The Best Practice Guide to Timber Plantations in Cyclonic-Prone Areas of Queensland: a review of the science and knowledge

Literature Review

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Contents

1.0 Introduction

Severe tropical cyclones (TCs) Larry, Ului and Yasi have had devastating effects on timber plantations in north Queensland over the past few years. Climate change projections indicating increased intensity of severe cyclones in this region in the future mean that there is an urgent need to develop best practice guidelines that address investment decisions - particularly species selection, management practices and target products - if the timber plantation growing and processing sector in the region is to continue.

Considerable investment into timber plantations has occurred in north Queensland over the past decade, much of which has been used to develop high-valued native and exotic species. Such significant investment in the northern tropics is partly due to the need to find an alternative supply of timber following the cessation of logging in native forests and the declaration of the Wet Tropics World Heritage Area, which occurred in 1988 (Catterall *et al*, 2005; Erskine *et al*, 2007; Kanowski *et al*, 2008).

Steady growth of the plantation estate in north Queensland over the past 15 years is also due to consumers investing into timber plantations through Managed Investment Schemes (MIS), although the MIS sector investment has stalled completely after Cyclone Yasi. High quality timber products, fast growth rates and the promise of quick returns in addition to favourable tax conditions were the reasons for the recent growth in the forestry industry.

Tropical cyclones have and most likely always will be a prominent weather feature of northern Australia. Cyclones in north Queensland already account for much of the natural disturbance forests are currently subjected to. However it is still unclear what effects cyclones will have on timber plantations in north Queensland over the coming years and what the best strategies are for managing timber plantations in cyclone-prone regions. Much of the information available on the effects of cyclones on plantations in north Queensland is limited and often anecdotal.

It is estimated by NFI (2007) and Parsons and Garmen (2007) that Queensland has 233, 000 ha of plantations. Within north Queensland there has been over 12,000ha of monoculture and mixed-species timber plantations and 1,000ha of restoration plantings that have been established on cleared land in the region, in addition to the 9000ha of softwood plantations currently being managed by Forestry Plantations Queensland (FPQ) between Ingham and Tully (Kanowski et al 2008; FPQ, 2012).

It is well known that naturally occurring species found in cyclonic areas have evolved through time and have various design features to help deal with high wind loads. These include their tree diameter versus height ratio (slenderness ratio), species wood density and the ability of the tree to respond under severe stress. However, to date this knowledge transfer has failed to be incorporated into the overall management and risk assessment of growing timber plantations in north Queensland.

This literature review will explore much of research conducted by a number of authors to help inform *The Best Practice Guide for Timber Plantations in Cyclonic Areas*. Some of the variables of particular interest include the history and frequency of cyclones in northern Australia, species architecture or morphology and their ability to withstand wind loads, plantation design, the location of various species in the landscape and the effects of different silvicultural regimes.

2.0 Tropical Cyclones

The Bureau of Meteorology defines a cyclone as a *"non-frontal synoptic scale, cyclone rotational, low pressure system of tropical origin, in which ten minute mean winds of at least gale force (63 km/h) occur, the belt of maximum winds being in the vicinity of the system's centre* (BOM, 1978).

In Australia, cyclone intensity is described in terms of categories ranging from 1 (weakest) to 5 (strongest), and is related to the maximum mean wind speed as shown in Table 1.0. A severe tropical cyclone can be defined as a cyclone with maximum wind gusts of ≥164 km/hr. with very destructive winds (BOM, 2012).

Table 1.0: A description of the Category system used in Australia for Tropical Cyclones (BOM, 2012)

Category	Maximum Mean Wind (km/h)	Typical Strongest Gust (km/h)	Central Pressure (hPa)	Typical Effects
1	63 - 88	< 125	> 985	Negligible house damage. Damage to some crops, trees and caravans. Craft may drag moorings
2	89 - 117	125 - 164	985 - 970	Minor house damage. Significant damage to signs, trees and caravans. Heavy damage to some crops. Risk of power failure. Small craft may break moorings. (e.g Ului)
3	118 - 159	165 - 224	970 - 955	Some roof and structural damage. Some caravans destroyed. Power failures likely. (e.g. *Winifred*)
4	160 - 199	225 - 279	955 - 930	Significant roofing loss and structural damage. Many caravans destroyed and blown away. Dangerous airborne debris. Widespread power failures. (e.g. *Tracy*, *Olivia*)
5	> 200	> 279	< 930	Extremely dangerous with widespread destruction. (e.g. *Vance*)

Although there have been numerous reports that focus on wind disturbance on a global scale, until recently there has been no attempt at defining the term. Xi and Peet (2010) discussed the difficulty in defining catastrophic wind disturbance due to the variation in wind within and between events in intensity, size and frequency. Xi and Peet (2010) describe the synthesis of catastrophic wind disturbances as a form of large infrequent disturbance (LID), which can be identified through their high mean wind speed and maximum gusts (Foster and Boose 1992; Everham and Brokaw 1996; Peterson 2000; Xi and Peet 2010).

Across the globe, there are a few key wind disturbance events that occur regularly. Tornadoes are associated with the strongest winds with a maximum wind speed of about 125 metres per second (m/s) and average of 100 m/s. Hurricanes form when the wind speed reaches higher than 35 m/s, with the average wind speed of around 70 m/s (Xi and Peet (2010). Gales (average wind speed about 50 m/s) and severe wind storms (average wind speed of about 30-50 m/s), usually produce winds of moderate intensity (Xi and Peet 2010).

The USA uses the Saffir-Simpson hurricane intensity scale. The term ‘Typhoon’, which is a regionally specific name for a severe tropical cyclone (sustained winds of more than 118 km/h or64 knots), is used in the Northwest Pacific Ocean west of the dateline (BOM 2011). Figure 1 provides a comparison of the USA hurricane scale with the Australian Bureau of Meteorology's 5-point tropical cyclone (TC) categories.

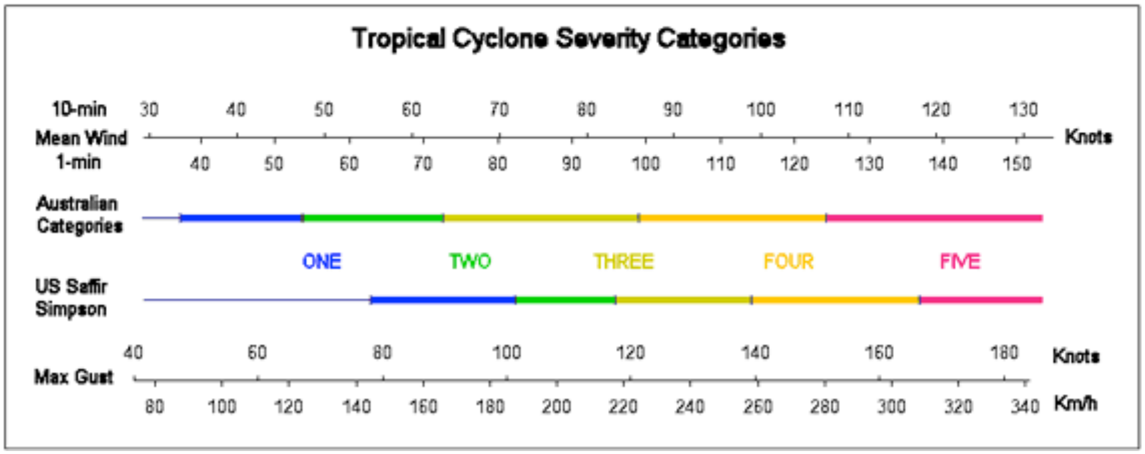


Figure 1.0 Comparison of Australia Vs USA category system. One-minute winds have been converted to 10-minute winds using a conversion factor of 0.871. The demarcation points are not precise - this table is intended to provide a rough comparison only (BOM, 2011).

2.1 Cyclone History

According to Lourensz (1981), the north-east coast of Queensland experiences the highest incidence of cyclones in Australia, with 43% (115 cyclones) of all cyclones occurring in north Queensland in the period 1909 to 1980 (see Figure 2). On average, the cyclone season begins in late November and continues through to April, with the greatest activity usually occurring during January to March (Webb 1958; Lourensz 1981).

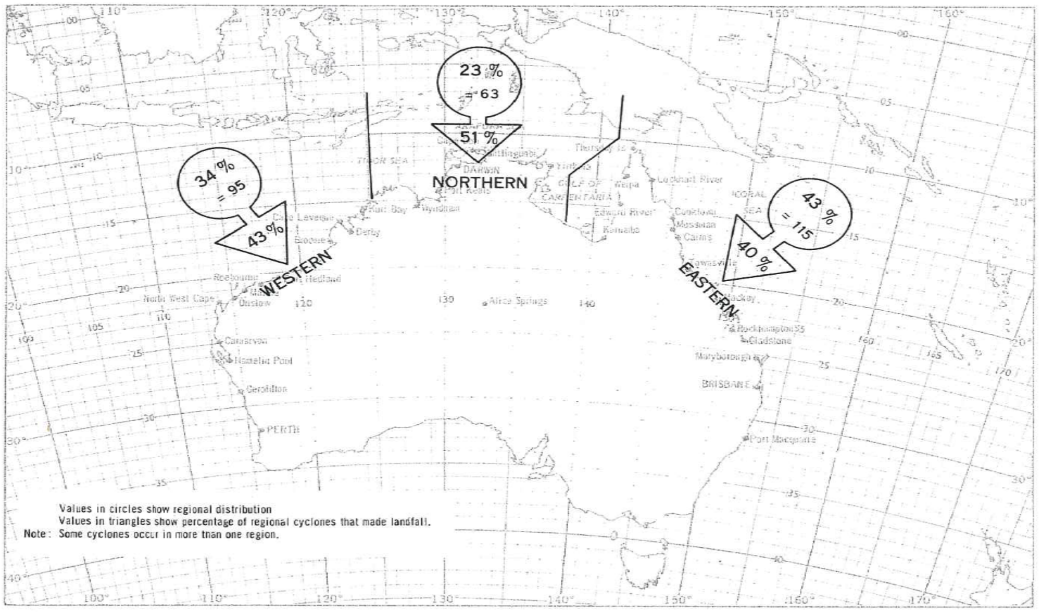


Figure 2.0 - Tropical Cyclone occurrences in the regions with percentages of landfall (Laurensz 1981).

Laurensz (1981) determined the frequencies with which tropical cyclones threatened various parts of the coast, with proximity of cyclones assessed in 100km coastal sections. It was found that the annual incidence of tropical cyclones was 10.5 per annum, of which a further 4.8 cyclones actually crossing the coast, comparing similarly with a previous study by Laurensz (1977).

In order to establish the average occurrence of tropical cyclones, Laurensz (1981) detailed cyclone events in 100km sections down the coastline, listing each cyclone that passed through the region, either from water to land or land to water, with the exclusion of cyclones that *"merely touched the coast and moved back out to sea again"* (Laurensz 1981).

The average annual distribution of cyclone occurrences over the 3 regions in Figure 2, including cyclones that traversed more than one region, was 5.5 for the eastern region, 3.0 in the northern and 5.5 in the western region (Laurensz 1981). As can be seen in Figure 2, 40% made landfall in the eastern region, 51% in the northern region, while 43% made landfall in the western region (Laurensz 1981). Figure 3 illustrates the total recorded crossings in a histogram per 100km section of the western, northern and eastern zones of Australia.

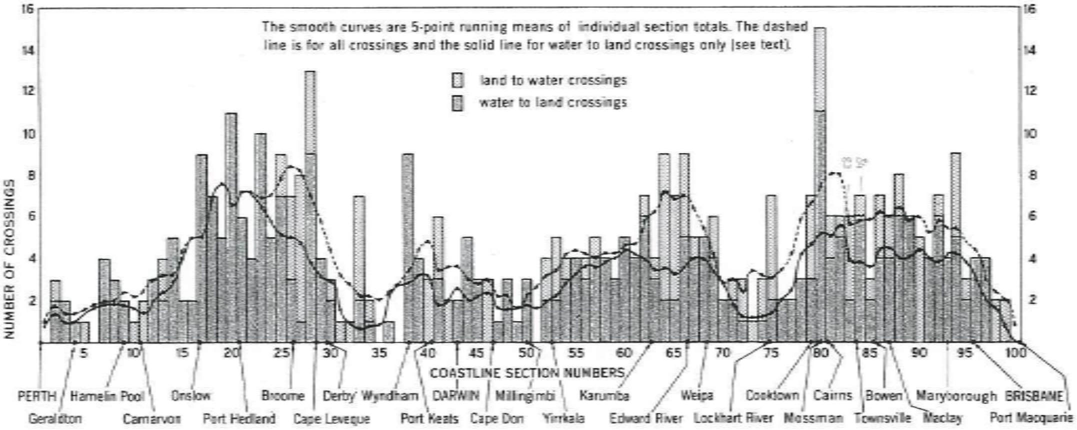


Figure 3 - Known crossings of tropical cyclones over 100km sections of coastline from July 1909 to June 1980 (Laurensz 1981)

Calvert (2011) and Trollope *et al* (1972) note that the coastline between Cooktown and Mackay is known to be the most cyclone prone stretch of coast in Queensland. Over the past 6 years, this stretch of coastline has been impacted by two severe tropical cyclones; TC Larry- 2006 and TC Yasi-2011; the latter being the main impetus for this report. Huges (2003) believes the occurrence of TCs in Australia has declined since satellites observations commenced in 1969/70; however the number of more intense cyclones has increased by 10-20%. A summary of the frequency and intensity of cyclones by Turton (2008) can be found in **Table 2**.

Table 2: Frequency and intensity of tropical cyclones that have made east to west landfall along the wet tropical coast of north Queensland, Australia (Cooktown - Ingham) over the period 1858 - 2011 (updated from Turton, 2008; Turton, pg 6, 2011)

Australian Category	Peak Gusts (km h $^{-1}$)	Central Pressure (Hpa)	Number Recorded (n)	Return Interval (RI) (years)^1
1	90 – 124	986 – 985	20	3
2	125 – 169	971 – 985	12	8
3	170 – 224	956 – 970	10	23
4	225 – 279	930 – 969	2	67
5	>279	<930	1	192

In a study by Bruce *et al* (2008), reasons why the overall skill in determining TC intensities has improved over the past 30 years are described when they review the historical TC intensity on the northern coast of Western Australia and the possible implications of climate change through a trend analysis. The authors bring attention to the critical reliance on empirical and remote sensing analysis to accurately measure TC intensity. They raise many questions in regard to the reliability of past BoM TC historical data sets and the trend towards overestimating the intensities of TC due to much more accurate data being available in recent times (Bruce *et al* 2008).

Similarly, Laurensz (1981) concludes that the apparent increase in tropical cyclone occurrence in the Australian region is mainly attributed to when satellite imagery became available, based on available data up to 1981.

Further attempts to address the issue of limited data of past cyclones along north- eastern Australia were undertaken by Nott *et al*.(2007) who analysed the isotopic signature of rainwater at Chillagoe Caves incorporated into limestone stalagmites. The signatures were then cross referenced with BoM cyclone data over the past 100 years. Nott *et al*. (2007) found signatures of all major cyclones and was able to identify 75% of cyclones that came within 300km from the site (Nott *et al*. 2007). The results by Nott *et al*. (2007) were extended back 800 years, from AD 2004 to 1200. Nott *et al*. (2007) notes the frequency of cyclones were highly variable during the periods 1400-1500 and 1600 to 1800, however cyclonic activity since then was considered to be relatively quiet (Nott *et al*. 2007).

2.2 Future Predictions and Climate Change

Turton (2008) documented the history of cyclones by examining (unpublished) historical data about tropical cyclones impacting the east coast of Australia between 1858 and 2006. An updated analysis by Turton (2011) found that *“comparatively weak cyclones (Category 1) are likely to cross the wet tropical coast quite often with a return interval of about one in three years, compared with a frequency of about one in 23 years for moderate to severe cyclones (Category 3) and about one in 67 years for severe cyclones (Category 4) such as Larry and Yasi”* (Turton, pg 5, 2011).

Turton (2008) believes the occurrence of catastrophic cyclones (Category 5) such as the 1918 Innisfail cyclone, have a return interval of one in 192 years, and therefore concludes on the basis of the historical data that both cyclone Larry and Yasi were one in 70 year events for the wet tropics region.

Interestingly, previous studies by Nott and Hayne (2001) and Nott (2003) suggest such a short historical record underestimates the frequency of severe cyclones in the Cairns region. Nott (2003) utilises geomorphic evidence to demonstrate that the frequency of category 5 ‘super cyclones’ for north – east Queensland is in the range of 200 – 300 years (Nott 2007).

Nott (2003) suggests that such extreme events have not occurred since European settlement of the region, but draws attention to the imminent cyclone of such high magnitude to occur sometime in the future and that the impact to forests, human infrastructure and livelihoods could exceed anything witnessed to date (Nott 2003; Turton 2008).

Calvert (2011) discusses the likelihood of future cyclones by firstly highlighting the fact that our understanding of the patterns of cyclones impacting on the northern Queensland coast has been hindered by the relative short existence of instrumental records and meteorological observations (Calvert 2011). It is therefore difficult to draw conclusions about increases in intensity since the quality of data collected had increased dramatically over the past 30 years, particularly numerical modelling and satellite sensing (Bruce *et al 2008*; Calvert 2011; Terry 2007).

Historical analysis of Sea Surface Temperatures (SST) in the Atlantic Ocean were recently used by Knuston *et al* (2010) to ascertain the attribution of climate change to severity of tropical cyclone projections in the future. The projection statements by Knuston *et al* (2010) were intended to apply roughly to the IPCC A1B Scenario 2 as of the late twenty-first century. All likelihood statements follow conventions used by the IPCC2 (Supplementary Information S4).

Knuston *et al* (2010) predict that cyclone intensities are expected to increase by between 2-11% by 2100 and an overall decrease in the global average frequency of tropical cyclones by 6-34% depending on the oceanic basin under consideration (Knuston *et al* 2010; Turton 2011).

Similar results were found in recent modelling studies by Walsh and Ryan (2000) and Emmanuel (2005), who suggest that rising global temperatures may have little impact on storm frequency, but strong effects on storm severity.

Locally, Nott (2007) and Calvert (2011) discuss the implications of climate change and the likely decrease in frequency of cyclones even though increase in cyclone intensity is also expected. Nott (2007) predicts that the increase in intensity combined with an increase in frequency (if that were to occur) could have severe implications for coastal developments that expanded during the recent lull in cyclone activity (Calvert 2011; Nott 2007).

3.6 Wind Speed Regions of Australia

As a result of past cyclones, tighter regulations on building codes and advances in technology and warning systems associated with cyclones, including the use of satellite imagery and meteorological modelling have progressed dramatically. Damage to buildings is now less of an issue as it was in the past and there is now greater awareness and preparedness for such events when they occur in the future.

One practical and useful method for gauging the potential risk of building failure is to compare the building in question to the Australian Standard AS/NZS 1170.2 (2002), which is used as the benchmark standard and provides guidelines for structures subject to wind actions and is used for buildings less than 200m high. James (2010) specifies the usefulness of the standard to investigate the factors that influence critical wind speeds in different locations; however he also notes the standard doesn’t specifically mention trees.

Nonetheless, the amended version released in 2008 (Australian Standard AS 4055-2006) provides useful mapping to guide the wind speed regions of Australia (Figure 3), and it is hoped that such a guide can lead to similar risk assessment matrix, applicable to growing trees in north Queensland. The map is split into 5 Regions (A1, A2, B, C and D), with Region C having particular significance for *The Best Practice Guide for Timber Plantations in Cyclonic Areas,* as can be seen in Figure 4.

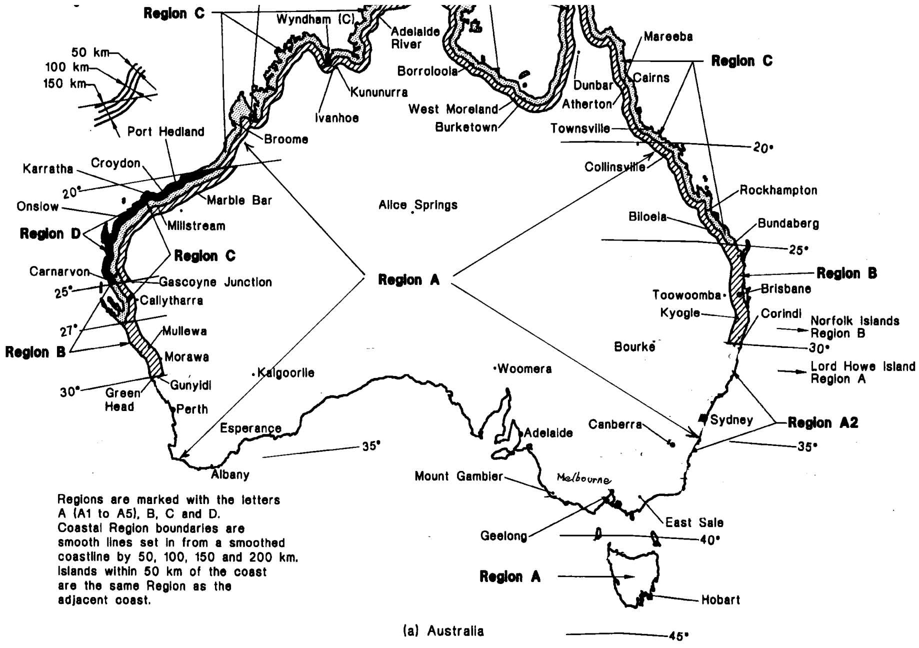


Figure 4.0 Wind speed regions in Australia, according to the Australian Standard AS4055-2006 (Australian Standards, 2012)

Similarly, the map produced by Laurensz (1980) is a good reference for associated risk when planting trees along the Queensland coastline. As mentioned earlier, Laurensz (1981) mapped the frequency of cyclones that have crossed the coast within 100km sections of the coast. The occurrence of cyclones in 5° latitude and longitude squares in Australia, for data between 1909 to June 1980 can be seen in Figure 6.

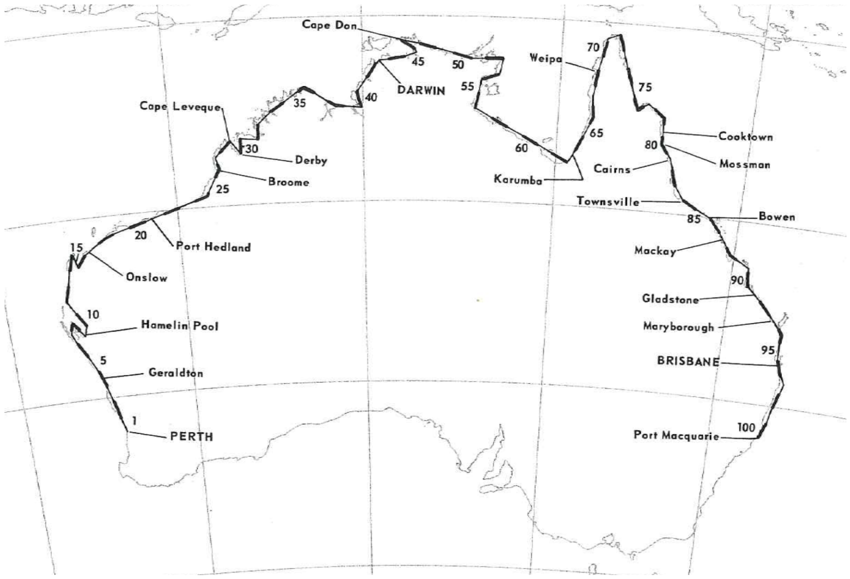


Figure 5.0 Division of idealised coastline into 100km numbered sections (Laurensz 1981).

3.0 Impacts of Wind on Trees

Tree failure due to wind damage is a substantial economic problem for forest growers around the world, causing severe economic losses and changes to forest ecosystems (James, 2010). For example, the UNECE/FAO (2000) calculated that European forests suffered losses of over 180 million m ^{3} of levelled timber during severe storms in 1999, while in Sweden, Zeng *et al* (2007) estimated that 70 million m^3 of timber was lost in storms with a further 7 million m^3 was damaged in Finland in 2001.

The economic damage due to wind in managed forests is discussed by Petola (1996) and Moore and Maguire (2005). The believe the economic damage is often more severe due to yield reductions and having to account for unscheduled thinnings and clear felling below the sustainable cutting yield. They believe it is important to assess the effects of wind in timber plantations due to windthrow and trunk failures in storms.

Trees are no different to other living organisms faced with the challenges of surviving in a natural environment that is often unforgiving and relentless. In areas where there has been regular extreme weather events, the role of genetics, evolution and natural selection seems to have been played out to such an extent that remaining species not only survive when subjected to extreme wind events, but they have learnt to regenerate and thrive in such environments.

A report recently released by Greening Australia, authored by Calvert (2011) examines in detail many of the same issues that impact the management of timber plantations in cyclonic areas of Queensland. This report alone is a valuable resource of past work that has been conducted in this area, and many of the findings by Calvert (2011) are expected to influence *The Best Practice Guide to Timber Plantations in Cyclonic Areas.*

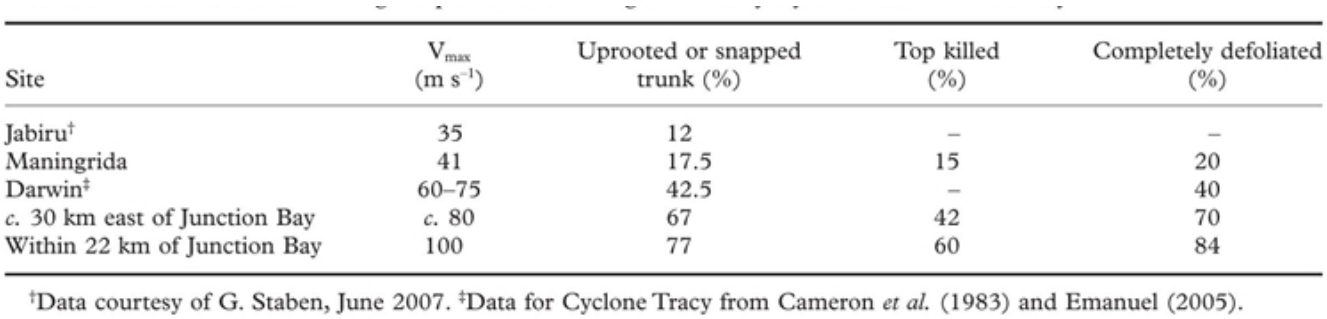
Calvert (2011) discusses the history of cyclone events and their effects on trees. He also discusses the significant benefits trees can have in both urban and rural environments. These include reducing the wind loading on buildings, intercepting potentially lethal flying debris, offering protection to other plants, reducing erosion along flooded rivers, beachfronts, and potentially even preventing the loss or roofs from buildings (Calvert 2011). His work is focussed primarily on north Queensland where cyclones have recently devastated local communities between Cairns and Townsville.

Much of the literature that is available focuses on the impacts of wind on trees has been conducted in temperate zones, particularly North America and Europe. As Calvert (2011) alludes to, the work that has been completed on the impacts of cyclones on trees in Australia was done either after Cyclone Tracy (Cameron *et al* 1981, Fox 1980, Stocker 1976, Van der Sommen 2002) or Cyclone Larry (eg. Bruce *et al* 2008, Curren *et al* 2008, Kanowski *et al* 2008, Kupsch 2006, Pohlmen *et al* 2008 and Turton 2008).

Further studies have also focused on the impact of wind and trees in Australian tropical savannas, in particular some of the lessons learned from Cyclone Monica in 2006. Cook *et al* (2008) describe the relationship they found between the damage to trees and the estimated maximum gust speed that was likely to have occurred at the time Cyclone Monica passed though. Cook & Goyens (2008) focus on analysing the effects of one of the most intense tropical cyclones recorded to make landfall in the southern hemisphere on savanna tree dynamics. They explore the immediate impacts of Cyclone Monica on savanna trees and put this into context of tropical cyclones as recurrent disturbances. Measurement of tree damage took place by surveying several sites along a section of coast between Maningrida Road and Maningrida and Junction Bay, in northern Western Australia. At each site, 50m × 10m belt transects were assessed. Data was captured on the proportion of trees uprooted or snapped as well as recording the direction of the fall of the tree if it had snapped.

In order to determine the relationship between gust speed and tree damage, anemometer records together with the tree fall angles were used by Cook & Goyens (2008) to examine the progressive damage to trees as the cyclone approached and receded. The results indicated a steady increase in the proportion of trees uprooted or snapped, top killed and defoliated with increasing maximum gust speed (see Table 3).

Table 3. The effect of maximum gust speed on the damage to trees by Cyclones Monica and Tracy



Site	V_{max} (m s^{-1})	Uprooted or snapped trunk (%)	Top killed (%)	Completely defoliated (%)
Jabiru[†]	35	12	–	–
Maningrida	41	17.5	15	20
Darwin[‡]	60–75	42.5	–	40
c. 30 km east of Junction Bay	*c.* 80	67	42	70
Within 22 km of Junction Bay	100	77	60	84

[†]Data courtesy of G. Staben, June 2007. [‡]Data for Cyclone Tracy from Cameron *et al.* (1983) and Emanuel (2005).

The relationship between the proportions of trees uprooted or snapped to perpendicular distance from the cyclone path was described by peaked lognormal equations. The results of the equations allowed the calculation of the Annual Exceedence Probabilities (AEP) for cyclonic gust speeds with distance inland and the probability of windthrow. Results showed that about once every 100 years (AEP = 0.01), about 67% or more of trees could be expected to be windthrown owing to cyclone damage along the coast, and about 42% or more windthrown from thunderstorms or cyclones 25km or more inland, as can be seen in Figure 6.

The damage levels found along various sections of the cyclone Monica's path by Cook & Goyens (2008) are consistent with the damage expected in the tropical Pacific from cyclonic gusts greater than 90 m s^{-1}. Their findings were consistent with historical records and suggest tree damage caused by windthrow in northwest Australia has profound implications for ecological processes including tree dynamics and fluxes of carbon and water in Australian tropical savannas (Cook *et al* 2008).

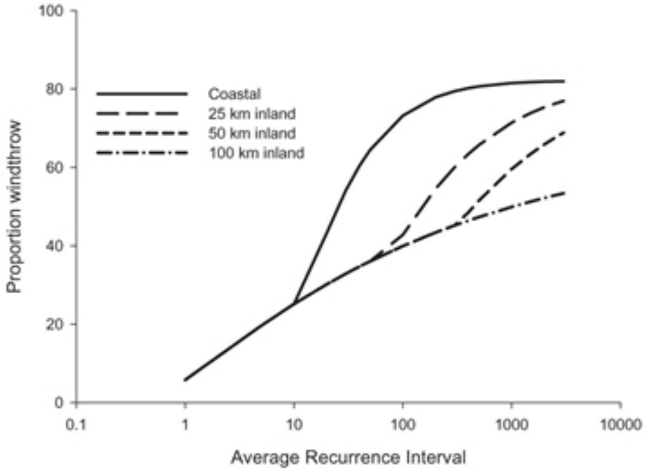


Figure 6.0 - Average Recurrence Interval of windthrow events for savanna trees with varying distances inland in the Darwin region

Plant resistance to cyclones is often seen as most relevant when considering the immediate impacts of cyclones due to the extensive lead time to regenerate. It can take weeks or months for plants to start resprouting after sustaining damage from cyclones (Webb 1958; Unwin *et al*, 1988 Walker 1991).

Plant functional traits often associated with cyclone resistance include tree size, wood density and buttress roots (Curran *et al* 2008). There have been a number of studies (Putz *et al*, 1983; Walker 1991; Franklin *et al* 2004) that have linked cyclone damage and tree size, in respect to either height of the tree or diameter at breast height (dbh). Most studies found that large trees were more likely to be uprooted; however research by Bellingham *et al* (1995) found no such link.

To understand patterns of wind disturbance in forests, Xi and Peet (2010) believe the risk factors need to be examined at relevant spatial and temporal scales and the correct context when dealing with site conditions and their history. In a recent study that examines the complexity of catastrophic wind impacts on temperate forests, Xi and Peet (2010) consider both abiotic (eg winds, topography, soil) and biotic factors (eg. Individual tree characteristics, tree species, stand attributes) and their interaction with one another to generate complex damage and mortality patterns.

As can be seen in Figure 5 by Ackerman *et al* (1991), the importance of wind and individual features of particular species and the attributes of communities decreases as wind intensity increases.

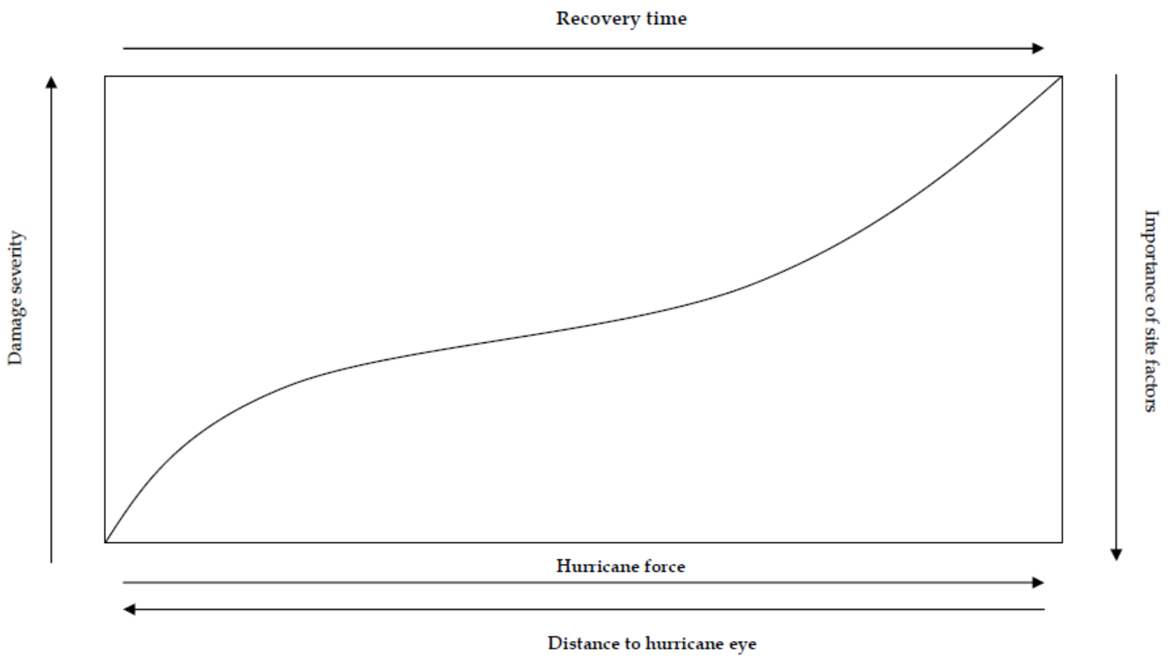


Figure 7.0 - Hypothesized relationship among cyclone force, forest damage severity, recovery time, and importance of site factors. Both forest damage and recovery time increase with cyclone force. The importance of site factors decreases when cyclone force increase (Ackerman *et al* 1991)

Structural analysis of individual trees can influence the response of a structure to an applied load (James 2010). The two main methods used are defined as i) static and ii) dynamic , depending on the nature of the load and the response of the structure (James 2010). James (2010) describes how dynamic analysis differs from static analysis because it doesn't have a single solution whereas dynamic analysis is often complex and time consuming (James 2010). Furthermore, dynamic analysis deals with inertial forces opposing acceleration produced by dynamic loads, compared to static systems which are solely based on the principles of force equilibrium (James 2010). The basic difference between static and dynamic loads is illustrated by Clough and Penzien (1993) in Figure 8.0

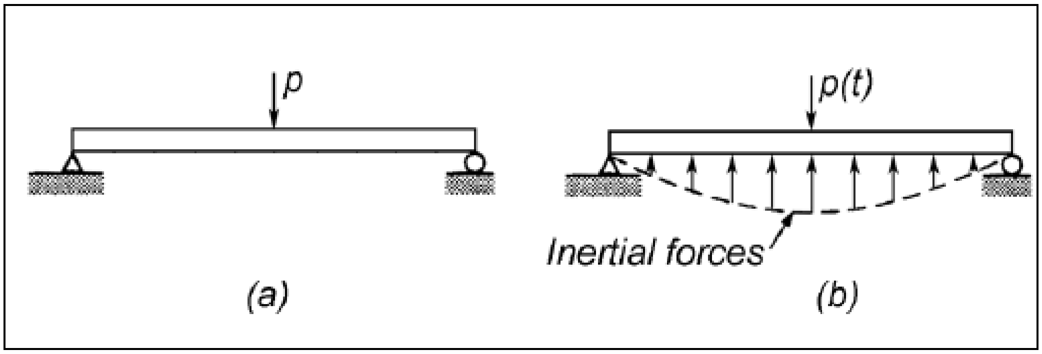


Figure 8.0 - Basic Difference between static and dynamic loads: (a) static loading; (b) dynamic loading (Clough and Penzien 1993).

3.1 Critical Wind Speeds and Topography

There have been detailed studies on the effects of wind speeds at both the individual tree and forest stand level. It is clear that extreme wind events are often distributed over a broad range of spatial scales and certain levels of damage can only be observed at specific scales in the context of a specific process (Xi and Peet 2010). Broadly speaking, tree damage increases linearly with wind speed (Fraser 1962). Little damage can be expected below wind speeds of 17.5 m/s (63 kph) according to Powell *et al* (1991) while most trunk failures and uprooting of trees occurred at wind speeds above 33 m/s (118 kph) (Powell *et al* 1991).

Higher damage levels to plantations and native forests can often be attributed to their location in the landscape. The relatively high frequency of cyclones in tropical north Queensland is thought to contribute to the structure and function of tropical rain forests in cyclone-prone areas, with many of the ecosystem recovery processes occurring at several spatial scales (Grove *et al* 2000;McGregor and Nieuwolt 1998; Bellingham 1991; Bellingham *et al* 1992; Harrington *et al* 1997; Webb 1958; Whitmore 1989; Yih *et al* 1991).

Topography has been described by some authors as a major factor in the overall protection and shelter from destructive winds (Webb 1958; Unwin *et al* 1988; Reilly 1991; Grove *et al*. 2000), however just how much protection certain areas get depends on the direction of the destructive winds.

In some cases, trees that are located deep in valleys can be affected by wind tunnels which actually increased wind speeds resulting in increased damage levels (Reilly 1991; Grove *et al*. 2000). Webb (1958) examined the lowland area between Cairns and Tully and attributed the erratic pattern of aspect (with cyclone damage more common on exposed ridges than gullies), as responsible for increased turbulence. Following damage assessments taken after Cyclone Agnes in March 1956, Webb (1958) observed defoliation and shattering of tall trees was less extensive on the sheltered valley bottoms than on the exposed adjacent slopes (Webb 1958).

However, Konowski *et al.* (2008) concludes that there is no evidence that topographical location influenced damage levels in timber plantations and therefore it is difficult for them to argue that restoration plantations escaped *"severe damage because they were located in sheltered parts of the landscape"* (Konowski *et al.* Pg 491, 2008). Kanowski *et al* (2008), demonstrate in their study that *"the protection afforded by location and topography is not absolute"* (Kanowski *et al*, 2008 pg 491).

Sagar and Jull (2001) found that topography can have a marked effect on wind speed. The authors measured wind speeds in British Columbia over a five year period (1995-2000) in 10 different locations. Ten towers were erected, all at a height of 9.1 m and then one second wind records were recorded with an anemometer and wind vane (Young Model 05130). In the study, extreme wind events were defined as one-second wind speed exceeding 20 m/s (72 km/h). Results showed that such extreme wind speeds occurred at three sites with a maximum value of 28 m/s (100 km/h). It was found that spatial and temporal distribution of extreme wind events was dependent on local topography and that wind was very gusty in nature.

Critical wind speeds were estimated at 17 m/s (61.2 kph) at tree tops when some trees failed in the forest. Comparison of this figure was made with critical wind speed estimates based on static pull tests which predicted that wind speeds of 40-45 m/s (144-162 kph) were necessary for tree overturning to occur (Sagar and Jull 2001). James (2010) suggests that the static pull test conducted in this experiment over estimates the critical wind speed needed to cause tree failure.

Calvert (2011) discusses the complexity involved when modelling tree behaviour, and the importance of treating wind stress on trees as a dynamic process, due to the gusting effects which vary in intensity and frequency. To date detailed research into the physics of tree movements hasn't been conducted on Australian species (Calvert 2011).

Another important factor to consider when assessing the overall wind damage and associated wind speed is the existing soil conditions. Pre-cyclone soil moisture has been found to be correlated to the uprooting of trees or trunk failure (Calvert 2011; DeCoster 1996). In situations where the soil is dry, uprooting is more difficult, and it is likely the trunk will reach failure threshold before the root system (Calvert 2011). Alternatively, wet soils are more likely to cause uprooting (Calvert 2011; Xi 2005).

Trunk failure in north Queensland and across northern Australia is also related to termites hollowing the trunks of trees, particularly in Acacias and Eucalypts which were found to be the most susceptible to such attack in a recent study by Jackes (2011).

3.2 Tree Architecture

Calvert (2011) describes the key to understanding why different species show varying levels of susceptibility to cyclones and hence have different patterns of damage. Many of the studies that have focused on wind damage to trees after a cyclone event usually follow the same categories used to assess the damage to trees from Cyclone Tracy (Calvert 2011):

- Windthrow (uprooting);
- Bole Leaning;
- Tree Standing; and
- Bole Trunk, broken or severely fractured (Stocker 1976)

In most cases, trees sustain various levels of damage and it is important to remember that trees have features that make them more or less susceptible to cyclone damage (Calvert 2011). In many cases, the variation of wind damage between species has more to do with a particular species' susceptibility or resistance to wind damage, rather than the environmental conditions (Calvert 2011).

3.3 Tree Dynamics

James (2010) states that for "*nearly all trees, the greatest load is from wind that comes as gusts of rapid, periodic, dynamic events*" (James 2010 pg 1). In similar terms Jacobs (2010) proclaims *"Wind is the most persistent of the harmful natural forces to which any individual tree or forest stand is subjected"*(Jacobs 2010 pg 1).

The importance of forest managers making the right decisions based on assessing the tree's structure and being able to accurately estimate its ability to withstand future windstorms of varying and unknown intensity, is discussed by James (2010). James (2010) mentions the difficulty in measuring trees due the lack of tree assessment tools that use actual data from real wind loads on trees. Earlier methods of measuring tree sway were largely thought to have been impeded by the lack of technology and only broad changes in dynamic behaviour could be detected, with the importance of other dynamic influences such as branches often being missed (James 2010).

The development of technology over time has lead to improvements in measurement of tree motion and currently there are two main methods for investigating dynamic responses of trees, both of which are discussed in detail by James (2010): One method examines the upper canopy and the other focuses on the basal trunk area.

According to James (2010), instruments used in the canopy of trees are able to accurately measure the dynamic response of the trunk section and branches, however some may miss the interaction of other branches.Instruments placed at the bottom of the trunk are able to accurately measure all the integrated motions of the tree and the sum of the whole dynamic motion of the tree passes from the canopy through the trunk and into the root plate (James 2010). For that reason, most new instruments focus on the trunk region where a total response of the tree can be captured (James and Kane 2008).

3.4 Static and Dynamic Methods

Structural analysis of trees involves examining the response of a structure to an applied load (James 2010). The two main methods used are known as static and dynamic ; with the choice of method depending on the nature of the load and the response of the structure (James 2010).

In the past, a structural approach to tree biomechanics that used a static force analysis was presented by Mattheck and Breloer (1994), who went on to develop a term known as "the axiom of uniform stress". It was thought by Mattheck and Breloer (1994) that the growth of a tree was in response to the loads placed upon it, highlighting the importance of understanding the loads trees endure and where more stress can be expected, such as in structural components of the branches and trunk of the tree (Mattheck and Breloar 1994; James 2010). This mechanical analysis was limited to a static approach and no dynamic analysis was attempted.

In recent years Brudi (2002) developed the static tree pull test, but its adoption hasn't been widespread due to the relation of the test to the dynamic tree loading. The static pull test evaluated the wind forces by pulling a tree to an equivalent of an estimated wind force while measuring the stability of the tree (James 2010).

However, James (2010) alludes to the fact that caution should be practiced when using this approach as earlier studies by Hassinen *et al* (1998) reported cases where trees have blown over or snapped at wind speeds considerably lower than the static test due to the inability of static tests being able to replicate the real effects of wind loading (Calvert, 2011). The static pull test doesn't simulate wind loading because there is no allowance for dynamic sway and the direction of pull is usually from one direction only (Oliver and Mayhead 1974; Gardiner 1997).

Vogel (1996) compares different storm-resisting features of trees, and how they utilise flexible structures such as trunks, leaves, branches and roots. He compares trees to human technology and our focus on more rigid materials such as metals, ceramics and dried wood, while also bringing attention to the fact humans have very little experience when it comes to designing structures that change shape in the wind. Applying the same engineering analysis to trees as used in rigid structures may not provide the required solutions. Vogel (1996) suggests that trees not only twist and bend but they also absorb, store and dissipate energy.

Many studies in the past have focused on the structure of trees using static analysis. However Niklas (1992) cautions against applying the well developed engineering beam theory because it may not accurately reflect how trees respond under high wind loading. Niklas (1992) states one of the most frequently used simplifications is to treat a tree as a beam or a tapered pole without considering its branch dynamics. Similarly, Spatz and Bruechert (2000) describe wood as being a composite material that is anisotropic (ie with different strength in different planes), and that heterogeneous and mechanical failure is not an 'all-or-none' process (Spatz and Bruechert 2000).

James (2010) discusses this concept when applied to trees under varying wind loads. The swaying motion associated with the canopies of trees requires a dynamic analysis where the inertial forces of branches are also considered (James 2010).

James (2010) examines in detail the structural perspective of trees in his PhD. He acknowledges, along with Niklas (1992); Niklas and Spatz (2000), that plants are unable to escape the laws of physics. As trees grow, they increase in size and height, and that the extra biomass develops greater self-loading while also exposing the upper reaches of trees to greater wind speeds causing more bending at the base (Niklas and Spatz 2000).

3.5 Tree Diversity and Stand Structure

Mechanical forces have challenged plants throughout their evolutionary history (Grace 2003). The size and form of an individual tree is the product of a basic genetic blueprint that has been largely shaped by the external environment over time (Grace 2003).

Vogel (1996) draws upon the same link specifically in the context of wind, by suggesting a large part of the explanation for the diversity lies in different species' ability to stand up to the wind and the different functions that structural elements contribute during wind loading (Grace 2003).

Galilei (1638) was the first to describe the physical limitation of the height and size of a tree due to the physical limitations of the strength of its wood. Similarly, Niklas (1997) described the height of a tree with respect to the trunk diameter occurring throughout the life of trees as they age and grow larger (Niklas 1997).

The dynamic response of trees to wind is largely decided by the structure of forests, their growing conditions and whether or not they are subjected to frequent windy environments. In many forest ecosystems including plantations, trees grow very close together,and compete for both nutrients and sunlight, or as in the case of monoculture plantations, mainly just sunlight. The result in plantations is most likely tall and slender trees with little side-branch development.

Another important factor influencing the damage caused by wind is the size of trees and differences in morphology between large and small trees. Mayhead (1973) states that it is unsound to test trees less than 3 - 4.5 metres in height due to the differences in morphology between smaller and larger trees. He discusses the variability in results arising from differences in morphology and the need to allow for natural variation for individuals of a particular species and also the variation that is evident across species when trying to interpret extrapolated data (Mayhead 1973).

The ability of a tree to withstand wind is normally directly correlated to the slenderness of the tree (James 2010). Slenderness is defined by James (2010) as the ratio between the height (h) and the trunk diameter at breast height (DBH), with the ratio of height to diameter (h/DBH) giving a measure of slenderness (Petola 1996). Therefore a tree that is shorter, thicker and therefore more stable is able to withstand higher wind loads than a lower slenderness ratio tree which can become too slender and can buckle under its own weight (James 2010).

The slenderness of particular trees is also thought to be correlated to the silvicultural regime of particular stands and the age. Cucchi (2005) simulated a silvicultural thinning of *Pinus pinaster* and found a decrease in slenderness ratio of 70 to 54 from age 25-50 years as the trees grew taller.

Examples of very tall slender forests include trees that have a central trunk and very few branches and are likely to respond dynamically like a pole or chimney (James 2010; Kerzenmacher and Gardiner 1998). An extreme example of high slenderness ratio was studied by Rudnicki *et al* (2001) in a stand of *Pinus contorta* in Alberta, Canada, with a height range of 9.4 to 15.3m and a slenderness ratio of 160, which means these trees would not stand without support of their neighbours (Rudnicki *et al* 2001).

Slenderness coefficients of above 100 generally indicate low stability with such trees likely to buckle under their own weight (James 2010). Forest trees with a slenderness ratio below 80 are considered by James (2010) and Slodical and Novak (2006) as having excellent stability. Comparatively, trees in urban areas have been shown to have slenderness ratios below 50 (Niklas 1992). This is thought to be due to the windy environment they are exposed to in urban situations (Niklas 1992).

On the other hand, the tallest gymnosperm in the world, Californian Redwood *(Sequoiadendron giganteum)*, has a slenderness ratio of just 10.5, which is testament to that species' survival over many centuries. A graphic illustration of different slenderness ratios is provided in Figure 9 below.

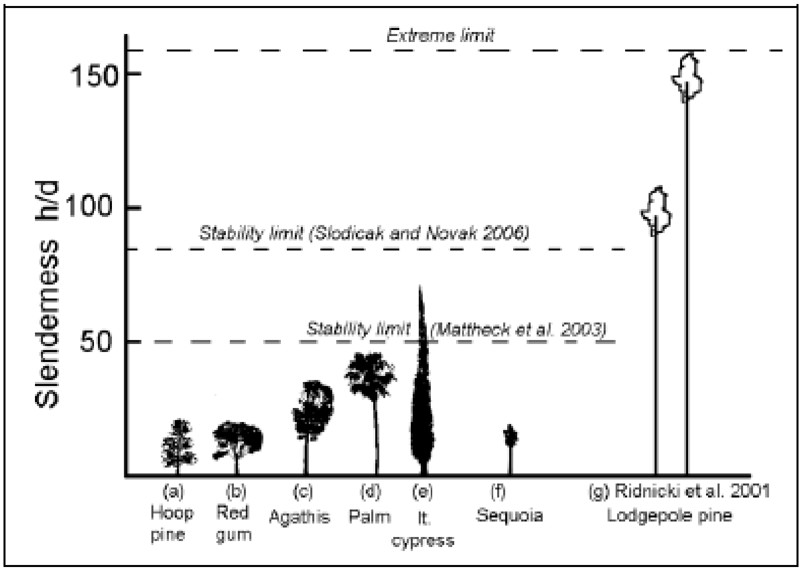


Figure 9.0 - Comparison of slenderness ratios of trees, (a) Hoop Pine *(Araucaria* cunninghamii*)* (b) Red gum *(Eucalyptus tereticornis)* (c) NZ Kauri Pine *(Agathis australis)* (d) Palm *(Washington robusta)* (e) Italian Cypress *(Cupressus sempervirens)* (f) Sequoia *(Sequoiadendron giganteum)* (Niklas 1992; James pg 13 2010)

As can be seen in Figure 9, Hoop Pine, Kauri Pine and Red Gum all have relatively low slenderness ratios. All three species are found naturally in cyclone prone areas along the eastern coast of Australia and are of particular interest.

4.0 Timber Plantations in Cyclonic Areas

The expansion of timber plantations in north Queensland has attracted considerable interest during the past 20 years, however successive tropical cyclones (TC's Larry and Yasi), and subsequent widespread damage to existing plantations, has diminished confidence in growing timber plantations of any species.

As mentioned earlier, much of the research that has focused on cyclones and timber plantations has been carried out in the Caribbean where there has been severe damage caused to timber plantations by cyclones in the past (Tanner *et al* 1991; Fu *et al* 1996). Within Australia, specific research about the effects of cyclones on timber plantations is minimal.

4.1 Plantation Design

Plantation management and design are known to contribute further to the susceptibility of plantations to cyclone damage. In particular, timber plantations are more susceptible due to their relatively open structures which result from trees being planted in widely spaced rows (Kanowski *et al* 2008; Lugo 1997).

Subsequent pruning and thinning regimes are also thought to contribute to the overall damage caused by cyclonic winds due to winds being allowed to flow through the stands much further than would otherwise be expected in a normal native forest scenario where there are low branches, shrubs and many other understory species (Kanowski *et al* 2008). The results of an assessment by Kanowski *et al* (2008) of different forest types directly impacted by the cyclone Larry supported such findings.

Kanwoski et al (2008) point out that unlike timber plantations, mixed species restoration plantings are often stocked at much higher densities and aren't subjected to pruning and thinning. Kanowski *et al* (2008) state that a young restoration planting, comprised of dense stands of small-diameter trees with well-developed understory of seedling and saplings, has more wind resistance than timber plantations.

Damage levels to monoculture timber plantations were found to be significantly higher as a result of Cyclone Larry, even though it was found that the damage levels were not confounded by proximity to the cyclone path (Kanowski *et al* 2008).

Traditional forestry management regimes have favoured monoculture plantations. However Bristow (2008) contrasts the pros and cons of growing *Eucalyptus pellita* firstly in monocultures and secondly in mixed species. Apart from some obvious advantages over monocultures (i.e. greater production, environmental services and risk aversion from pests and diseases as well as climate change), there may also be increased structural and biological diversity in mixed species stands, increasing the resilience to disturbance at the stand or landscape level.

However, one of the main reasons monocultures are preferred is due to their simplicity and uniformity, as well as more uniform silvicultural costs. Perhaps reducing the risk of wind damage should play a greater role in the decision making process of tropical forestry managers?

4.2 Species Performance

More often than not, plantation species that have been used in plantations throughout Queensland and northern Australia have come from provenances in subtropical Australia or other areas of the world where cyclones don't regularly occur. An example of this is the Hoop Pine provenances planted throughout Queensland, much of which originated in subtropical Australia, while other material came from New Guinea (Bristow et al 2005; Killin 2006).

Kanowski *et al* (2008) discuss the possibility of locally occurring (endemic) species being better able to withstand cyclonic winds than species that originate outside the subequatorial cyclone belt due to natural selection in regions where cyclones occur regularly. Calvert reaffirms this by suggesting the environment in which a tree grows naturally may assist in predicting cyclone resistance. Calvert (2011) says that many cyclone resistant species grow in environments where they are exposed to high-energy extremes of wind and water, where the tree trunk and roots are exposed to high wind loading.

Calvert (2011) uses the example of *Melaleuca leucadendra*, a cyclone resistant species commonly found along fast flowing flood prone rivers in Australia (Calvert 2011). He breaks down exactly where in the landscape highly resistant species are most commonly found, and they include:

- species found along fast moving rivers (*Eucalyptus raveretiana, Lophostemon grandiflorus, Millettia pinnata*);

- along wind-swept beachfronts (i.e. *Argusia argentea, Calophyllum inophyllum, Ficus drupacea, Hibiscus tiliaceus, Mimusops elengi, Pandanus tectorius, Syzygium forte*);
- on exposed wind-swept outcrops (i.e *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*) (Calvert, pg 93, 2011)

Calvert (2011) lists the cyclone behaviour of some commonly grown species and grades the species according to the damage that can be expected from a cyclone of each category. He grades each species against 3 damage types (1. Uprooting 2. Trunk 3. Branches). Even though observations of many of the trees assessed were in an open urban setting, some of the species observed by Calvert (2011) are commonly grown for timber in plantations throughout north Queensland

Of particular interest to *The Best Practice Guide For Timber Plantations in Cyclonic Areas* is the performance of *Khaya senegalensis* (African Mahogany) and *Agathis robusta* (Kauri Pine). Calvert (2011) found a lot of variation in damage within these species, particularly *Khaya senegalensis,* where many uprooted trees showed signs of being grown in a pot and having little or adversely affected tap root development (Calvert 2011).

Kauri Pine and *Alstonia scholaris* (Milky Pine) showed particularly high wind resistance against all 3 measures, in nearly all cyclone categories. Kauri Pine wasn't uprooted on any occasion, with snapping rare and damage to branches only in category 4 cyclones and above (Calvert 2011).

4.3 Wood Density

Wood density has been researched by many authors in the past (Curren et al 2008, Falster 2006, Van Gelder et al. 2006) and has been shown to contribute to the overall strength of the tree and therefore an ability to resist damage from cyclones (Curren et al 2008).

Curren *et al* (2008) researched the ability of species to withstand disturbance (resistance) and their ability to recover biomass following disturbance (resilience) following Cyclone Larry. After studying six species, Curren *et al* (2008) found a positive correlation between the portion of trees experiencing minor damage only and wood density, supporting the hypothesised association of resistance and mechanical strength. However resilience was negatively correlated to wood density meaning species with lower wood density were more likely to suffer stem and branch damage to due to cyclones, however they are also the first species to re-sprout and re-develop biomass (Curren et al 2008).

Calvert (2011) brings attention to the fact that wood density alone can only be used to predict levels of trunk damage and in many cases, it has been found that higher rates of root failing is linked to lower rates of trunk failure. Calvert (2011), using African Mahogany as an example, found that this species rarely snaps its trunk in wind but frequently uproots, even though it isn't regarded as a slow growing species.

As a consequence, Calvert (2011) proposes two additional predictors of cyclone sensitivity and resistance:

1. Average longevity of the species
2. Natural habitat of the species

He suggests that species with shorter life-spans invest fewer resources in developing wind resistant features to help improve their prospect of long-term survival. This includes the development of denser wood and deeper roots (Calvert 2011).

Wood density has been shown to be correlated with cyclone resistance (Putz *et al* 1983; Zimmerman *et al* 1994; Curran *et al* 2008), with species of higher wood density appearing to have less damage than those with a lower wood density. This general correlation wasn't found by Bellingham *et al* (1995). While it is generally accepted that trees with higher wood densities are less likely to snap or be damaged during a cyclone, they are more likely to be uprooted (Putz *et al* 1983).

More recently Curren *et al* (2008) examined species' response to disturbance caused by a severe tropical cyclone to test the trade-off between high-density, slow-growing species and low-density, fast-growing species. Six species from three remaining fragments of Mabi forests in the Atherton Tablelands were categorised into damage categories.

A positive correlation was found for both resistances of species to wood density and the proportion of trees experiencing minor damage only and wood density. Resilience, or the ability of species to recover biomass following disturbance was negatively correlated to wood density (Curren *et al,* 2008). Curren *et al* (2008) concluded that species with low wood densities were more likely to have stem and branch damage after a cyclone event, suggesting a species position along the resistance- resilience spectrum can be predicted by wood density.

The buttresses of trees have long been associated with playing an important role in tree support (Henwood, 1973; Richter 1984; Warren *et al* 1988; Young and Perchoka 1994; Richards 1996), however to date there is little information available about their role in a particular species' cyclone resistance.

4.4 Leaf Traits

Leaf traits are also considered to have some bearing on cyclone resistance and the level of damage caused by a cyclone (Curren *et al* 2008). Niklas (1999) demonstrated that leaf size (area, length and width) and the petiole length could influence the drag forces experienced during a windstorm. The same may be said for traits that relate to leaf strength (Curren *et al* 2008). Specific leaf area (SLA) is a measurable attribute of leaf strength that has a negative correlation between leaf force to fracture and leaf toughness (force to fracture/leaf thickness) (Curran *et al* 2008; Wright and Cannon 2001).

However Cook & Goyens (2008) discuss the likelihood of sclerophyllous leaves of eucalypts resisting defoliation for longer than rainforest trees, in addition to harder wood resisting breakage. They believe that because of this, and regardless of wood strength, leaf retention is thought to contribute to an increase in the proportion of trees snapped or uprooted due to the greater wind load (Cook & Goyens

(2008). However, while this may be a factor in some species there are obvious exceptions. There are numerous cyclone resistant species that retain the bulk of their foliage, even in Category 3-4 wind speeds (eg. *Melaleuca leucadendra, Morinda citrifolia, Flindersia* spp). Other tree species that have very low SLA values are known to suffer significant damage at much lower wind speeds (eg. *Casuarina* spp.).

4.5 Wind Risk Management

From the early 1960s, a shortfall in construction timbers was predicted, both nationally and internationally, and as a result Queensland's plantings of exotic pines in sub-tropical and tropical regions expanded dramatically (Bristow, 2008). The forestry management regimes addressed ongoing wood quality issues through genetic improvement through tree breeding and refined plantation silviculture of monocultures. However, to date it seems there has been very little consideration given to risk management of wind damage, particularly damage caused by cyclones in north Queensland.

Kanowski *et al*. (2008) suggests that, regardless of the species, those still interested in growing timber plantations in north Queensland need to try and reduce the risk of cyclone damage, even though some risk is simply unavoidable (Webb 1958; Unwin *et al* 1988; Konowski *et al.* 2008) as high levels of damage are likely to occur whenever a severe tropical cyclone crosses the coast on or near timber plantations.

Kanowski *et al*. (2008) also raise the prospect of longer rotation plantations being at a higher risk due to return intervals of TCs to the region. Therefore, questions can be raised about the prospect of growing timber plantations for carbon sequestration in north Queensland as any potential project will have to deal with the added risk of knowing that planted trees must be maintained for a period of 50-100 years to be considered permanent under regulations in the recently announced Carbon Farming Initiative (CFI) (DCCEE 2012). An alternative option to reduce the long-term risk is to plant trees on short-rotations, for the use of biofuel or biochar, knowing that any damaged vegetation could be used in the manufacture of biochar or fuel.

The possibility of reducing wind damage to timber plantations was also explored by Kanowski *et al*. (2008) who explore the idea of reducing risk through careful location and design of plantations. Kanowski *et al*. (2008) suggest one strategy could be to simply plant trees away from the coastline where destructive winds are usually most intense (Webb 1958). In addition to this, planting in valleys and other sheltered areas away from over exposed clearings could help to reduce the risk posed by wind damage (Van Bloem *et al* 2005). However, as previously stated, it has been shown that valleys can be affected by wind tunnels which actually increased wind speeds resulting in increased damage levels to trees (Reilly 1991; Grove *et al*. 2000).

However, Cook and Goyens (2008) make the point that historic observations of tree damage from tropical cyclones were usually made in coastal settlements and many of the records are suspected of being incomplete and possibly under-estimating the effects inland. They go on to say that despite the overland decay in cyclone intensity, TCs could still cause substantial tree damage 100km inland. The degree of inland penetration is obviously dependant on the size, energy and forward speed of the cyclone at the point of landfall. Category 4 Cyclone Yasi was still generating Category 1 winds as far inland as Julia Creek (Calvert 2011), located some 550 km inland from its point of landfall at Mission Beach.

There is also potential for plantations to be designed in a way that reduces the risk of wind damage. Tucker *et al* (2004) suggests the idea of surrounding plantations themselves by windbreaks of denser restoration plantings. Alternatively Keenan *et al* (2005) and Kanowski *et al* (2008) discuss stocking plantations at higher rates while also reducing the traditional silvicultural management regime, including thinning and pruning, effectively increasing stand density and wind resistance. The trade-off for reducing the wind damage risk is that the quality of timber produced may suffer (Keenan 2005).

Kanowski *et al* (2008) conclude by acknowledging the majority of the north Queensland plantation estate (prior to the MIS expansion) is composed of exotic conifers, and reinforces the need to consider species that are native to the area, that have evolved in an environment of recurring cyclones of varying intensities. It is also likely that local species can be improved genetically over time, although as many authors note (Kanowski 2008; Keenan *et al* 2005; Nikles and Robson 2005) there could well be trade-offs between growth rates and wind resistance.

In other research, Zeng et al 2007 describe how the overall risk of wind damage can change due to the above characteristics changing dynamically as the forest grows. Zeng *et al.* (2007) evaluate forest planning at the landscape level, and explain how clear felling forests can affect the local wind speed and the direction of airflow at the downward edges of the clearings, and consequently the level of risk in these conditions.

The risk of wind damage can be reduced at a regional scale by avoiding the cutting of new edges in old stands and cutting the most vulnerable stands first (Zeng et al 2004). Conversely, as a new stand matures and the gaps are filled with regeneration, the risk of wind damage decreases. In most cases, the objectives of timber production is given priority and therefore the spatial and temporal patterns observed in clear cuts can affect the overall risk of wind damage to an individual stand (Zeng *et al* 2007).

There have been many previous wind damage models developed (eg. Petola *et al* 1999; Gardiner *et al* 2000; Ancelin *et al* 2004) that Zeng *et al* (2007) refer to in their research. Most are based on tree and stand characteristics and environmental factors that have been developed to predict wind speeds needed to cause uprooting or stem breakage. More recently, some models were used in combination with forest growth model (SIMA) and a mechanistic wind damage model (HWIND) into GIS software (ArcGIS) to help build a Decision Support System (DSS). The DSS is able to assess the influence of certain forest management regimes on the risk of wind damage at both the stand and regional levels, even though such models are not yet capable of optimizing the management regimes to minimize the risk of wind damage (Zeng *et al* 2007).

Similar to the other models, Zeng *et al* (2007) used optimisation methods to include the risk management of wind damage into forest planning, in addition to the objectives concerning timber harvesting. The forest growth model (SIMA), was combined with the mechanistic wind damage model (HWIND) and GIS software (ArcGIS). The models were used to optimise the temporal and spatial patterns of clear-cuts to calculate the risk of wind damage and timber harvest over a 30-year simulation period.

The results highlighted the complex nature and difficulty involved in trying to assess the impacts of a clear felling regime on the risk of wind damage while also finding an optimal silvicultural regime based on traditional simultaneous timber harvesting methods Zeng *et al* 2007). By comparing three different heuristic techniques (1.simulated annealing (SA) 2. tabu search (TS) and 3. genetic algorythms (GA)) for optimal harvesting schedules and patterns for minimal or maximum wind damage, they found that with *"a proper intensity, interval and placement of cuttings, it is possible to reduce the risk of wind damage in a forest* (Zeng *et al,* 2007 pg 198)". Zeng *et al* (2007) go onto say that the total length of edges could be reduced by:

1. Aggregating clear-felling operations
2. Locating clear-felling at the edge of young stands (i.e. tree height >10m) and;
3. Making the landscape smooth in terms of stand height

However Zeng *et al* (2007) note that due to the requirements of an even flow of timber for processing, the possibilities to decrease the overall risk of wind damage may be limited.

5.0 Conclusions

Tropical cyclones (TCs) in north Queensland have caused severe damage to plantations in recent years. Future projections of climate change suggest TCs in this region will be less frequent but more intense. Therefore managers of timber plantations in north Queensland should consider minimising the risk of wind damage as a high priority, while maintaining a productive and profitable system.

There is currently little information available about just what the compromises are for wood quality, growth rates and the risk of wind damage, so in order to find the right balance, it is important that further research be undertaken to establish a financial model with wind risk factored in. Given that it is likely a TC will hit any given plantation along the north Queensland coast at some stage during the rotation, more consideration should be given to the species used in plantations, and where plantations are located in the landscape.

To this end, species that have a high slenderness ratio should be investigated further, particularly species that occur naturally in north Queensland. It is possible that mixed species plantations may provide more protection than monocultures. Furthermore species may grow better in mixed species environments (i.e. Red Mahogany – *Eucalyptus pellita*) and this fact could be considered in future plantation development. Research suggests that there are some local rainforest species with valuable timber that can be grown commercially in plantations, while at the same time provide a reduced risk of cyclone damage.

A number of ideas about how to manage timber plantations in cyclonic areas and reduce the risk of wind damage have been put forward. These include reduced pruning, higher-density plantings, use of cyclone resistant species, location in the landscape, using environmental plantings as wind breaks, and careful planning of harvesting operations. However, there is little information that attempts to establish the cost benefits of undertaking additional management actions and therefore it is unclear whether such actions are feasible or necessary at this stage.

6.0 Recommendations

Having reviewed the available literature, the following recommendations should be considered in the future:

- Conduct further research into the viability of growing proven wind resistant species (i.e. Kauri Pine, *Flindersia* spp) in plantations in north Queensland.
- Undertake tree-breeding programs that consider wind resistance within and between species as a desirable trait.
- Conduct a cost- benefit analysis to identify the balance required to minimise risk while also maintaining profitable operations.
- Encourage the development and use of heuristic models that consider wind risk as well as growth models, such as those commonly used in Scandinavia.

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