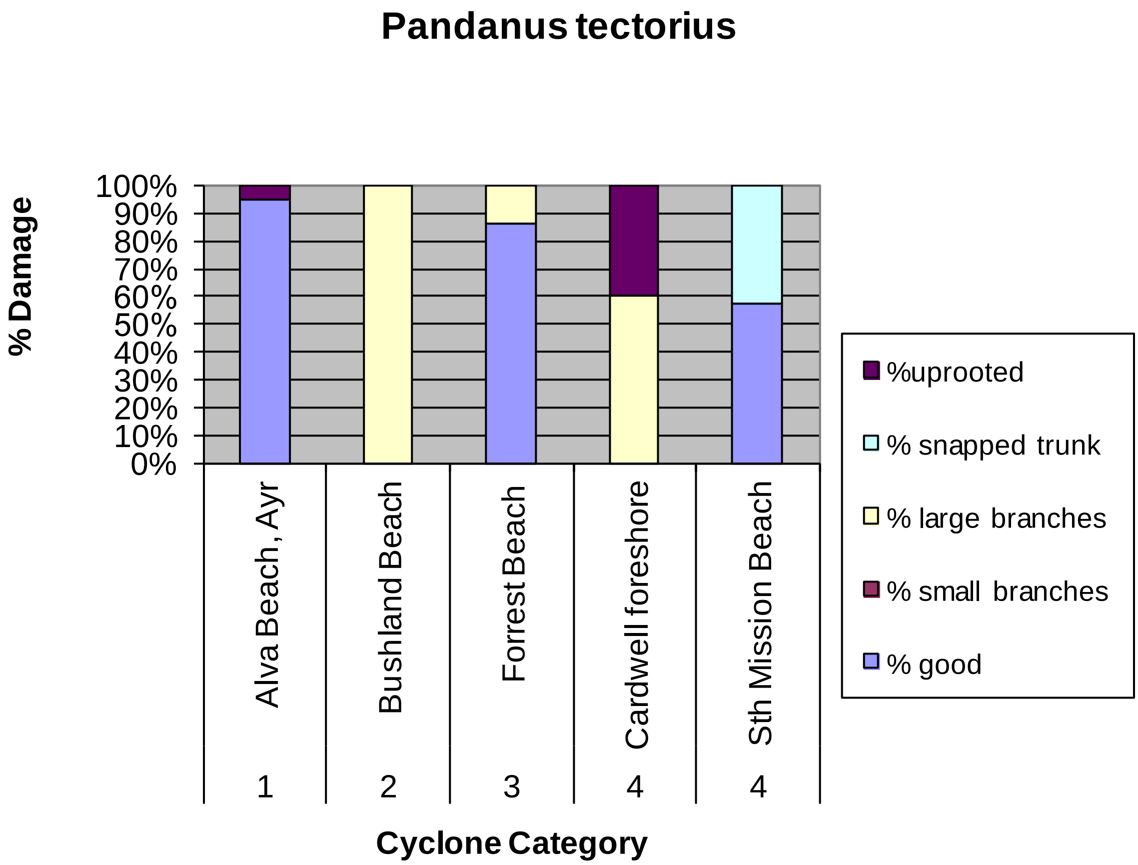


Coconuts are not native to Queensland (Bostock & Holland 2010), but are widely planted along tropical beaches. While Cameron *et al* (1982) describes them as being moderately stable, others describe them as being susceptible to uprooting (Calvert 2006, Stocker 1976). In Category 1 and 2 cyclones, coconuts sustained none or very little damage. During Category 3 events, nearly half the trees had minor broken fronds, but trees were extensively uprooted during category 4 events. At these locations, the strong wave and storm surge action had resulted in large quantities of beach sand being removed, resulting in the coconuts being bare-rooted and toppling over. Bare-rooting resulting in toppling was also evident at several other beach-front locations assessed during green waste assessments, and on beach fronts this remained the primary cause of damage. Snapped trunks were more common in urban areas. The small fine roots and dense, compact root ball makes this species highly susceptible to the impacts of storm surge and bulk sand removal. A higher proportion of trunk snapping might be expected if uprooting did not occur, and greenwaste surveys show this is more likely to occur if the trees are fully laden with nuts.

Figure 21 Differences in root architecture alter resilience to storm surge, sand depletion and cyclonic winds: coconuts in Townsville (Category 2) and Alexandrian laurels in Cardwell (Category 3)

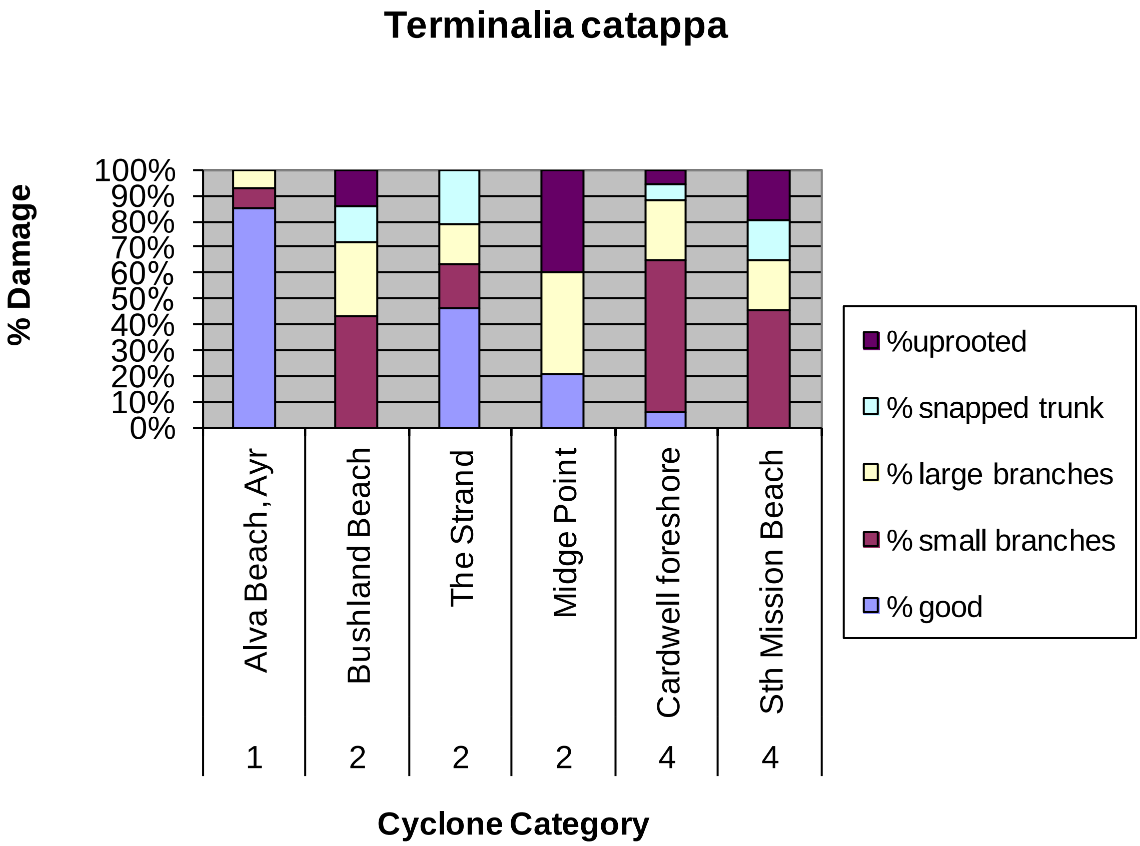
Coastal screw pines are a distinctive and common native beachfront species. Other pandanus species have been noted as being resistant to cyclone damage (Tucker *et al*. 2006). Trends in damage to coastal screw pine with increasing cyclonic damage are difficult to interpret. During Category 1-3 cyclones, trees are either mostly undamaged or suffer broken branches, but at higher cyclone categories, the rate of uprooting or trunk breakage increases. Uprooting was a consequence of being bare rooted by storm surge impacts on sand erosion. The clumping and branching habits of the coastal screw pines generally allows these trees to recover from breakages.

Figure 22 Changes in levels of cyclonic damage to coastal screw pine (Pandanus tectorius)



Sea almonds are common along beach front parks, both naturally and planted. The literature relating to sea almonds in cyclones is conflicting. While Cairns City Council (1986) and Jackes (2011) describe them as wind resistant, others describe them as unstable (Cameron *et al* (1982) and prone to severe failure (Roach 2006). A moderate view is taken by Tucker *et al*. (2006), who noted that during Cyclone Larry, the leaves were shredded but the main trunk remained intact. During Cyclone Yasi, trends in damage showed a general decrease in undamaged trees with increase in cyclone intensity. At every location, broken branches seemed to be the most common type of damage, supporting the observations of Tucker *et al*. (2006). Although damage was minimal in Category 1 cyclones, there was no discernable trend in uprooting or trunk breakage with increased cyclone strength but a general increase in the rate of branch breakage. This tree has large leaves that can offer a lot of wind resistance, but an open tiered branching architecture that reduces wind loading. The loss of branches during high winds further reduces the wind loading, allowing the main trunk to survive in most cases.

Figure 23 Changes in levels of cyclonic damage to sea almond (Terminalia catappa)



Characteristics of tree damage by different cyclone categories

To assist residents in cyclone-prone areas prepare for the likely impacts of different category cyclones, the Emergency Management Systems & Bureau of Meteorology (2007) have prepared a list of typical indicative effects on houses, infrastructure and crops (Table 2). This document makes reference to damage to trees but it is limited in description and detail. Although there are many variable characteristics of cyclones as discussed in Section 5.3, by examining the similarity of impacts of different cyclones of the same category, it is possible to generate an indicative description of the likely impacts on vegetation. In addition to observations made at different points along the wind profile generated by Cyclone Yasi, other cyclones used to generate these indicative descriptions are listed in Table 30 below.

Table 29 Historic cyclones used to provide indicative descriptions of cyclone damage to vegetation

Cyclone Category	Cyclone
1	Neville (1992), Tessie (2000), Monica (2006)
2	Steve (2000), Monica (2006), Ului (2010)
3	Winifred (1986), Monica (2006)
4	Althea (1971), Tracy (1974), Larry (2006), Monica (2006)
5	Ingrid (2005), Monica (2006)

Category 1 (90-125 kph gusts):
Many trees will start losing leaves and small twigs once wind speeds exceed 80kph, but the majority of species will avoid any significant damage. Natural vegetation will mostly appear unaffected, except where topography or cyclone-spawned tornadoes may create higher wind speeds. The majority of damage in urban areas will be limited to a minority of highly susceptible species, and these may cause road blockages, power outages and damage to houses and infrastructure. Damage to other tree species can usually be traced to other influencing factors such as termite or fungal damage, being planted as a large advanced specimen or damage to root systems.

Category 2 (125-164 kph gusts):
Loss of foliage will be widespread but many trees will still retain most of their foliage. Many of these remaining leaves will be wind-burnt, and salt burn will be prominent in coastal vegetation communities. Damage to susceptible species will be widespread, with populations of susceptible trees likely to sustain more than 70% damage. Road blockages and power outages from susceptible species is likely to be widespread. A greater diversity of trees are likely to be impacted, and few species will emerge completely undamaged. Fruit orchards are likely to suffer moderate damage. Minor defects in branch attachment are more likely to manifest as damage. While damage to urban vegetation will be greater than natural vegetation, some plant populations may be reduced by 5%.

Category 3 (165-224 kph gusts):
Damage to trees increases dramatically between the lower and upper limits of Category 3 wind speeds. Large areas of vegetation will be bare after having all foliage stripped, with about 25% still retaining foliage. Fruit orchards (particularly litchi, avocado, paw paw and banana) and timber plantations may suffer extensive damage. Damage to urban parks and gardens will be widespread, and susceptible species may suffer 8-100% damage. Extent of fallen trees on roads, powerlines, and fences will be significantly increased, greatly reducing mobility after the cyclone has passed. The buffering effect of wind breaks will be increasingly noticeable to residents but flying debris will be relatively uncommon. Damage to mangroves is noted to increase dramatically at a threshold of between 170 and 185 kph (Smith 1986). There may be significant differences in the levels of damage to medium-resistant trees caused from a weak Category 3 compared to a strong Category 3.

Category 4 (225-279kph gusts):
Most trees will be entirely defoliated, with only a small minority of species still retaining leaves. In native vegetation, canopy species will be particularly defoliated and damaged while understorey plants and saplings may be undamaged except from falling debris. Damage to mangroves may be extensive in exposed locations. Damage to highly susceptible species will be almost complete except where those trees have received shelter. Broken trunks and uprooted trees will be abundant in urban

areas. Most trees still remaining standing will have lost limbs, and this loss of wind loading will have prevented uprooting or trunk breakage. Cyclone-resistant species will be prominent in the post-cyclone landscape, including canopy and emergent species. Wind loading on houses will approach or exceed the ultimate limit state design for buildings and flying debris will become a significant issue. The value of trees will be particularly noted for their role in catching flying debris and buffering wind loading on houses.

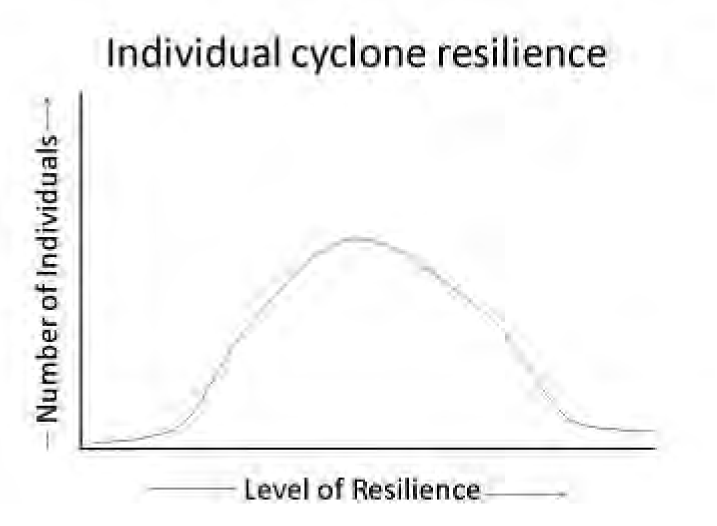
Category 5 (>280 kph gusts):
No records of impacts of Category 5 Cyclones on large urban areas in Australia exist in the modern literature. Category 5 Cyclone Monica generated winds of 360kph but had degenerated to 147kph (Category 2) by the time it had reached Maningrida (Cook & Goyens 2008). In rare instances where Category 5 cyclones have made landfall, nearly all the trees were reported as either snapped or uprooted. Photographs of exposed areas of Elizabeth Bay (NT) following the impact of Cyclone Ingrid (2005) show the majority of trees still standing are immature, with highly flexible trunks. Occasional mature trees are still standing and stripped back to their basic framework, but most trees are uprooted or snapped. Nearly all plants, irrespective of size, are stripped of foliage and the majority of their stems and branches. It is likely that in urban areas, the majority of trees would fail, but any remaining trees still standing would be making a significant contribution to reducing flying debris as houses shed roofs and other structural components.

Identifying traits of susceptible or resistant trees

It is evident from the literature and from data collected during several cyclones including Cyclone Yasi, that different tree species can be expected to behave very differently, and that this behaviour often changes predictably as wind speeds increase.

However, it is evident that the way a particular species responds to a cyclonic disturbance is not identical for every individual of that species. There is an obvious trend in most species examined for there to be a proportion of the trees that are more susceptible than average, and some that are more resistant than the average, and so resistance of any species to cyclonic wind is likely to fit roughly to a standard bell-shaped curve as shown in Figure 24 below.

Figure 24 Individual cyclone resilience of a particular tree species, as a proportion of the population



This behaviour can also vary depending on the soil type, management and surrounding landscape, as outlined in the Section 5.3 above. However, the impact a particular category cyclone will have on a collection of trees is more likely to be influenced by the species composition of those trees than by the way they are managed.

Inherent species-specific susceptibility to a cyclone may be due to a broad range of contributing factors including, but not limited to:

- Tendency to be shallow-rooted in proportion to their wind resistance;
- Poor radial distribution of supportive roots;
- Tendency to have low density wood with poor resistance to bending or torsion;
- Low flexibility (high elastic moduli);
- Tendency towards asymmetry of the crown;
- Tendency to be hollowed by termites; and
- Susceptibility to fungi and diseases.

Natural systems are rarely comprised entirely of either cyclone resistant or sensitive species, but usually a combination of both. In a native plant community, a combination of tree species resistance (able to withstand disturbance) and resilience (able to recover from disturbance) provides the broader vegetation community with a wider range of regeneration and survival mechanisms after a cyclone (Van der Sommen 2002). The rapid growth rates of the pioneer species makes them popular in urban gardens where people want to rapidly generate the shade and aesthetic benefits of trees. However, while the tendency to snap and rapidly regenerate may have advantages in natural ecosystems, it can have significant disadvantages in urban areas where damage to infrastructure may occur.

The suggestion that all tree species have some mechanism to cope with cyclonic disturbance ignores the fact that urban gardens often contain species from other parts of Australia or the world where cyclones are not a feature of their climate. Therefore, there is no reason to believe that these species would necessarily possess the necessary evolutionary traits necessary for responding to cyclones. While many introduced species do have demonstrated resistance to cyclone damage, green waste scores indicate a higher proportion of introduced species amongst damaged trees.

Several authors have speculated on the characteristics that make a species resistant to damage by cyclones. If common characteristics could be identified, it would assist in prediction of which species would show resistance or susceptibility to cyclones. Some of these likely characteristics are listed by Jackes (2011):

- good flexibility (e.g. palms with thin flexible stems);
- good well-developed root system (particularly with a good taproot and lacking any significant damage from excavations, road works or similar);
- ease of defoliation (the ability to lose leaves quickly and reduce wind resistance such as many eucalypts);
- plants with fine leaves offer little resistance (e.g. *Leptospermum*, bottlebrushes, *Delonix regia*, or may appear leafless eg. *Casuarina*):
- open branch system that allows the wind to pass through easily (eg. sea almond and other species of *Terminalia*, *Alstonia* spp.);
- lack of a dense top heavy canopy or crown; and
- healthy trees with vigorous growth and no termites.
- slow growing trees.

Some of these characteristics are species specific, while others may be more important for an individual tree. Only one of these characteristics – the role of leaf size – is apparently contradicted by the available data. Many species such as *Peltophorum* and *Casuarina* with small leaves have been shown to have low levels of resistance, while many large-leaved species such as *Bismarckia nobilis* or *Nauclea* are noted as being very resistant species. While larger leaves undoubtedly increase the wind resistance and wind loading, it is possible that the trees compensate for this, although there is no data available to support this theory.

A number of these characteristics are described in the available literature, as previously discussed in Section 5.3.

Flexibility – Brittleness; a lack of flexibility, has been described as a significant cause of urban tree failure damage following Cyclone Winifred (Cairns City Council 1986). The flexibility of tree trunks is significantly correlated with stem apparent elastic modulus (relative flexibility) (Asner & Goldstein 1997). Breakage of trunks was noted to be more frequent in species that had a significantly higher apparent elastic moduli than those that remained standing or were uprooted (Asner & Goldstein 1997). The present study noticed that flexible palms and tree saplings tend to have reduced frequency of trunk snapping, however, the survival of many resistant species with broad and inflexible trunks cannot be attributed to this trait.

Root System – The size and extent of the root system provides stability through the increased weight of the root soil plate (Van der Sommen 2002). Trees with a more even and uniform root spread are generally more stable (Rodgers *et al*. 1995). It is also reasonable to suggest that trees with a deeper taproot are less dependant for support on shallow soils that become saturated and waterlogged, losing their mechanical strength. The present study found that the majority of trees uprooted in urban areas had the majority of their roots anchored in the top 20cm of soil, which is prone to waterlogging. Few uprooted trees showed any development of a tap root, and some species in particular (e.g African mahogany) never showed any evidence of a tap root in any of the uprooted specimens examined.

Ease of Defoliation – As wind speed increases, the greater the proportion of trees that will be defoliated. It has been observed that the wind loading on a trunk will often reduce dramatically as the plant loses leaves and branches, and this sacrifice of this material can often save the main trunk from breaking (Jackes 2011, Stocker 1976). It would be logical then to assume that if defoliation would occur before the critical bending moment of the trunk or roots, then snapping or uprooting might be delayed or avoided. While Jackes (2011) notes that many eucalypts will shed leaves early, the majority of uprooted and snapped eucalypts in Category 2 impacts still had the majority of their canopy intact, so loss of foliage does not always precede critical failure loading of the trunk and/or roots. While defoliation may play a significant role in protecting the trees overall architecture of some species (e.g. *Terminalia catappa*), it is not a trait common to all resistant species. A number of highly resistant species (eg. mango, Alexandrian laurel, *Flindersia* spp) were noted as being both upright and still retaining the majority of their foliage after a Category 4 event.

Open branching habit: Arborists note that preventative pruning to reduce the aerodynamic drag, or wind resistance should aim to open the canopy to allow wind to pass through it (Roach 2000, Yuruga Nursery 2009). Therefore it would be logical to assume that trees that already had an open branching canopy would intrinsically have reduced wind resistance and be less susceptible to cyclone damage. This generalisation has not proved to be true in many cases, as some trees with open branching habits may possess other weaknesses with regards to low wood density and shallow roots that negate the positive influence of their open branching habit. It is noted that a number of canopy emergent species with high cyclone resistance do have open branching habits (e.g. *Alstonia scholaris, Elaeocarpus grandis*), however, other open branched species are noted as being particularly sensitive (e.g. *Casuarina equisetifolia, Terminalia microcarpa*). It should be concluded then that while an open branching habit may explain a part of a tree's resistance to cyclones, it does not confer high resistance if it's in isolation of other resistance mechanisms.

Dense top-heavy canopy or crown: Similar to the comments above about an open branching habit, the presence of a dense and top-heavy canopy confers high levels of wind resistance, which will transfer significant stress onto the trunk and root systems. It has been noted that increasing the crown size by applying fertilisers and irrigation can increase the degree of wind damage (Van der Sommen 2002). Arborists attempt to thin out dense canopies when conducting preventative pruning. A number of cyclone resistant species (eg. mango, Alexandrian laurel, scrub wilga) do possess relatively dense canopies, while many cyclone sensitive eucalypts often possess very open canopies, so this rule cannot be used alone to predict cyclone resistance or susceptibility.

Termite resistance: Termite damage is a leading cause of tree failure in some species, and following Cyclone Tracy in 1974, it was found that the level of crown damage in eucalypt forests was proportional to the degree of termite damage (Stocker 1976). It is not always easy to identify trees weakened by termites, however, it has been noted that many trees damaged during Category 1 cyclones had termite damage (Calvert 2000, Tano Buono pers. Comm.). As wind speeds increase, however, a greater proportion of urban trees unaffected by termites will fail, and a number of sensitive species rarely show any evidence of termite damage. So susceptibility to termites is a useful measure to predict sensitivity to cyclones, but resistance to termites does not necessarily imply resistance to cyclones.

Growth Rates: The relationship between growth rates and wood density has been explored by several researchers (e.g Curran *et al* 2008, Falster 2006, Van Gelder *et al*. 2006), and in many cases one may be used as a surrogate for the other. As trees allocate greater resources and biomass towards dense timber, this results in slower growth rates, but higher wood density increases the mechanical strength and ability of the tree to resist damage from cyclones (Curran *et al* 2008). The opposite would also appear to be true, that many fast growing pioneer species have low wood density, and were more likely to suffer stem and branch damage owing to cyclonic winds (Curran *et al* 2008). Wood strength alone can only be used to predict levels of trunk damage, and it has been observed that higher rates of uprooting may be related to low rates of trunk failure (Van der Sommen 2002). During numerous cyclones, it has been noted that African mahoganies rarely snap their trunks, but frequently uproot. While this species evidently has greater mechanical resistance in the wood than in the roots, it is not regarded as a slow-growing species

As a consequence of this present research, two additional predictors of cyclone sensitivity and resistance are proposed:

- Average longevity; and
- Natural habitat type

Longevity: Plants with short lifespans (average < 15 years) feature heavily amongst the list of cyclone sensitive species, especially some *Acacia* and *Grevillea* species. Plants with limited lifespans invest less resources into long-term survival mechanisms such as denser wood and deeper roots, and more resources into reproduction. In rainforest habitats, short lived species tend to be those pioneer species that rapidly colonise disturbed areas with high light availability, and die out as they are overtaken by longer-lived climax species, leaving behind a dormant seed bank. In many cases, these short-lived species are of small stature and their failure has minimal negative consequences, however, some pioneer *Acacia* species can obtain enough size to cause structural damage when they fail.

Following the impact of Cyclone Monica on the town of Jabiru (NT), the greatest frequency of tree failure and tree-related damage to infrastructure was from the earpod wattle *Acacia auriculiformis* (Calvert 2006).

Natural habitat type: The environment in which a tree species has evolved may assist in predicting cyclone resistance. Many cyclone resistant species grow in environments where they are exposed to high-energy extremes of wind and water, where the tree trunks and roots are exposed to high loading. This trend is noticeable in some genera, such as *Melaleuca*, where species that grow along fast flowing flood-prone rivers show high levels of resistance (eg. *M. fluviatilis, M. leucadendra, M. viminalis*), while species that occur naturally in open woodlands and floodplains are less resistant (e.g. *M. nervosa, M. viridiflora*). Following Cyclone Monica, vast areas of *M. nervosa* were windthrown (pers. Obs.), while Cyclone Althea resulted in widespread loss of *M. viridiflora* (Donahue 1975). After both cyclones, the riparian *M. leucadendra* was a notable survivor. Many other highly resistant species occur naturally either:

- along fast moving rivers (e.g. *Carallia brachiata, Eucalyptus raveretiana, Lophostemon grandiflorus, Millettia pinnata, Nauclea orientalis, Syzygium tierneyanum*);
- along windswept beach fronts (e.g. *Argusia argentea, Calophyllum inophyllum, Ficus drupacea, Hibiscus tiliaceus, Mimusops elengi, Pandanus tectorius, Syzygium forte*);
- on exposed windswept outcrops (e.g. *Adansonia gregorii, Brachychiton australis, Dypsis decaryi*, Ficus obliqua, Wodyetia bifurcata*); or
- as exposed emergents above rainforest canopies (e.g. *Agathis robusta, Alstonia scholaris, Archontophoenix alexandrae, Argyrodendron* spp., *Bismarckia nobilis*, Elaeocarpus grandis, Flindersia* spp., *Normanbya normanbyi, Swietenia* spp*., *Toona ciliata*).

There are a number of exceptions to this generalisation, as these communities also contain a number of cyclone sensitive species. Ecologically, this should be expected as any community would be expected to contain species that are both resistant and resilient to cyclones (Van der Sommen 2002). For example, the common beachfront species *Casuarina equisetifolia* is often badly damaged during cyclonic winds at and exceeding Category 2, but are fast to regenerate. It should also be noted that many resistant species do not occur naturally in high energy environments, but occur in open woodland situations where the majority of other species could be expected to suffer significant structural damage during cyclones.

The other likely habitat to seek cyclone resistant species are areas where the traits of being slow growing, shade tolerant and deep rooted are necessary. Many rainforest climax species may be expected to possess these characteristics, however, deeper rooting would be expected in areas where soil moisture is limited and survival would be dependant on being able to access soil moisture at greater depths. Vine forest species that occur in exposed gullies tend to show very limited amounts of damage. Unfortunately, most of these species are rarely cultivated except by native plant enthusiasts, so it is difficult to assess their response to cyclones in an urban environment. Slow growing, shade tolerant, deep rooted and drought tolerant vine forest species known to be resistant to damage from cyclonic winds includes *Aidia racemosa, Alstonia actinophylla, Denhamia obscura, Ficus virens, Geijera salicifolia, Glycosmis trifoliata, Pleiogynium timorense*, and *Sterculia quadrifida*. While extensive damage to monsoon forest communities was noted following Cyclone Tracy (Fox 1980), the ability to identify resistant and sensitive species was hampered by including trees struck by falling trees and debris. It was observed that collections and stands of local dry vine thicket species cultivated in Townsville under irregular watering regimes sustained very low rates of damage during Cyclone Yasi, and this should be explored further. A list of potentially resistant species is included in Appendix B.

Taxonomy: Several authors have attempted to identify genera and families that show uniform resistance or susceptibility to cyclone damage. In assessing tree damage from Cyclone Tracy, Van der Sommen (2002) identified the worst families as Meliaceae (eg *Khaya*), Rutaceae (*Citrus*), Anacardiaceae (*Mangifera*), Cupressacease (*Callitris*), Casuarinaceae (*Casuarina*), and potentially Rubiaceae (*Nauclea cadamba*), Lythraceae (*Lagerstroemia*), Mimosaceae (*Acacia*), Leguminosaceae (i.e. Fabaceae), Verbenaceae (i.e. Lamiaceae), and Bignoniaceae (*Spathodea*). Families identified as performing poorly were those that tend to have more pioneer vs climax species (Van der Sommen 2002).

The most resistant families following Cyclone Tracy were Guttiferae (i.e. Clusiaceae), Malvaceae, Moraceae, Sapindaceae, Apocynaceae (*Alstonia*), and Musaceae (*Ravenala*) (Van der Sommen 2002).

These sorts of generalisations along taxonomic lines are difficult, since different species within a family or even genus do not necessarily grow in the same habitat, and are likely to have different evolutionary traits depending on the environment in which they occur. Evidence from Cyclones Winifred, Tessi, Larry, Monica and Yasi show that most of these families contain both resistant and susceptible species, so extrapolating the response of one or two species to an entire family ignores the broad range of form and habitat specialization within the group.

Although the family Musaceae contains the highly resistant travelers palm (*Ravenala madagascariensis*), it also contains the highly susceptible banana (*Musa acuminata*). Even genera such as *Alstonia* that contain several highly resistant species (e.g. *A. actinophylla, A. scholaris, A. spectabilis*) also contain susceptible species such as *A. muelleriana* (Jeffers 2006). The genus *Acacia* is generally regarded as containing mostly susceptible species since most tropical coastal species are short lived pioneers, however, *Acacia fasciculifera* is a long-lived, slow growing and shade tolerant vine thicket species that demonstrates strong resistance.

Results of the present study have shown that there is a trend towards high resistance in the Family Clusiaceae (e.g. *Calophyllum, Garcinia*) but that most families were highly variable. Some consideration for trials and experiments should however, be given to a number of promising vine thicket shrub species of the Family Rubiaceae, particularly as many of them are highly ornamental and relatively low growing. Example include *Aidia racemosa, Atractocarpus spp., Cyclophyllum coprosmoides, Guettarda speciosa, Ixora timorensis, Larsenaikia ochreata, Pavetta* spp., *Psychotria spp., Psydrax* spp., and *Timonius timon*. Similarly, some non-pioneer trees and shrubs of the Rutaceae family should also be trialled, including *Acronychia* spp., *Flindersia* spp., *Glycosmis trifoliata, Melicope rubra*, and *Murraya ovatifoliolata*.

Conclusion: It is evident that no single trait is effective at identifying resistant species, though several traits are strongly correlated with sensitive species. It is concluded that resistant species must possess a range of traits to achieve their resistance, and that it may be possible to develop a weighted scoring system using the traits described to predict the likelihood of resistance or susceptibility to cyclone damage.

It is likely that there are a broader range of trees that have increased resilience to cyclonic winds, but too few have been observed to be able to form any conclusions. One of the issues facing identifying cyclone-resistant trees and shrubs is that many dry tropics species have never been observed after being subjected to higher category cyclonic winds. Many commonly grown tree species in Townsville and the lower Burdekin are not grown in wet tropics gardens where most recent cyclone activity has been focused. While the habitats described above do not contain exclusively resistant species, these may be good environments to seek additional plants worthy of trial in cultivation to test their cyclone resistance.

Assessing Cyclone Resistance

Lists of cyclone resistant and cyclone susceptible trees are provided in Appendices B and C respectively. These lists are derived from a variety of sources, including field observations following Cyclone Yasi, available literature relating to previous cyclones and predictions based on limited observations. The source of the listings are provided in the tables.

The definitions of 'resistant' and 'susceptible' are obvious at lower wind speeds (Category 1-2), where susceptible species suffer significant damage and resistant species are generally undamaged. Trees that usually sustain unrepairable damage in these wind speeds are generally labelled as being susceptible. The definitions become increasingly blurred and somewhat subjective at higher wind speeds, but could be defined as a species whose basic structure or framework is unaffected in wind speeds exceeding Category 3 with low rates of trunk snapping or uprooting (Cairns City Council 1986). The loss of leaves and small branches is expected even in resistant tree species.

Species that showed very low rates of damage in the higher wind speeds of Cyclone Yasi are obviously included in the list of resistant trees, but also include those species that performed particularly well during the Category 2 wind speeds in Townsville. The ability of these trees to survive Category 3 and 4 wind speeds is unknown, as many of these species do not occur naturally and are not cultivated in those wet tropics areas that experienced the higher wind speeds. Their high levels of resistance during lower category events do mirror other species known to be resistant at higher wind speeds.

It is likely that the majority of cultivated species are neither highly resistant nor susceptible, but fall into a middle category. One definition of a medium-tolerance species is one that can be expected to suffer damage in a Category 3 cyclone, losing fairly large branches but with the trunk and majority of branch framework remaining intact (Cairns City Council 1986).

Numerous previous authors have attempted to generate lists of tree species they regarded as being relatively resistant to cyclones. Their recommendations have been included in this list, except where their recommendations are contrary to the evidence of tree damage following Cyclone Yasi. For example Jeffers (2006) recommend coconut (*Cocos nucifera*) and cadaghi (*Corymbia torelliana*), both of which were significantly damaged during Cyclone Yasi and both are specifically mentioned in other Australian cyclone literature as being susceptible species. The same report also labeled *Elaeocarpus grandis, Flindersia schottiana and Syzygium forte* as being 'high hazard' species, although site inspections and other available literature suggests that these are actually highly resistant species. Many cyclone reports date back to the 1970s, and there have been numerous taxonomic changes since that time. All efforts have been made to ensure the current correct taxonomy has been used in the current report.

Unfortunately, there have been few attempts by many authors to cross-reference to other studies on tree damage, resulting in both repetition and contradiction. As every cyclone passes, our ability to add, subtract and further refine these lists will improve. Thus, the lists in Appendix B and C should be seen as 'works in progress', as opposed to the final definitive word on cyclone resistance. The passage of a Category 4 or 5 through the dry tropics of North Queensland would prove the ultimate test for many species predicted to have high cyclone resistance.

Appendix D illustrates for 143 species, the relative cyclone damage expected in different cyclone categories, and allows for discussion of common plant species that cannot be described as either highly resistant or highly susceptible. These cyclone categories are provided as surrogates for unidirectional wind speed of maximum gusts. When the eye of a cyclone passes over an area, wind comes from the opposite direction and the damage caused could be expected to be in a higher category. In situations where trees are exposed to cyclone-spawned tornadoes, the tree damage levels would correspond to the wind speed of the tornado, and not of the average wind gusts.

As previously stated, most species show a range of resilience between individuals, so terms such as 'rarely', 'sometimes' and 'often' are used to reflect that degree of variation.

Where question marks are shown, there are no observations for the impact of this wind speed on this species. The colour shown indicates what the minimal level of damage the plant is likely to experience based on behaviour at lower wind speeds, as levels of damage many not increase, but are never going to decrease with increased wind loading. When the maximum level of damage has been achieved at a lower wind speed, this has been extrapolated to the higher wind speed categories.

When using this chart to assess how a particular tree might be likely to perform, damage is likely to be one category worse if:

- the tree is subjected to opposing wind directions from the wall of the cyclone
- the tree is subjected to higher wind speeds at the top of slopes, where wind is funneled through hills or buildings, or where subjected to cyclone-spawned tornadoes;
- uprooting may be worse if very heavy prolonged rain is experienced before the cyclone crosses;
- trunk breakage (snapping) may be worse if no significant rain is recorded before the cyclone crosses;
- if the tree is subjected to prolonged exposure to damaging winds due to the large diameter or slow movement of the cyclone; or
- the tree is suffering any previous injury, has been poorly pruned, was pot bound or planted in a poorly prepared site, or has been subject to shallow watering.

It can be seen that some species have a tendency to suffer one particular type of damage over another. For example, African mahoganies don't often snap or drop branches, but are often uprooted. Some species will exhibit a particular level of damage at a lower cyclone category, but this level of damage doesn't increase with increased wind speed. In these cases, it must be assumed that individuals damaged are suffering an abnormal growth defect, and this will cause tree failure regardless of wind speed. All tree species can be expected to suffer some sort of damage during higher category cyclones, however, some individuals may escape damage altogether. Desirable species are those that do not, or rarely uproot or snap at lower cyclone categories. Undesirable species are those that often exhibit significant damage even during lower cyclone categories.

recommendations for risk mitigation

Recommendations for Risk Mitigation

Potential for use of tree cyclone ratings in planning schemes

Considering the significant impact of cyclones on communities, there is little argument against the need to have cyclone resilience incorporated into building design. That cyclones continue to have such a significant impact on communities, from damage to buildings, loss of electrical supply and massive green-waste clean-up bills is testimony to the fact that our tropical coastal communities still have a long way to go to increase their cyclone resilience. It was interesting to note that in a multi-hazard risk assessment of Cairns, Granger *et al*. (1999) noted that the 10 cyclones to affect Cairns since 1975 have had minimal impact on buildings but significant impact on vegetation and powerlines, yet the report did not include any recommendations for vegetation management in their list of Risk Mitigation Strategies.

Trees have an undisputed role in both causing much of the damage seen, and also in buffering and protecting buildings from cyclonic winds. Issues dealing with increasing cyclone resilience of trees to cyclones are a complex affair, involving both tree maintenance and species selection. To expect that the majority of the community is going to take the time to understand these complexities is naive, however, there is a strong opportunity for the council to lead by example with cyclone resilient street tree plantings, and by engaging the nursery industry, landscape architects and garden enthusiasts to champion the concept of cyclone resilience, with the hope that this will infiltrate into the broader community consciousness.

It needs to be recognised that in Category 1-3 cyclones, most buildings are capable of withstanding the resulting wind loading, and that the majority of observed damage is the result of damage to trees, and the damage that those trees subsequently cause when failure occurs. The value of trees in cyclones is not apparent at these lower wind speeds, but is more graphically demonstrated in Category 3-4 events when trees are extremely valuable in catching flying debris and reducing wind loading on buildings.

Low category cyclones are relatively common events, while large category events are quite rare. It is prudent, therefore, to ensure a high level of resilience during cyclones of Category 1-3 intensity. While the majority of work into increasing cyclone resilience has previously focused on the various aspects of building design, it is now time to focus on the cause of the majority of damage, which is tree failure.

From examination of the relevant literature, and from the results of the present study, it can be seen that different tree species pose different levels of risk during cyclones. This risk can be managed to a degree by correct planting, watering, pruning and management, however, the greatest predictor of the degree of cyclone damage comes from the species composition of a stand of trees.

When managing risk, it is usual to consider two elements – the likelihood of a particular event, and the consequence of that event occurring. These two elements are usually combined into a ‘Risk matrix’ as shown in Figure 25 below:

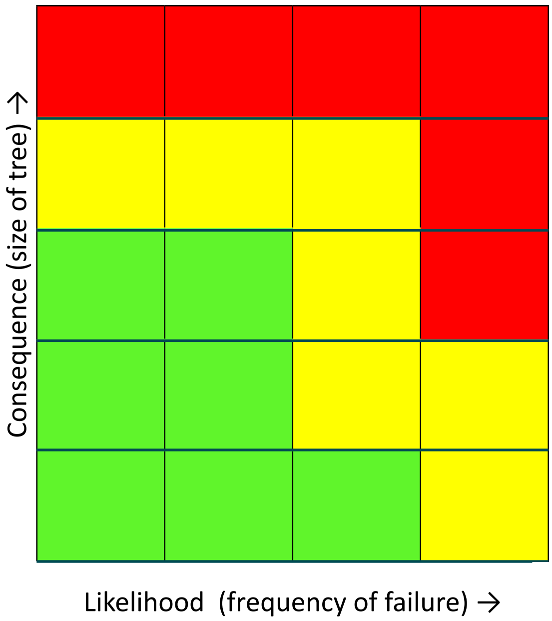


Figure 25 Risk Matrix for tree failure during cyclones

At the lowest risk are plants that very rarely fail and are of small size, so their failure would only have minimal consequences. The highest risk comes from trees that are large in size and have a high frequency of significant failure. Consequences may also be seen to increase from dropping small branches (low consequence) to uprooting (high consequence). From that perspective, the 'green waste scores' presented in Appendix A and discussed in Section 7.1 could be seen as a surrogate for 'risk'. While this data by itself lacks a degree of robustness in terms of separating impact from abundance, it does have the benefit of equating directly to the relative cost of each species to the community. By combining it with the results of the species contribution to power failure (Section 7.2), proportions of damage to trees in parks and avenues (Section 7.3) and results of a literature review into tree failure during previous cyclones (Appendix C), there is clear evidence that the majority of damage can be attributed to a small number of highly susceptible tree species.

Results of the green waste survey revealed that 55% of green waste generated in Townsville by Cyclone Yasi came from five tree species,

- yellow flame tree (*Peltophorum pterocarpum**);
- African mahogany(*Khaya senegalensis**);
- river blue gum (*Eucalyptus tereticornis*);
- weeping fig (*Ficus benjamina*); and
- pink trumpet tree (*Tabebuia impetiginosa** (syn*. T. palmeri*))

Of the power failures investigated in Aitkenvale and Mundingburra, 57.12% were caused by these species. If the entire $100 million damage bill for Townsville following Cyclone Yasi was caused by tree failure, then these five tree species cost the Townsville community $55 million. These trees are abundant in Townsville, as street trees, in parks and in private gardens. Removal of all remaining individuals would be an extremely expensive exercise, and would likely have a undesirable negative impact on the green and shady nature of some areas of Townsville. The river blue gum is a local native species that provides food and shelter for native fauna species and is part of the natural character of our local waterways. However, the continued use of these species in plantings will have a direct and measurable financial cost during future cyclonic events.

As surviving trees continue to grow, it is likely that they will become increasingly top-heavy, and in addition to an increased likelihood of damage by termites, diseases and senescence, be more likely to fail during cyclones even of the same or less intensity than Cyclone Yasi. Many of the surviving trees suffered considerable damage to their crowns, and resulting coppicing shoots are likely to have poor levels of attachment and increasing likelihood of branch failure, even during relatively low wind speeds. While reducing the likelihood of failure is possible through intensive management by preventative and restorative pruning, the size and abundance of these trees also make this an expensive and ongoing cost. The consequence of failure can be managed by reducing their abundance in areas where their failure is likely to result in damage to infrastructure.

Following Cyclone Tracy, it was predicted that individual residents would continue to plant trees based on their overall appeal, rather than solely on its wind stability (Cameron *et al*. 1981), and this prediction has certainly proved true. Despite numerous reports into the impacts of cyclones on trees that specifically name these and other tree species as being particularly susceptible, their use in plantings continue. Incorporating a consideration of cyclone resistance into a statute of planning schemes may be the best way to ensure that the mistake of allowing highly susceptible species to proliferate during inter-cyclone periods is avoided in future. It is recommended that as a minimum response, these five species be removed from allowable planting lists for areas where their failure can have significant consequences. This includes:

- in proximity to electrical transmission lines
- in proximity to buildings and other built infrastructure; and
- along roadsides where their failure can block road access.

The continued use of these tree species should only be allowed in areas where their failure has minimal consequences, such as the continued use of river blue gum in natural bushland revegetation projects. Revegetation and ecological-based projects should not be restricted to using cyclone resilient species, as a greater range of post-cyclone recovery options may be of greater importance to plant community cyclone resistance *per se*.

Many other tree species suffered disproportionaly high levels of damage during Cyclone Yasi, and many of these have been noted during previous cyclonic events as having notably poor resistance (Appendix C). Ideally, and ultimately, council should discourage the use of all tree species in Appendix C in areas of high potential impact (particularly large, cyclone sensitive tree species), and encourage the use of species listed in Appendix B. Trials of tree species suspected of having increased cyclone resistance should be encouraged to increase the diversity of species for use in sensitive areas. Cyclone resistance should not be the only criteria – invasiveness may be an overriding factor in many cases. A number of previously popular garden plants are now listed as Class 3 weeds in Queensland and banned from sale, but many other popular introduced garden plants also show invasive behaviour, including the highly cyclone resistant mock orange (*Murraya paniculata* cv. *exotica*).

One comment received during the present survey was that “Trees and cyclones don’t mix”, and that the best way to ensure that your house avoids cyclone damage is to remove all the trees. A consequence of this belief is that trees are removed or lopped indiscriminately, regardless of their degree of cyclone resistance or susceptibility. Lopping of trees prior to cyclones is a common current practice that results in poorly formed and cyclone sensitive regrowth so this incorrect lopping can actually increase the cyclone sensitivity of a tree in the long term.

The current practice of pruning tree canopies on one side to achieve the minimum clearance distances can increase tree susceptibility to cyclones by creating crown asymmetry and the likelihood of significant torsional damage to tree trunks during cyclones. It would be a more desirable outcome to remove these trees, particularly if they are an identified susceptible species, rather than incur the ongoing costs of pruning.

Recognising that most home owners have undertaken the clean up and maintenance of trees on their own properties, council should set up a webpage assisting residents not only in identification of susceptible and resistant species, but also recommendations for the pruning and post-cyclone care and maintenance of damaged trees as poorly managed regrowth can become a significant future hazard.

Figure 26 Low growing plants are often cyclone resistant but provide little or no protection to property

The current belief that trees are all hazards during cyclones needs to be targeted, and replaced with the message that trees are a valuable asset during cyclones and that a minority of tree species are dangerous and unacceptable hazards. Replacing trees with low growing shrubs may reduce the damage that these plants can have on infrastructure, but are incapable of delivering any benefits such as debris catchers or wind breaks during intense cyclone events. Townsville residents should be informed about the likelihood of failure of these highly susceptible species, so they can make informed decisions about their retention or removal. The role of highly susceptible tree species in causing power failure should be incorporated into the Ergon Energy / Greening Australia 'Plant Smart' program. Public education projects should be undertaken using a process of thematic-based communication, targeting the relationship between tree damage and their recent experiences of Cyclone Yasi while their memory of this event is still fresh and relevant. Giveaways of cyclone resistant species would be a good way to ensure the use of these species in areas that have suffered vegetation loss as a consequence of cyclone damage.

In terms of reducing the level of power failure, cyclone sensitive trees in proximity to powerlines should be targeted for progressive replacement. Where cyclone sensitive trees have been removed as a consequence of a cyclone or other tree removal requirement, it should be replaced by a species with known or suspected levels of increased cyclone resistance. It was shown during the current survey that underground placement of services does not necessarily protect them from damage from inappropriate tree species.

In terms of reducing impact to beachfronts from storm surge impacts, it can be seen that the loss of the supporting sand is one of the primary causes of tree failure. Species with small and ball-like roots systems such as coconut palms have a very limited ability to either reduce rates of sand loss or to survive it's removal. Preferred species for beachfront species should be those resistant to salt spray and trunk breakage, but also be broadly rooted species with an enhanced capacity to resist or survive sand removal.

The planting and ongoing management of trees in the urban landscape should also be examined for the way in which it may contribute to tree damage during cyclones. Particularly in planting on roadside verges, Council should consider a moratorium on planting advanced dicotyledonous plants in pots exceeding 25 L, as there is an undeniable relationship between this practice and the likelihood of failure of that tree.

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Appendix A: raw data for observed impacts of Cyclone Yasi on trees in Townsville

Appendix A: Raw data for observed impacts of Cyclone Yasi on trees in Townsville

(* Denotes species not native to Queensland)

Scientific name	Common name	Tree size	Uprooted	Trunk broken	Branches broken	Total individuals	Green waste Score
Acacia auriculiformis	earpod wattle	2	5	6	2	13	64
Acacia crassicarpa	thick podded salwood	2	5	1	1	7	53
Acacia decora	showy wattle	1	2			2	10
Acacia flavescens	yellow wattle	1		1		1	2
Acacia mangium	black wattle	2	1	1		2	12
Adenanthera pavonina	red bead tree	2	1	5	1	7	21
*Albizia lebbeck**	Indian siris	5	24	9	27	60	645
Albizia procera	forest siris	2	3	2		5	34
Aleurites moluccanus	candle nut	5			2	2	2
Alphitonia excelsa	soap bush / red ash	1	1			1	5
Alstonia actinophylla	milkwood	2		1	2		4
Alstonia scholaris	milky pine	5			2	2	2
*Anacardium occidentale**	cashew	2			2	2	2
Araucaria bidwillii	bunya pine	2		2		2	4
Araucaria cunninghamii	hoop pine	5	2	1	1	4	53
Archontophoenix alexandrae	Alexandra palm	2	1			1	10
Arenga australasica	arenga palm	2	1			1	10
Avicennia marina	grey mangrove	1				0	0
Azadirachta indica *	neem	2	2	1	2	5	24
Barringtonia asiatica	fish poison tree	2	1			1	10
Barringtonia racemosa	freshwater mangrove	2	2	4	1	7	29
*Bauhinia variegata**	bauhinia	1	2	1	1	4	13
*Bismarckia nobilis**	Bismark palm	5	1			1	25
Bombax ceiba	silk cotton tree	5		2	3	5	7
Brachychiton acerifolius	flame tree	2	8	4		12	88
Brachychiton rupestris	bottle tree	2	1			1	10
Buckinghamia celsissima	ivory curl tree	2		1	2	3	4
*Caesalpinia ferrea**	leopard tree	2	28		4	32	284
*Calliandra haematocephala**	red powder puff	1	3			3	15
Calophyllum inophyllum	Alexandrian laurel	5			2	2	2
Cananga odorata	ylang ylang	2		2	1	3	5
Carpentaria acuminata	Carpentaria palm	2	8			8	80
Caryota mitis *	clumping fishtail palm	2	4	1	3	8	45
*Caryota urens**	fishtail palm	2	14			14	140
*Cassia fistula**	golden shower tree	2	2	4		6	28
Castanospermum australe	black bean	5	1	8	12	21	53
Casuarina cunninghamiana	river she oak	2	1	13	2	16	38
Casuarina equisetifolia	beach she oak	2	2	8	7	17	43

Scientific name	Common name	Tree size	Uprooted	Trunk broken	Branches broken	Total individuals	Green waste Score
Ceiba pentandra *	kapok (introduced)	5	1		3	4	28
Cerbera manghas	native frangipani	2	1			1	10
*Chrysophyllum cainito**	star apple	2				0	0
Citharexylum quadrangulare *	fiddlewood	2	22	12	2	36	246
*Cocos nucifera**	coconut	2	24	3		27	246
Cordia dichotoma	glue berry	2	1	2		3	14
*Cordia sebestena**	red cordia	2	1			1	10
Corymbia citriodora	lemon scented gum	5	16	11	5	32	427
Corymbia clarksoniana	bloodwood	5	2		5	7	55
Corymbia dallachiana	Dallachy's gum	5	2	1	1	4	53
Corymbia leichhardtii	rusty jacket	2		3	1	4	7
Corymbia peltata	rusty jacket	5		4	2	6	10
Corymbia ptychocarpa	swamp bloodwood	2	2	2	5	9	29
Corymbia tessellaris	Moreton Bay ash	5	29	10	17	56	762
Corymbia torelliana	cadaghi	2	3	7	9	19	53
Cupaniopsis anacardioides	beach tuckeroo	1	12	5	2	19	72
*Cupressus sempervirens**	pencil pine	2	12			12	120
*Delonix regia**	poinciana	5	9	3	5	17	236
Deplanchea tetraphylla	golden bouquet tree	2		2	1	3	5
*Duranta erecta**	duranta	1	39	4		43	203
Dypsis decaryi *	triangle palm	2	2			2	20
Dypsis lastelliana *	redneck palm	2	1			1	10
*Dypsis lutescens**	golden cane palm	1	5	1	5	11	32
Elaeocarpus grandis	blue quandong	5	1	1		2	27
Eucalyptus (unspecified)	eucalypt	5	4	1		5	102
Eucalyptus camaldulensis	river red gum	5		1		1	2
Eucalyptus crebra	narrow-leaved ironbark	2	8	12	22	42	126
Eucalyptus paedoglauca	Mt Stuart ironbark	2	1			1	10
Eucalyptus platyphylla	poplar gum	5	13	11	10	34	357
Eucalyptus raveretiana	black ironbox	5		1	1	2	3
Eucalyptus tereticornis	river blue gum	5	53	65	30	148	1485
*Ficus benghalensis**	banyan fig	5		2	36	38	40
Ficus benjamina	weeping fig	5	38	6	10	54	972
*Ficus elastica**	rubber tree	5		1	2	3	4
*Ficus longifolia**	long-leafed fig	2	1			1	10
*Ficus lyrata**	fiddleleaf fig	2	2			2	20
Ficus microcarpa var. hillii	fig	2	2		1	3	21
Ficus nodosa	Rocky River fig	2		1		1	2

Scientific name	Common name	Tree size	Uprooted	Trunk broken	Branches broken	Total individuals	Green waste Score
Ficus opposita	sandpaper fig	2	1	1	5	7	17
Ficus racemosa	cluster fig	5		7	4	11	18
Ficus virens	white fig	5	1			1	25
*Fraxinus griffithii**	Griffith's ash	2	3		1	4	31
Glochidion harveyanum	button wood	2	1			1	10
Grevillea 'honey gem'	Grevillea 'honey gem'	1	1			1	5
Grevillea pteridifolia	golden grevillea	1	1	1		2	7
Grevillea robusta	silky oak	5	1	2	2	5	31
Harpullia pendula	QLD tulipwood	2		2		2	4
*Hibiscus rosa-sinensis**	red hibiscus	1	3			3	15
Hibiscus tiliaceus	beach hibiscus	2	3	1	2	6	34
*Jacaranda mimosifolia**	jacaranda	2		2		2	4
*Khaya senegalensis**	African mahogany	5	116	21	17	154	2959
Kleinhovia hospita	guest tree	2		1		1	2
*Lagerstroemia indica**	crepe myrtle	2	6		1	7	61
Leptospermum madidum	weeping tea tree	1			12	12	12
*Leucaena leucocephala**	leucaena	1		6		6	12
*Litchi chinensis**	lychee	1	1		1	2	6
Lophostemon grandiflorus	northern swamp box	2	1	2	1	4	15
Macadamia integrifolia	Macadamia nut	2	2			2	20
Macaranga tanarius	heart leaf	2		5		5	10
*Mangifera indica**	mango	5	1	1	4	6	31
Maniltoa lenticellata	cascading bean	2			1	1	1
Melaleuca fluviatilis	paperbark	5			4	4	4
Melaleuca leucadendra	weeping paperbark	5		1	4	5	6
Melaleuca linariifolia	snow-in-summer	2	5	3	5	13	61
Melaleuca nervosa	paperbark	5	8	2	2	12	206
Melaleuca viminalis	weeping bottlebrush	1	6	9	15	30	63
Melaleuca viridiflora	broad-leaved tea tree	1				0	0
Melia azedarach	white cedar	5	1				25
Melicope elleryana	pink euodia	5	2			2	50
Millettia pinnata	pongamia	2		5		5	10
Nauclea orientalis	Leichhardt tree	5			2	2	2
*Nerium oleander **	oleander	1		1		1	2
Pandanus cookii	screw pine	2			2	2	2
*Pandanus sp 'variegated'**	variegated screw pine	1		1		1	2
Pandanus tectorius	coastal screw pine	2		1	3	4	5
*Parkia javanica**	sataw	2			1	1	1
*Peltophorum pterocarpum**	yellow flame tree	5	169	178	193	540	4774
*Persea americana**	avocado	2	1			1	10
*Phoenix dactylifera**	date palm	2	1			1	10
*Phoenix roebelenii **	dwarf date palm	1	1			1	5

Scientific name	Common name	Tree size	Uprooted	Trunk broken	Branches broken	Total individuals	Green waste Score
*Phyllanthus acidus**	star gooseberry	1		1	1	2	3
*Pinus caribaea**	slash pine	5	3			3	75
*Platycladus orientalis**	book leaf pine	1	3			3	15
*Plumeria obtusa**	frangipani	1	11	3	8	22	69
Podocarpus elatus	plum pine	2	1			1	10
*Polyalthia longifolia**	Indian mast tree	2	7	3		10	76
*Pterocarpus indicus**	Burmese rosewood	5	17	12	8	37	457
*Roystonea regia**	Cuban royal palm	5	5	1	41	47	168
*Samanea saman**	rain tree	5	2	4	36	42	94
Schefflera actinophylla	umbrella tree	2		3	5	8	11
*Schinus terebinthifolius **	Brazilian pepper tree	1	21	2		23	109
*Senna siamea**	Siamese cassia	2	15	5	8	28	168
*Senna spectabilis**	spectacular cassia	2			1	1	1
*Spathodea campanulata**	African tulip	5	10	3	2	15	258
Sterculia quadrifida	peanut tree	1		1		1	2
*Syagrus romanzoffiana**	queen palm	2	25	1		26	252
Syzygium australe cult.	lillypilly	1	15			15	75
*Syzygium cumini**	Javan plum	2	9	25	15	49	155
*Syzygium jambos**	rose apple	2	1	2		3	14
Syzygium luehmannii	small-leaved lilly pilly	2	2	1	2	5	24
Syzygium tierneyanum	river cherry	2			3	3	3
*Tabebuia aurea **	yellow tabebuia	2	7	13	3	23	99
Tabebuia heterophylla (syn. T. pallida)*	pink trumpet tree	2	5	39	61	105	189
*Tabebuia impetiginosa ** (syn. *T. palmeri*)	Pink trumpet tree	2	55	175	3	233	903
*Tamarindus indica**	tamarind	5	1		2	3	27
*Tecoma stans**	yellow bells	1	5			5	25
Terminalia catappa	sea almond	5	3	4	11	18	94
Terminalia microcarpa	brown damson	5	9	4	11	24	244
Terminalia muelleri	Mueller's damson	2		2		2	4
Thespesia populnea	portia tree	2			1	1	1
*Tipuana tipu**	tipuana tree	2	2	1		3	22
Waterhousia floribunda	weeping lillypilly	2		2	1	3	5
Wodyetia bifurcata	foxtail palm	2	2			2	20
Xanthostemon chrysanthus	golden penda	2	9	1	3	13	95

Appendix B: Tree species considered likely to be resistant to impacts by tropical cyclones

Appendix B: Tree species considered likely to be resistant to impacts by tropical cyclones

(* denotes species not native to Queensland)

FAMILY	Scientific Name	Identified in this study	Insufficient evidence in this study	Previous research
Mimosaceae	*Acacia fasciculifera*		1	
Myrtaceae	*Acmena hemilampra*		1	Bruce *et al* (1998), Tucker *et al*. (2006)
Bombacaceae	*Adansonia gregorii*			Cameron *et al* (1981), Van der Sommen (2002)
Araucariaceae	*Agathis robusta*	1		Roach (2006)
Rubiaceae	*Aidia racemosa*			Fox (1980)
Casuarinaceae	*Allocasuarina inophloia*			Donahue (1975)
Apocynaceae	*Alstonia actinophylla*	1		Cameron *et al* (1981), Roach (2006), Stocker (1976), Van der Sommen (2002)
Apocynaceae	*Alstonia scholaris*	1		Donahue (1975), Kupsch (2006), Tucker *et al.* (2006)
Apocynaceae	*Alstonia spectabilis*		1	
Arecaceae	*Archontophoenix alexandrae*	1		Cairns City Council (1986), Jeffers (2006), Roach (2006), Tucker *et al.* (2006)
Boraginaceae	*Argusia argentea*	1		
Sterculiaceae	*Argyrodendron* spp			Curran *et al* (1998), Tucker *et al*. (2006)
Moraceae	*Artocarpus altilis**			Cameron *et al* (1982)
Moraceae	*Artocarpus heterophyllus**			Cameron *et al* (1982)
Rubiaceae	*Atractocarpus fitzalanii*		1	
Avicenniaceae	*Avicennia marina*	1		Stocker (1976)
Myrtaceae	*Baeckea virgata* var. *parvula*			Donahue (1975)
Poaceae	*Bambusa vulgaris**	1		Cameron *et al* (1982)
Proteaceae	*Banksia dentata*		1	
Lecythidaceae	*Barringtonia calyptrata*	1		Tucker *et al*. (2006)
Arecaceae	*Bismarckia nobilis**	1		
Sterculiaceae	*Brachychiton australis*	1		
Anacardiaceae	*Buchanania arborescens*		1	
Anacardiaceae	*Buchanania obovata*			Calvert (2006)
Cupressaceae	*Callitris intratropica*		1	Calvert (2006)

FAMILY	Scientific Name	Identified in this study	Insufficient evidence in this study	Previous research
Clusiaceae	*Calophyllum inophyllum*	1		Cairns City Council (1986), Calvert (2000), Calvert (2006), Cameron *et al* 1982, Donahue (1975), Kupsch (2006), Roach (2006), Tucker *et al.* (2006), Stocker (1976), Van der Sommen (2002)
Clusiaceae	*Calophyllum sil*			Stocker (1976)
Rhizophoraceae	*Carallia brachiata*	1		Bruce *et al* (1998), Cairns City Council (1986), Calvert (2006)
Caesalpiniaceae	*Cassia fistula**			Roach (2006)
Fabaceae	*Castanospermum australe*			Calvert (2000), Donahue (1975), Tucker *et al.* (2006)
Caesalpiniaceae	*Colvillea racemosa**	1		Cameron *et al* (1981)
Laxmanniaceae	*Cordyline spp*	1		Tucker *et al.* (2006)
Amaryllidaceae	*Crinum pedunculatum*	1		
Euphorbiaceae	*Croton variegatus**	1		
Lauraceae	*Cryptocarya hypospodia*			Tucker *et al.* (2006)
Lauraceae	*Cryptocarya laevigata*			Jeffers (2006)
Sapindaceae	*Cupaniopsis anacardioides*			Cairns City Council (1986), Roach (2006)
Cycadaceae	*Cycas spp*	1		Cameron *et al* (1981)
Fabaceae	*Dalbergia latifolia*			Cameron *et al* (1981)
Caesalpiniaceae	*Delonix regia**			Cairns City Council (1986), Cameron *et al* 1981
Celastraceae	*Denhamia obscura*			Cameron *et al* (1981)
Celastraceae	*Denhamia parvifolia*			
Araceae	*Dictyosperma album**			Cairns City Council (1986),
Dilleniaceae	*Dillenia alata*			Cameron *et al* (1981)
Putranjivaceae	*Drypetes deplanchei*		1	
Arecaceae	*Dypsis decaryi **	1		
Arecaceae	*Dypsis lastelliana **	1		
Arecaceae	*Dypsis lutescens**	1		Jeffers (2006)
Elaeocarpaceae	*Elaeocarpus grandis*	1		Roach (2006), Tucker *et al.* (2006)
Myrtaceae	*Eucalyptus grandis*			Jeffers (2006)
Myrtaceae	*Eucalyptus raveretiana*	1		
Myrtaceae	*Eucalyptus resinifera*			Roach (2006)
Myrtaceae	*Eugenia reinwardtiana*	1		

FAMILY	Scientific Name	Identified in this study	Insufficient evidence in this study	Previous research
Myrtaceae	*Eugenia uniflora**	1		
Moraceae	*Ficus congesta*			Tucker *et al.* (2006)
Moraceae	*Ficus destruens*	1		
Moraceae	*Ficus drupacea*	1		Tucker *et al.* (2006)
Moraceae	*Ficus 'Green Island'**	1		
Moraceae	*Ficus hispida*			Tucker *et al.* (2006)
Moraceae	*Ficus macrophylla*			Roach (2006)
Moraceae	*Ficus microcarpa var. hillii*	1		Roach (2006), Tucker *et al.* (2006)
Moraceae	*Ficus obliqua*			Roach (2006)
Moraceae	*Ficus racemosa*			Roach (2006)
Moraceae	*Ficus scobina*			Fox (1980)
Moraceae	*Ficus septica*			Tucker *et al.* (2006)
Moraceae	*Ficus virens*	1		Cameron *et al* (1981), Tucker *et al.* (2006), Van der Sommen (2002)
Rutaceae	*Flindersia australis*			Roach (2006)
Rutaceae	*Flindersia bennettiana*			Roach (2006)
Rutaceae	*Flindersia bourjotiana*	1		
Rutaceae	*Flindersia collina*			Roach (2006)
Rutaceae	*Flindersia laevicarpa*			Cameron *et al* (1981)
Rutaceae	*Flindersia schottiana*			Kupsch (2006), Roach (2006)
Rutaceae	*Flindersia spp*	1		Kupsch (2006)
Oleaceae	*Fraxinus griffithii*	1		
Clusiaceae	*Garcinia warrenii*		1	
Rutaceae	*Geijera parviflora*		1	
Rutaceae	*Geijera salicifolia*	1		
Phyllanthaceae	*Glochidion benthamianum*			Bruce *et al* (2008)
Phyllanthaceae	*Glochidion sumatranum*			Bruce *et al* (2008)
Rutaceae	*Glycosmis trifoliata*	1		Fox (1980)
Lamiaceae	*Gmelina leichhardtii*			Cairns City Council (1986)
Proteaceae	*Grevillea baileyana*	1		Jeffers (2006), Roach (2006)
Proteaceae	*Grevillea parallela*	1		
Proteaceae	*Grevillea striata*	1		
Malvaceae	*Hibiscus tiliaceus*	1		Stocker (1976), Cameron *et al* 1981, Van der Sommen (2002)
Caesalpiniaceae	*Intsia bijuga*	1		
Rubiaceae	*Ixora coccinea**	1		

FAMILY	Scientific Name	Identified in this study	Insufficient evidence in this study	Previous research
Lythraceae	*Lagerstroemia speciosa**			Cairns City Council (1986), Jeffers (2006)
Rubiaceae	*Larsenaikia ochreata*		1	
Myrtaceae	*Leptospermum brachyandrum*			Cairns City Council (1986)
Myrtaceae	*Leptospermum petersonii*			Jeffers (2006)
Arecaceae	*Licuala grandis**		1	
Arecaceae	*Licuala ramsayi*	1		Roach (2006)
Arecaceae	*Livistona spp*	1		Calvert (2006)
Myrtaceae	*Lophostemon grandiflorus*	1		Calvert (2000)
Combretaceae	*Lumnitzera racemosa*	1		Stocker (1976)
Anacardiaceae	*Mangifera indica**	1		
Caesalpiniaceae	*Maniltoa lenticellata*	1		
Myrtaceae	*Melaleuca argentea*			Donahue (1975)
Myrtaceae	*Melaleuca dealbata*	1		
Myrtaceae	*Melaleuca fluviatilis*	1		
Myrtaceae	*Melaleuca formosa*			Donahue (1975)
Myrtaceae	*Melaleuca leucadendra*	1		Calvert (2000), Calvert (2006), Roach (2006)
Myrtaceae	*Melaleuca linariifolia*			Donahue (1975)
Myrtaceae	*Melaleuca polandii*			Donahue (1975)
Myrtaceae	*Melaleuca quinquenervia*			Bruce *et al* 1998, Cairns City Council (1986), Roach (2006)
Myrtaceae	*Melaleuca sp. 'Dawson River'*			Jeffers (2006)
Myrtaceae	*Melaleuca sp. 'Tinaroo'*			Donahue (1975)
Myrtaceae	*Melaleuca viminalis*	1		Bruce *et al* (1998)
Fabaceae	*Millettia pinnata*	1		Bruce *et al.* (2008), Cairns City Council (1986), Stocker (1976)
Sapotaceae	*Mimusops elengi*	1		Fox 1980, Stocker (1976)
Rubiaceae	*Morinda citrifolia*	1		
Rubiaceae	*Nauclea orientalis*	1		Bruce *et al* (1998), Calvert (2000)
Apocynaceae	*Nerium oleander**	1		
Arecaceae	*Normanbya normanbyi*			Roach (2006)
Pandanaceae	*Pandanus conicus*	1		
Pandanaceae	*Pandanus cookii*	1		
Pandanaceae	*Pandanus spiralis*			
Pandanaceae	*Pandanus tectorius*	1		
Arecaceae	*Phoenix dactylifera**	1		Cameron *et al* (1981)

FAMILY	Scientific Name	Identified in this study	Insufficient evidence in this study	Previous research
Arecaceae	*Phoenix roebelenii* *	1		Cairns City Council (1986), Cameron *et al* (1981)
Pittosporaceae	*Pittosporum venulosum*			Jeffers (2006)
Lecythidaceae	*Planchonia careya*			Calvert (2006)
Anacardiaceae	*Pleiogynium timorense*	1		
Podocarpaceae	*Podocarpus grayae*		1	
Annonaceae	*Polyalthia nitidissima*		1	Fox (1980)
Araliaceae	*Polyscias elegans*			Jeffers (2006)
Musaceae	*Ravenala madagascariensis**	1		Van der Sommen (2002)
Arecaceae	*Roystonea regia**			
Arecaceae	*Sabal palmetto**		1	Cameron *et al*. (1981)
Araliaceae	*Schefflera actinophylla*	1		Cameron *et al.* (1981), Jeffers (2006)
Caesalpiniaceae	*Schotia brachypetala**		1	Cairns City Council (1986), Cameron *et al.* (1981)
Sapotaceae	*Sersalisia sericea*	1		Fox (1980)
Sterculiaceae	*Sterculia quadrifida*		1	
Meliaceae	*Swietenia mahogani**			Roach (2006)
Myrtaceae	*Syzygium forte*	1		Calvert (2006)
Myrtaceae	*Syzygium nervosum*		1	Cameron *et al.* 1981, Van der Sommen (2002)
Myrtaceae	*Syzygium suborbiculare*			Cairns City Council (1986), Calvert (2006)
Myrtaceae	*Syzygium tierneyanum*	1		Bruce *et al* (2008)
Caesalpiniaceae	*Tamarindus indica**	1		Cairns City Council (1986)
Lamiaceae	*Tectona grandis**		1	Stocker (1976)
Combretaceae	*Terminalia catappa*			Cairns City Council (1986)
Meliaceae	*Toona ciliata*		1	Cameron *et al*. 1981, Van der Sommen (2002)
Arecaceae	*Wodyetia bifurcata*	1		Cairns City Council (1986), Roach (2006)
Myrtaceae	*Xanthostemon chrysanthus*			Jeffers (2006)
Meliaceae	*Xylocarpus moluccensis*			Stocker (1976)

Appendix C: Tree species considered likely to be sensitive to impacts by tropical cyclones

Appendix C: Tree species considered likely to be sensitive to impacts by tropical cyclones

(* denotes species not native to Queensland)

FAMILY	Scientific Name	This study	Previous Research
Mimosaceae	Acacia auriculiformis	1	Calvert (2000), Calvert (2006)
Mimosaceae	Acacia celsa		Jeffers (2006)
Mimosaceae	Acacia crassicarpa	1	
Mimosaceae	Acacia mangium	1	Bruce et al (2008)
Mimosaceae	Adenanthera pavonina	1	Cameron et al (1981)
Mimosaceae	Albizia lebbeck*	1	Calvert (2000)
Mimosaceae	Albizia procera	1	
Apocynaceae	Alstonia muelleriana		Jeffers (2006)
Araucariaceae	Araucaria cunninghamii	1	Cairns City Council (1986), Jeffers (2006), Kupsch (2006), Roach (2006)
Araucariaceae	Araucaria heterophylla		Jeffers (2006)
Rubiaceae	Atractocarpus fitzalanii		Cairns City Council (1986)
Proteaceae	Banksia spp		Cairns City Council (1986) (note that Banksia dentata performed well during Cyclone Monica)
Caesalpiniaceae	Bauhinia purpurea*		Jeffers (2006)
Caesalpiniaceae	Bauhinia variegata*		Cairns City Council (1986)
Caesalpiniaceae	Caesalpinia ferrea*	1	Cairns City Council (1986)
Arecaceae	Caryota urens*	1	Cairns City Council (1986), Calvert (2006)
Casuarinaceae	Casuarina cunninghamiana	1	Calvert (2000), Calvert (2006), Jeffers (2006)
Casuarinaceae	Casuarina equisetifolia	1	
Rhizophoraceae	Ceriops tagal		Stocker (1976)
Oleaceae	Chionanthus ramiflorus		Bruce et al (2008)
Verbenaceae	Citharexylum quadrangulare*	1	Calvert (2000), 'Calvert (2006)
Cochlospermaceae	Cochlospermum gillivraei	1	
Arecaceae	Cocos nucifera*	1	Calvert (2000), Calvert (2006), Stocker (1976)
Byttneriaceae	Commersonia bartramia		Jeffers (2006)
Boraginaceae	Cordia dichotoma	1	
Myrtaceae	Corymbia citriodora	1	Calvert (2000)
Myrtaceae	Corymbia clarksoniana	1	
Myrtaceae	Corymbia dallachiana	1	
Myrtaceae	Corymbia tessellaris	1	

FAMILY	Scientific Name	This study	Previous Research
Myrtaceae	Corymbia torelliana	1	Calvert (2000), Cairns City Council (1986)
Fabaceae	Erythrina variegata		Cairns City Council (1986)
Fabaceae	Erythrina vespertilio		Cairns City Council (1986)
Caesalpiniaceae	Erythrophleum chlorostachys		Stocker (1976)
Myrtaceae	Eucalyptus camaldulensis	1	Calvert (2000), Calvert (2006), Cameron et al (1981)
Myrtaceae	Eucalyptus microcorys		Jeffers (2006), Tucker et al. (2006)
Myrtaceae	Eucalyptus miniata		Calvert (2006)
Myrtaceae	Eucalyptus platyphylla	1	Donahue 1975
Myrtaceae	Eucalyptus tereticornis	1	Calvert (2000)
Myrtaceae	Eucalyptus tetrodonta		Calvert (2006)
Phyllanthaceae	Glochidion sumatranum		Jeffers (2006)
Proteaceae	Grevillea pteridifolia		
Proteaceae	Grevillea robusta	1	Jeffers (2006)
Euphorbiaceae	Homalanthus novoguineensis		Bruce et al (2008)
Bignoniaceae	Jacaranda mimosifolia*		Jeffers (2006)
Meliaceae	Khaya senegalensis*	1	Calvert (2000), Calvert (2006), Cameron et al (1981)
Lythraceae	Lagerstroemia speciosa*		Cameron et al (1981)
Rubiaceae	Larsenaikia ochreata		Jeffers (2006)
Myrtaceae	Leptospermum luehmannii		Jeffers (2006)
Hamamelidaceae	Liquidambar styraciflua*		Jeffers (2006)
Sapindaceae	Litchi chinensis*	1	Jeffers (2006), Oliver & Wilson (1986)
Euphorbiaceae	Macaranga tanarius	1	Bruce et al (2008)
Euphorbiaceae	Mallotus paniculatus		Bruce et al (2008)
Myrtaceae	Melaleuca bracteata		Jeffers (2006)
Myrtaceae	Melaleuca nervosa		Calvert (2006)
Myrtaceae	Melaleuca viminalis	1	Jeffers (2006)
Myrtaceae	Melaleuca viridiflora		Donahue 1975
Meliaceae	Melia azedarach		Cameron et al 1981
Rutaceae	Melicope elleryana		Bruce et al (2008)
Muntingiaceae	Muntingia calabura*		Calvert (2000)
Musaceae	Musa acuminata*		Calvert (2000)
Caesalpiniaceae	Peltophorum pterocarpum*	1	Cairns City Council (1986), Calvert (2000), Calvert (2006), Cameron et al 1981
Lauraceae	Persea Americana*		Oliver & Wilson (1986)
Pinaceae	Pinus caribaea*		Oliver & Wilson (1986), Stocker (1976)

FAMILY	Scientific Name	This study	Previous Research
Pinaceae	Pinus elliottii*		Jeffers (2006)
Myrtaceae	Psidium guajava*	1	Cameron et al. 1981
Fabaceae	Pterocarpus indicus*	1	
Arecaceae	Ptychosperma macarthurii	1	Cairns City Council (1986)
Anacardiaceae	Rhus taitensis	1	Bruce et al (2008)
Mimosaceae	Samanea saman*	1	Cairns City Council (1986)
Bignoniaceae	Spathodea campanulata*	1	Cairns City Council (1986), Calvert (2000)
Arecaceae	Syagrus romanzoffiana*		
Myrtaceae	Syzygium cumini*	1	
Bignoniaceae	Tabebuia aurea *	1	Calvert (2000)
Bignoniaceae	Tabebuia heterophylla* (syn. T. pallida)	1	Calvert (2000)
Bignoniaceae	Tabebuia impetiginosa * (syn. T. palmeri)	1	Calvert (2000)
Bignoniaceae	Tecoma stans*		Calvert (2000)
Combretaceae	Terminalia catappa		Roach (2006)

Appendix D: Cyclone damage behaviour of some commonly grown trees

Appendix D: Cyclone damage behaviour of some commonly grown trees

Before using this table, it is important to refer to the explanatory notes in Section 7.7 first.
? – Indicates that damage will be at least this severe, but there is no data available for this species at this wind speed

Uprooting		Trunk		Branches	
	no damage		no damage		no damage
	rarely uprooted		snapping rare		small branches or rarely large branches
	sometime uprooted		sometime snap		sometimes large branches
	often uprooted		often snap		often large branches
	many uprooted		many snap		many large branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Acacia auriculiformis	earpod wattle									Uprooting
										Trunk
										Branches
Acacia crassicarpa	thick podded salwood									Uprooting
								?	?	Trunk
								?	?	Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Acacia mangium	black wattle							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Adenanthera pavonina	red bead tree									Uprooting
										Trunk
						?	?	?	?	Branches
Agathis robusta	kauri pine									Uprooting
										Trunk
										Branches
Albizia lebbeck	Indian siris									Uprooting
										Trunk
										Branches
Albizia procera	forest siris							?	?	Uprooting
										Trunk
								?	?	Branches
Aleurites moluccanus	candle nut							?	?	Uprooting
										Trunk
										Branches
Alphitonia excelsa	soap bush / red ash					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Alstonia actinophylla	milkwood							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Alstonia scholaris	milky pine									Uprooting
										Trunk
										Branches
Anacardium occidentale	cashew							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Araucaria bidwillii	bunya pine									Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Araucaria cunninghamii	hoop pine									Uprooting
										Trunk
										Branches
Archontophoenix alexandrae	Alexandra palm									Uprooting
										Trunk
										Branches
Arenga australasica	arenga palm									Uprooting
										Trunk
										Branches
Argyrodendron spp	tulip oak									Uprooting
										Trunk
										Branches
Avicennia marina	grey mangrove									Uprooting
								?	?	Trunk
										Branches
Azadirachta indica	neem					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Barringtonia asiatica	fish poison tree					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Barringtonia racemosa	freshwater mangrove							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Bauhinia variegata	bauhinia							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Bismarckia nobilis	Bismark palm									Uprooting
									?	Trunk
										Branches
Bombax ceiba	silk cotton tree							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Brachychiton acerifolius	flame tree								?	Uprooting
									?	Trunk
									?	Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Buckinghamia celsissima	ivory curl tree					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Caesalpinia ferrea	leopard tree							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Calliandra haematocephala	red powder puff									Uprooting
								?	?	Trunk
								?	?	Branches
Calophyllum inophyllum	Alexandrian laurel									Uprooting
										Trunk
										Branches
Cananga odorata	ylang ylang					?	?	?	?	Uprooting
										Trunk
						?	?	?	?	Branches
Carpentaria acuminata	Carpentaria palm									Uprooting
										Trunk
										Branches
Caryota mitis	clumping fishtail palm									Uprooting
										Trunk
										Branches
Caryota urens	fishtail palm									Uprooting
										Trunk
								?	?	Branches
Cassia fistula	golden shower tree							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Castanospermum australe	black bean									Uprooting
										Trunk
										Branches
Casuarina cunninghamiana	river she oak							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Casuarina equisetifolia	beach she oak									Uprooting
								?	?	Trunk
								?	?	Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Ceiba pentandra	kapok (introduced)					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Citharexylum quadrangulare	fiddlewood									Uprooting
								?	?	Trunk
								?	?	Branches
Cocos nucifera	coconut									Uprooting
										Trunk
										Branches
Cordia dichotoma	glue berry					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Corymbia citriodora	lemon scented gum									Uprooting
										Trunk
										Branches
Corymbia clarksoniana	bloodwood							?	?	Uprooting
										Trunk
										Branches
Corymbia dallachiana	Dallachy's gum					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Corymbia leichhardtii	rusty jacket					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Corymbia peltata	rusty jacket					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Corymbia ptychocarpa	swamp bloodwood							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Corymbia tessellaris	Moreton Bay ash							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Corymbia torelliana	cadaghi							?	?	Uprooting
								?	?	Trunk
								?	?	Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Cupaniopsis anacardioides	beach tuckeroo							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Cupressus sempervirens	pencil pine					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Cycas sp.	cycad								?	Uprooting
									?	Trunk
										Branches
Delonix regia	poinciana									Uprooting
										Trunk
										Branches
Duranta erecta	duranta									Uprooting
									?	Trunk
									?	Branches
Dypsis decaryi	triangle palm								?	Uprooting
									?	Trunk
									?	Branches
Dypsis lastelliana	redneck palm							?	?	Uprooting
									?	Trunk
									?	Branches
Dypsis lutescens	golden cane palm							?	?	Uprooting
									?	Trunk
									?	Branches
Elaeocarpus grandis	blue quandong									Uprooting
										Trunk
										Branches
Eucalyptus camaldulensis	river red gum									Uprooting
										Trunk
										Branches
Eucalyptus crebra / drepanophylla	narrow-leaved ironbark					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Eucalyptus phoenicia	scarlet gum					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Eucalyptus platyphylla	poplar gum					?	?	?	?	Uprooting
						?	?	?	?	Trunk
										Branches
Eucalyptus raveretiana	black ironbox					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Eucalyptus tereticornis	river blue gum									Uprooting
										Trunk
										Branches
Euroschinus falcatus	ribbonwood						?	?	?	Uprooting
							?	?	?	Trunk
							?	?	?	Branches
Ficus benghalensis	banyan fig							?	?	Uprooting
								?	?	Trunk
										Branches
Ficus benjamina	weeping fig									Uprooting
										Trunk
										Branches
Ficus elastica	rubber tree									Uprooting
										Trunk
										Branches
Ficus lyrata	fiddleleaf fig					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Ficus microcarpa var. hillii	Hill's weeping fig					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Ficus opposita	sandpaper fig					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Ficus racemosa	cluster fig					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Ficus virens	white fig									Uprooting
										Trunk
										Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Fraxinus griffithii	Griffith's ash									Uprooting
									?	Trunk
										Branches
Geijera salicifolia	scrub wilga					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Grevillea paralella	beefwood					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Grevillea pteridifolia	golden grevillea									Uprooting
										Trunk
										Branches
Grevillea robusta	silky oak							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Grevillea striata	beefwood					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Harpullia pendula	QLD tulipwood					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Hibiscus rosa-sinensis	red hibiscus									Uprooting
								?	?	Trunk
								?	?	Branches
Hibiscus tiliaceus	beach hibiscus							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Jacaranda mimosifolia	jacaranda					?	?	?	?	Uprooting
							?	?	?	Trunk
							?	?	?	Branches
Khaya senegalensis	African mahogany									Uprooting
								?	?	Trunk
								?	?	Branches
Leptospermum madidum	weeping tea tree									Uprooting
										Trunk
										Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Litchi chinensis	lychee									Uprooting
										Trunk
										Branches
Livistona spp	cabbage palm									Uprooting
										Trunk
										Branches
Lophostemon grandiflorus	northern swamp box							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Macadamia integrifolia	Macadamia nut								?	Uprooting
									?	Trunk
									?	Branches
Macaranga tanarius	heart leaf					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Mangifera indica	mango									Uprooting
										Trunk
										Branches
Maniltoa lenticellata	cascading bean					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Melaleuca dealbata	cloudy tea tree									Uprooting
										Trunk
										Branches
Melaleuca fluviatilis	paperbark							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Melaleuca leucadendra	weeping paperbark									Uprooting
										Trunk
										Branches
Melaleuca linariifolia	snow-in-summer							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Melaleuca nervosa	paperbark								?	Uprooting
									?	Trunk
									?	Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Melaleuca quinquenervia	paperbark							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Melaleuca viminalis	weeping bottlebrush									Uprooting
										Trunk
										Branches
Melaleuca viridiflora	broad-leaved tea tree									Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Melia azedarach	white cedar									Uprooting
										Trunk
										Branches
Melicope elleryana	pink euodia									Uprooting
										Trunk
										Branches
Millettia pinnata	pongamia					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Mimusops elengi	red coondoo									Uprooting
										Trunk
										Branches
Murraya paniculata cv. Exotica	mock orange							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Nauclea orientalis	Leichhardt tree									Uprooting
										Trunk
										Branches
Nerium oleander	oleander							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Pandanus cookii	screw pine							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Pandanus tectorius	coastal screw pine							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Peltophorum pterocarpum	yellow flame tree									Uprooting
										Trunk
										Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Persea americana	avocado							?	?	Uprooting
										Trunk
								?	?	Branches
Phoenix dactylifera	date palm									Uprooting
								?	?	Trunk
								?	?	Branches
Phoenix roebelenii	dwarf date palm									Uprooting
								?	?	Trunk
								?	?	Branches
Pinus caribaea	slash pine									Uprooting
										Trunk
										Branches
Pleiogynium timorense	Burdekin plum							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Plumeria spp.	frangipani							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Polyalthia longifolia	Indian mast tree							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Pterocarpus indicus	Burmese rosewood									Uprooting
										Trunk
										Branches
Roystonea regia	Cuban royal palm									Uprooting
										Trunk
										Branches
Samanea saman	rain tree									Uprooting
										Trunk
										Branches
Schefflera actinophylla	umbrella tree									Uprooting
										Trunk
										Branches
Schinus terebinthifolius	Brazilian pepper tree					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Senna siamea	Siamese cassia							?	?	Uprooting
								?	?	Trunk
								?	?	Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Spathodea campanulata	African tulip									Uprooting
										Trunk
										Branches
Sterculia quadrifida	peanut tree					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Syagrus romanzoffiana	queen palm								?	Uprooting
									?	Trunk
									?	Branches
Syzygium australe cult.	lillypilly							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Syzygium cumini	Javan plum							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Syzygium forte	white apple								?	Uprooting
									?	Trunk
									?	Branches
Syzygium jambos	rose apple					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Syzygium luehmannii	small-leaved lilly pilly					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Syzygium tierneyanum	river cherry									Uprooting
										Trunk
										Branches
Tabebuia aurea	yellow tabebuia					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Tabebuia heterophylla (syn. T. pallida)	pink trumpet tree							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Tabebuia impetiginosa (syn. T. palmeri)	Pink trumpet tree									Uprooting
										Trunk
										Branches

Scientific Name	Common name	Category 1		Category 2		Category 3		Category 4		Damage type
Tamarindus indica	tamarind									Uprooting
									?	Trunk
									?	Branches
Tecoma stans	yellow bells					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Terminalia catappa	sea almond									Uprooting
										Trunk
										Branches
Terminalia microcarpa (sy. T. sericocarpa)	brown damson									Uprooting
								?	?	Trunk
								?	?	Branches
Terminalia muelleri	Mueller's damson							?	?	Uprooting
								?	?	Trunk
								?	?	Branches
Waterhousea floribunda	weeping lillypilly					?	?	?	?	Uprooting
						?	?	?	?	Trunk
						?	?	?	?	Branches
Wodyetia bifurcata	foxtail palm									Uprooting
									?	Trunk
									?	Branches
Xanthostemon chrysanthus	golden penda									Uprooting
										Trunk
										Branches

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