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POST-TROPICAL CYCLONE FUEL ASSESSMENT AND BUSHFIRE RISK

Research for the Queensland Fire and Emergency Services

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Cover: Cyclone damaged vegetation after *Marcia*, Cawarral region, Queensland. Photo by Jim Gould.

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EXECUTIVE SUMMARY

POST-TROPICAL CYCLONE FUEL ASSESSMENT AND BUSHFIRE RISK

Fire managers need better estimates of fuel hazard and loading in post-cyclone damaged vegetation so they can more accurately predict the behaviour of potential fires and plan fire mitigation and suppression strategies. In February 2015, Tropical Cyclone Marcia caused massive defoliation across the central coastal region of Queensland, uprooting trees and snapping off stems and branches. The magnitude of the damage changed the fuel hazard and loads in forest areas. This study examined a proportion of the forests damaged to assess fuel hazard and loading of fine fuels and downed woody material.

A visual assessment technique was developed and tested to provide ratings of cyclone damage and fuel loads. Visual cyclone damage scores reflect the quantity and arrangement of the fuel to better predict fire behaviour and improve planning mitigation and suppression strategies. The study demonstrated that severity of a cyclone can increase the fire spread and fireline intensity by 1.5 and 2.5 fold respectively and impede fire line access. Results were used to develop a supplementary field guide that can be used with the existing fuel hazard guides.

END USER STATEMENT

Andrew Sturgess, *Queensland Fire and Emergency Service, Queensland*

The Queensland Fire and Emergency Service (QFES) is responsible for prevention of and response to fires and certain other incidents endangering persons, property or the environment. The QFES uses the five R's cycle shown in the figure below.

The work undertaken by Jim Gould aligns with this approach. Prior to the work being undertaken significant uncertainty existed around the increased severity of bushfires in the years following severe Tropical Cyclone Marcia.

The work addressed all aspects of the cycle. QFES staff and volunteers worked alongside Jim and this provided a learning opportunity that was maximised by volunteers and staff from various parts of the State.

Local and State Government partnerships were enhanced as a result in the collaborative approach to manage the increased risk in cyclone affected areas.

The focus was *community* risk reduction. Perhaps the greatest single challenge for QFES is the need to promote a shared responsibility between individuals, the community and emergency services. Reducing the risk of incidents occurring remains our greatest challenge and to this end significant hazard reduction burning continues in the cyclone damaged vegetation. These operations have been able to take place with increased confidence following the project completion.

Community information sessions and training in the field provided an opportunity to communicate the results of the work that was taken up by many local residents, volunteers and QFES staff.

QFES would like to take this opportunity to congratulate Jim and thank him for his commitment to addressing this pressing issue in such a professional manner.

INTRODUCTION

Tropical cyclones are significant natural disturbances to forest ecosystems in north-eastern Australia, especially in forested areas near the coast. These cyclones can be intense, causing massive defoliation, uprooting trees, and snapping stems and branches, resulting in open canopy conditions and changes in understorey microclimate conditions (Turton and Dale 2007; Catterral *et al.* 2008; Pohlman *et al*. 2008; Comita *et al*. 2009; Murphy and Metcalfe in review). Even continuous forest regions have been described as hyper-disturbed ecosystems. Patches of damaged forest are constantly recovering from previous cyclonic events and can also be subjected to other natural disturbances including floods, drought and bushfires (Turton and Dale 2007).

Given the frequency of cyclone events, there is a general consensus that they alter the forest structure at several spatial and temporal scales. Impacts of tropical cyclones on forests at the landscape scale (>10 km) are the result of the complex interaction of anthropogenic, meteorological, topographic and biotic factors. Turton and Dale (2007) describes three main factors that impact forest damage at these different scales:

- Wind velocity gradients resulting from cyclone size, speed of forward movement, intensity and proximity to the storm track, complicated by local convective-scale winds.
- Variation in site exposure and other effects of local topography (e.g. severe lee wave or leeward acceleration, windward exposure).
- Differing responses of individual vegetation types or ecosystems to wind disturbance as a function of forest structure.

Each year cyclones in north-eastern Australia attract attention that includes several days of anticipation prior to each storm and following the storms, many weeks of recovery from the destruction of property, disrupted infrastructure and in some cases the loss of human lives. For humans and other biota, cyclones (called hurricanes in the Atlantic) cause losses across a wide range of spatial and temporal scales (Lugo 2000). With sustained wind speeds exceeding 120 km/h over a width of tens of kilometres, cyclones strip most of the leaves and branches from tree canopies, snap stems and uproot trees and deposit large amounts of litter and woody debris onto the forest floor (Walker *et al*. 1991). The removal of the overstorey canopy alters understorey light, temperature and moisture. However, the impact of these changes on the risk and behaviour of subsequent bushfires are unknown.

Numerous studies describe the effects of windstorms on tropical and subtropical forests, including *Austral Ecology* (**33**) (Turton 2008) and *Forest Ecology and Management* (**332**) (Shiels and Gonzalez 2014) for tropical cyclones and hurricanes respectively. These journals predominantly discuss the effects on and responses of terrestrial ecosystems following cyclones. Despite the large number of studies that have documented the effects of cyclones on forests, there is limited understanding of how fuel hazard and fire behaviour changes in cyclone damaged vegetation. However, there are anecdotal reports of increased fuel hazard due to tropical cyclones. This increase will depend on the severity of tropical cyclones. The Bureau of Meteorology describes tropical cyclone severity in terms of five categories related to zones of maximum wind speeds (BoM, 2015a) (Table 1). The damage related to the different severity categories depends on the location of the maximum zone exposure; structural building standards; vegetation types; and potential flooding. The indicators of cyclone severity for increasing fuel hazard are:

- Increased surface fuel load from leaves and branches stripped from overstorey canopy trees.
- Reductions in canopy cover that change the microclimate and accelerate the invasion of exotic trees, vines, and grasses species.

- Potentially severe damage to understorey vegetation creating excessive vertical and ladder fuels (i.e., fuels that provide vertical continuity between the surface fuel and crown fuels in forest stands).
- Snapped and uprooted trees that impede fire line construction and increase risk to fire fighters.

Until there is a better understanding of the increase in fuel hazard following cyclones, fire managers may be constrained in their mitigation and response strategies in cyclone damaged fuel. Other practical factors such as fire weather, smoke management and fire crew safety are also a primary concern when conducting hazard reduction burns and planning suppression strategies in cyclone damaged fuel.

Table 1. Severity of tropical cyclones in terms of categories ranging from 1 to 5 related to the zone of maximum winds (BoM, 2015a)

Category	Strongest wind gust	Typical effects
1 Tropical Cyclone	<125 km/h Gales	Minimal house damage. Damage to some crops, trees and caravans. Boats may drag moorings.
2 Tropical Cyclone	125–164 km/h Destructive winds	Minor house damage. Significant damage to signs, trees and caravans. Heavy damage to some crops. Risk of power failure. Small boats may break moorings.
3 Tropical Cyclone	165–224 km/h Very destructive winds	Some roof and structural damage. Some caravans destroyed. Power failure likely.
4 Tropical Cyclone	225–279 km/h Very destructive winds	Significant roofing and structural damage. Many caravans destroyed and blown away. Dangerous airborne debris. Widespread power failures.
5 Tropical Cyclone	>280 km/h Extremely destructive winds	Extremely dangerous with widespread destruction.

Forest fuel bed characteristics are temporally and spatially complex and can vary across the landscape. Fuel such as leaf litter, twigs and bark (surface fuels); and understorey vegetation naturally accumulate rapidly and in less than a decade can reach dangerous levels that can drastically increase fire intensity in both planned and unplanned fires (Gould *et al*. 2011). A major wind storm and/or tropical cyclone can increase the amount of surface and coarse woody debris available for combustion which will affect the spread, flame structure, duration and intensity of bushfires. Given that tropical cyclones and other extreme wind events are known to have substantial impact on vegetation in Australia's north-east, there is a high likelihood that cyclonic winds greater than 110 km/h could affect trees within 100 km or more of the coast (Cook and Goyens 2008). The effect of tropical cyclones on bushfire risk and changes in fire behaviour is difficult to interpret, and no framework for assessing the changes in fuel hazard has been developed. Emergency services in Australia require a better understanding of how changes in fuel accumulation and structure affect fire behaviour to better prepare for the fire season following a cyclone.

This study examined the dynamics of fuel loading and hazard following Tropical Cyclone Marcia. The objective was to develop a supplementary field guide that could be used with the existing fuel hazard guides (Hines *et al*. 2010; Gould *et al*. 2007, 2011). The study is descriptive and the sampling was done in selected cyclone damaged areas. The estimated changes in the available fuel following cyclone was used to predict fire behaviour and suppression difficulties.

METHODS

Fuel characteristics affect fire spread and flame structure as well as the duration and intensity of bushfires. Describing and quantifying fuels are critical to accurately predict the fire behaviour and informing fire management activities, including prescribed burning, suppression strategies, fuel hazard assessment and fuel treatment. Measuring fuel characteristic in the field is difficult because it requires a complex integration of several sampling methods for implementation at disparate scales. What is needed is an inexpensive, easy and quick fuel sampling technique that can provide consistent estimates of fuel characteristics at the level of accuracy required by the fire behaviour analyst and for fuel treatment planning. The techniques for reliable and rapid assessment of fuel characteristics are therefore essential to support fuel and bushfire fire management decisions in post-tropical cyclone damaged vegetation. Furthermore, fuel characteristics are increasingly of interest to ecologists, air quality managers and carbon accounting modellers.

TROPICAL CYCLONE MARCIA

The Bureau of Meteorology identified Tropical Cyclone Marcia as a tropical low off the north-east coast of Queensland and began tracking on Sunday 15 February 2015. Over the next few days the tropical low drifted eastward then south-west and began intensifying to a category 1 cyclone by the evening of Wednesday 18 February. During the next few hours Tropical Cyclone Marcia underwent a period of rapid intensification to a category 4. Early on Friday 20 February, Tropical Cyclone Marcia made landfall north of Yeppoon as a category 5 cyclone with a forecasted wind speed of 195 km/h gusting to 295 km/h near the core of the system (BoM 2015b and c). The communities of Byfield, Cawarral and West Yeppoon received the most significant damage to property, infrastructure, and forested vegetation.

Tropical Cyclone Marcia weakened as it passed over the Rockhampton area in the early afternoon of Friday 20 February where wind gusts up to 113 km/h were recorded, resulting in significant damage. By early Saturday morning Tropical Cyclone Marcia weakened rapidly as it travelled parallel to the south-east coast of Queensland before moving off land near the Sunshine Coast on Saturday afternoon (BoM 2015c).

SELECTION OF SAMPLE SITES

Fuel was assessed at five areas in the vicinity of Tropical Cyclone Marcia's path. The sample sites were selected based on a field reconnaissance survey in late April 2015; priority areas advised by Queensland Fire and Emergency Services (QFES); and review of major vegetation types in the path of the cyclone. Five sites and their associated vegetation types (QFES Vegetation Code and Description used for the PHEONIX fire simulation model) were selected.

1. Byfield Area:
    i. 6. Exotic plantation
    ii. 9. Dry to moist eucalypt open forests to woodlands
    iii. 20. Rainforest and vine forests

2. West Yeppoon Area:
    i. 5. Dry to moist eucalypt open forests to woodlands
    ii. 9. Dry to moist eucalypt open forests to woodlands
    iii. 11. Moist to dry eucalypt woodlands
3. Cawarral Area:
    i. 4. Closed to open forest with heathland and associated scrubs and shrublands
    ii. 5. Dry to moist eucalypt open forests to woodlands
    iii. 11. Moist to dry eucalypt woodlands

4. Mount Archer Area:
    i. 9. Dry to moist eucalypt open forests to woodlands
    ii. 11. Moist to dry eucalypt woodlands
    iii. 20. Rainforest and vine forests
5. Mount Morgan Area:
    i. 1. Wet eucalypt tall open forest on uplands
    ii. 5. Dry to moist eucalypt open forests to woodlands
    iii. 9. Dry to moist eucalypt open forests to woodlands

Data and photographs of fuel hazard, fuel loading, cyclone damaged tree scores and downed woody material were collected within a plot layout design shown in Figure 1. All data were recorded onto a Post-Cyclone Fuel Assessment Field Sheet (See Appendix I).

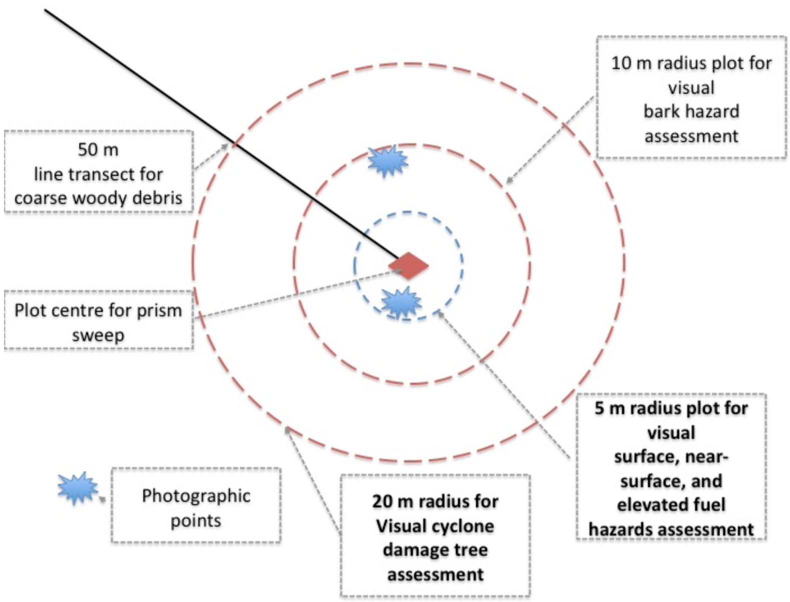

Figure 1. Schematic layout of the sample plots area (not to scale)

VISUAL ASSESSMENT OF FUEL HAZARDS

Vegetation fuels are high variable and are often defined by the physical components (e.g. loading, depth/height, size and bulk density) of live and dead fuels that contribute to fire propagation. However, these natural fuel beds are rarely uniformly compacted. They are stratified, with horizontally-compacted layers on the surface and aerated, less compacted layers above. The four fuel layers, broadly identified by a change in bulk density (i.e. compactness), can be visually assessed using fuel hazard guides developed by Hines *et al*. (2010) for categorical ratings or Gould *et al*. (2007, 2011) for numerical scores. The four visually obvious fuel layers associated with observed fire behaviour (Cheney *et al*. 2012) and suppression difficulty (Hines *et al*. 2010) are:

1. *Surface fuel layer* – leaf twigs and bark from the overstorey and understorey plants and damaged vegetation by the cyclone. The fuel components are generally horizontally layered. This layer usually makes up the bulk of the energy released by the fire. This layer burns by both flaming and smouldering combustion and determines the flame depth of a surface fire.
2. *Near-surface fuel layer* – grasses, low shrubs, creepers and collapsed understorey usually containing suspended leaf, twig, and bark material from overstorey vegetation. Additional fuel resulting from cyclone damaged overstorey and understorey vegetation could be present in this layer. The height of this layer can vary from just centimetres to over a meter high. The orientation of the components in this fuel layer includes a mixture ranging from horizontal to vertical and the layer is capable of supporting leaf and bark material above ground.
3. *Elevated fuel layer* – tall shrubs and other understorey plants without significant suspended material. This layer may include regeneration of the overstorey species intermixed with shrubs. The individual fuel components generally have an upright orientation and include live and dead material.
4. *Overstorey bark fuel* – dominant and co-dominant trees forming the uppermost canopy layer of the forest. Trees are pole size or greater. The flammable aspect is the bark, which depends on the tree species and the height and density of the forest. The bark type of different species can have a large impact on the rate of surface fuel accumulation transfer of a surface fire into the canopy and the generation of firebrands.

The Overall Fuel Hazard Assessment Guide for hazard ratings (Hines *et al.* 2010) and the Field Guide Fuel Assessment and Fire Behaviour Prediction in Dry Eucalypt Forest for the hazard scores (Gould *et al*. 2007) were used to assess the fuel hazard for the different fuel layers. Surface, near-surface and elevated fuels were visually assessed within a 5 m radius (See Figure 1). Individual scores and ratings were recorded, along with fuel depth or height. Bark hazard and dominant tree canopy height were recorded within a 10 m radius.

DESTRUCTIVE SAMPLING OF FUEL LOADS

The fuel load of the surface and near-surface (<25 mm deep) was sampled using rank set sampling – a cost-effective method to increase precision in estimating the population mean (McIntyre 1952, Cheney et al. 1992, Nahhas *et al*. 2002, Gould *et al*. 2011). The surface and near-surface fuel load was visually identified using the rules outlined in the Visual Assessment section above. Within a 5 m radius of the sample point, the assessor visually ranked the surface and near-surface fuel load as either light, medium or heavy. The plot ranked medium was then selected for sampling. All the material <25 mm deep was collected, sorted into three size classes (i) <6 mm, (ii) 6–10 mm and (ii) 10–25 mm, labelled and bagged. A 0.0625 m^2 quadrant (0.25 x 0.25 m) was used for surface fuel and 0.25 m^2 quadrant (0.5 x 0.5 m) used for near-surface fuel.

A similar procedure was used to rank the fuel load of the elevated fuel to select the medium-ranked sample for harvesting. The harvested fuel was collected in 1 m^2 quadrant (1.0 x 10 m) and sorted into three size classes (0–6 mm dead, 0–6 mm live and 6–10 mm dead), labelled and bagged. All samples were taken back to a laboratory and oven dried at 105°C for 24 hours and then weighed. Fuel load was expressed in tonnes per hectare (t/ha). Separating the near-surface fuel from the underlying surface fuel in the 0.25 m^2 quadrant samples proved impractical and these samples were expressed as combined surface and near-surface fuel load.

TROPICAL CYCLONE DAMAGE HAZARD ASSESSMENT

Tropical cyclone fuel hazard ratings

A visual assessment of vegetation damaged by tropical cyclones was developed following the concepts of Unwin *et al*. (1988), Turton and Dale (2007), Pohlman *et al*. (2008) and Vihnanck *et al.* (2009). The severity of damage depends on wind speed, trees species, tree size (height and diameter) and topography. Foliage loss and structural damage are essential damage characteristics (i.e. stripped canopy, broken branches, snapped stems, uprooted trees) and are obvious indicators of cyclone damaged vegetation. Table 2 outlines the six damage categories developed to subjectively assess cyclone damage to forest vegetation.

Table 2. Tropical cyclone damage ratings for trees and saplings (note: the underscored text was added to the field procedures after the sampling crew training sessions)

Cyclone Damage Score	Rating	Description ***Large trees*: dbh[1] >5 cm** ***Small trees (saplings)*: dbh <5 cm**
0	Nil	Intact – no obvious damage
1	Low	*Large trees:* minor branch damage of <25% branch lost *Small trees*: <u>few trees (<10%)</u> bent and unbroken
2	Moderate	*Large trees:* 25–50% branches lost, few trees (<10%) bend <45°, <10% of the trees trunk snapped off, no uprooted trees *Small trees:* substantial part of the canopy stripped off part of the small trees beneath other debris, <u>10–30% bent and unbroken</u>

3	High	*Large trees:* 50–75% branches lost, >75% of the canopy leaves stripped off, 10–30% of the trees trunk snapped off, <10% of the tree are uprooted *Small trees:* >75% of the branches lost, no fine twigs and small branches present, >30% bent and/or snapped
4	Very High	*Large trees:* no visible signs of twigs and small branches <10 cm, scattered large branch material on the ground, 30–50% of trees trunk snapped off, 10–30% of the trees uprooted *Small trees:* trunks snapped off low to ground or 30–50% uprooted trees
5	Extreme	*Large trees:* >30% of the trees are uprooted and flattened to ground *Small trees:* >50% uprooted or snapped off

[1]dbh; diameter at breast height (i.e. 1.5 m above ground)

Overall tropical cyclone damage assessment

At each location the overall number of cyclone damaged trees was scored within a 20 m radius of the centre of the plot. Prior to conducting the field surveys, the author conducted a training session for fuel assessors and additional training sessions for new assessors at the different sampling stages. After the initial training session additional information was added to better define the damage ratings in small trees (See Table 2 where additional information indicated by underscored text).

Individual tree damage assessment

To evaluate the proposed cyclone damage rating and overall cyclone damage score outlined in Table 2, individual trees were selected and their damage score recorded. It was impractical to establish a fixed radius plot to assess individual trees because uprooted trees made it difficult to establish plot boundaries. Therefore, a 2 metric basal area factor optical wedge prism (Husch *et al*. 1972) was used to select individual trees for damage assessment. Appendix II outlines the field procedures for the optical wedge prism. Weighted average damage score (W_{ds}) of the individual tree scores was calculated using:

$$W_{ds} = \frac{\sum s_i \cdot c_i}{\sum c_i}$$

where s_i is the score value i for score from 0 to 5, and c_i is the number of tree counts in each score class.

DOWNED WOODY MATERIAL

Downed wood material (DWM) was defined as fresh downed pieces of woody material resulting from the cyclone. The woody material was grouped into four size classes by diameter (i) <6 mm, (ii) 6–25 mm, (iii) 25–75 mm, and (iv) >75 mm. The procedure for sampling DWM was a line intersect transect based on methods from Van Wagner (1968) and Brown (1974). Appendix III describes the field procedures for collecting DWM information. All the fine fresh woody material (<75 mm) was counted along different intervals of the transect line. For each large piece (>75 mm), the diameter was recorded and it was noted if it was fresh or old wood. The downed woody material load (W, t/ha) was calculated using Brown's (1974) formula:

$$W = \frac{\pi^2 P_p}{8L} \sum_I d_i^2$$

where P_p is the wood density (0.56697 g/cm^3, Hollis *et al*. 2010), L is transect line length (i.e., 50 m), and d is recorded diameter (cm).

PHOTOGRAPHS

Photographs were taken to improve the ability of practitioners to appraise the different fuel hazard categories described in Table 2. The reference pole in the photographs was a 2 m pole painted in contrasting colours at 12.5 cm intervals (Figure 3 and 4). Each reference pole was placed 10 m from a camera with a focal length lens between 50 to 70 mm. Close-up photographs of the surface and near-surface fuel layers were taken using the sample quadrant as a reference scale. A vertical photograph of the canopy density and damage was also taken.

FIRE WEATHER DATA

Queensland Fire and Emergency Service Predictive Services provided historical fire weather from 1972 to 2010 for the Rockhampton region. This data included the daily weather observations (i.e. wind speed and direction, temperature, relative humidity, rainfall, time since last rain, etc.) as well as the calculated drought factor and forest fire danger index (McArthur 1967). This data set was used to investigate the impact of cyclone damaged fuels on fire behaviour and suppression difficulty for different percentiles in the Forest Fire Danger Indices (FFDI).

ANALYSIS

Fuel data collected included continuous variables (fuel load, depth, height) and categorical scores (fuel hazard scores, ratings, cyclone damage scores) so a variety of statistical methods were used to determine the changes in available fuel for combustion following cyclones. There were limited data on pre-cyclone fuel conditions and no similar vegetation types not impacted by the cyclone within the vicinity of damaged area for sampling. Therefore, the cyclone damage fuel score 1 (Low) was used as the benchmark to determine if there was an increase in fuel load and hazard. The results were analysed in R Statistical Packages (R Core Team 2015) using descriptive statistics, box and whisker plots and comparisons of means based on cyclone damage scores and grouping of vegetation types.

RESULTS

Forty eight sample plots were selected in five major cyclone damaged areas near Byfield, Cawarral, West Yeppoon, Mount Archer and Mount Morgan (See Figure 2). The plots represented seven different vegetation types and a summary of fine surface fuel load by vegetation type is given in Table 3. Two samples were taken in the rainforest and vine forest vegetation type[1] because the fire management strategy is to exclude or stop fire from encroaching into these vegetation types. The most visually damaged forests were the exotic pine plantations (See Figure 3) where there was up to 80 t/ha of downed woody material >75 mm. The mitigation of cyclone damaged pine plantation will predominantly be a commercial operation of salvaging trees over the next 12 months (S Watson[2] pers. comm.).

Table 3. Standard Queensland Fire and Emergency Service (QFES) fuel load values and the sample mean and range (brackets) of the fine fuels (<6 mm) for the different vegetation types affected by Tropical Cyclone Marcia

Vegetation Code[1]	QFES fuel load values by vegetation type (t/ha)				Post-cyclone sample fuel load by vegetation type (t/ha)			
	Surface	Elevated	Bark	Total	N[a]	Surface & Near-surface	Elevated	Total
1	4.5	0	0	4.5	1	9.4	0.6	10.1
5	20.9	1.9	0.9	23.6	11	15.5 (8.1–23.9)	3.0 (0.3–6.9)	18.7 (14.8–26.7)
6	15.0	0.3	0.4	15.6	3	13.3 (11.3–14.6)	5.3 (2.5–8.1)	18.3 (13.8–22.8)
9	11.2	0.5	0.9	12.6	20	12.3 (4.1–21.7)	2.6 (0.1–5.9)	17.0 (10.5–25.7)
11	19.3	1.1	0.8	21.2	3	13.6 (8.5–16.3)	1.8	15.4 (10.3–18.1)
12	6.1	0.7	0	6.8	1	14.9	0.1	15.0
20	7.2	2.7	0	9.9	2	16.5 (14.2–18)	0.1	16.6 (14.3–18.9)

[1] Vegetation codes (Queensland Fire and Emergency Service Predictive Services:
1= Wet eucalypt tall open forest on uplands and alluvia
5= Dry to moist eucalypt open forests to woodlands
6= Pine plantations
9= Dry to moist eucalypt open forest to woodlands
11= Moist to dry eucalypt woodlands
12= *Melaleuca* woodlands
20= Rainforest and vine forest

[a] N= number sample plots

[1] Queensland Fire and Emergency Services Predictive Service identified 64 vegetation types for bushfire risk and prediction of fire behaviour using the Phoenix fire simulation model (Tolhurst *et al.* 2008)
[2] S Watson, Operational Manager Central Queensland, HQ Plantations Pty. Ltd.

Figure 2. Location of the 48 sample plots in five locations that were affected by Tropical Cyclone Marcia in 2015

Figure 3. Extreme cyclone damaged vegetation (cyclone damage score 5) – snapped and uprooted trees in pine plantations near Byfield, Queensland

The other five fuel types were predominantly native eucalypt forests and woodlands. The local fire authorities (QFES; Queensland National Parks and Wildlife; and Department of Natural Resources and Mines) are implementing bushfire mitigation programs in cyclone affected areas. There was no correlation between the cyclone damage scores and vegetation type, therefore all the eucalypt forest and woodland vegetation types were grouped into one general vegetation type (native forest) for further analysis. Examples of cyclone damage by scores (see Table 2) in native forest vegetation are shown in Figure 4.

a) Cyclone damage score 1 (Low)

b) Cyclone damage score 2 (Moderate)

c) Cyclone damage score 3 (High)

d) Cyclone damage score 4 (Very High)

Figure 4. Examples of tropical cyclone damage in native forest vegetation by damage score

The cyclone damage scores did not reflect a change in the surface and elevated fuel hazard scores, which were either a score of two or three (Table 4). The most significant change in the fuel hazard score was the near-surface fuel score of two (moderate fuel hazard rating) with the scatter suspended leaf and twig material where the cyclone damage score was one. In the very high cyclone damaged forest (score of four) there were large amounts of leaves, twigs and bark that obscured logs, rocks and holes resulting in a fuel hazard score of four (extreme fuel hazard rating) (Table 4 & Figure 5a). Combined surface and near-surface fuel load increased steadily from 11.8 t/ha to 18.8 t/ha with increasing cyclone damage scores (Figure 5b). The fresh tops of fine leaves and twigs from fallen cyclone damaged branches added to the elevated fuel layer (Figure 6). This additional fuel contributed an extra 2 to 3 t/ha of fine fuel in the elevated fuel strata. There was very little difference in the elevated fuel loads between cyclone damage scores (Figure 5c) and elevated visual hazard scores were predominately two (moderate rating). There was no significant change in fuel depth and height of the surface, near-surface and elevated fuel respectively (Table 4).

In the native forest vegetation, the overall fuel hazard rating increased from moderate in the areas with low damage, to very high in the areas with high and very high cyclone damage.

Table 4. Mean and range (brackets) of fuel variables by cyclone damage class for the native forest vegetation types

Fuel Parameters	Cyclone Damage Score			
	1 (Low)	2 (Moderate)	3 (High)	4 (Very High)
Number of samples	10	13	10	1
Wt Cds	1.0	2.1	2.7	3.9
Fuel load (t/ha)				
SF + NSF 0–6 mm	11.8 (7.2–15.6)	13.6 (8.0–20.5)	16.0 (8.1–23.9)	18.8
SF + NSF 6–10 mm	1.0 (0.2–1.6)	1.2 (0.5–2.2)	1.1 (0.2–2.4)	1.2
SF + NSF 10-25 mm	2.3 (0.2–6.9)	2.6 (0.03–5.9)	1.7 (0.3–3.8)	0.4
EF 0 – 6 mm	2.1 (0.1–4.7)	2.6 (0.1–5.9)	3.1 (1.1–6.9)	3.1
EF 6–10 mm	0.6 (0.3–1.4)	0.6 (0.5–1.1)	0.5 (0.2–1.1)	0.6
DWM 0–6 mm	0.4 (0.04–0.7)	0.2 (0.03–0.8)	0.2 (1.6–3.9)	0.2
DWM 6–25 mm	2.2 (0.7–3.6)	2.6 (0.7–4.3)	2.7 (1.6–3.9)	2.7
DWM 25–75 mm	5.4 (0.0–12.9)	9.8 (2.7–22.2)	7.7 (3.7–16.65)	7.4
DWM 75+mm	6.1 (0.0–37.1)	13.1 (0.0–58.3)	49.7 (0.0–359.7)	36.4
Understorey fuel heights				
SF depth (mm)	27 (5–50)	23 (10-50)	30 (15–40)	35
NSF height (cm)	29 (10–45)	37 (6–70)	27 (12–55)	30
EF height (cm)	106 (50–200)	93 (60–120)	120 (70–180)	110
Understorey fuel hazard scores				
SF FHS	2.7 (1–3.5)	2.8 (2–4)	3.2 (3–4)	4
NSF FHS	2.5 (2–3.5)	3.2 (3–4)	3.5 (3–4)	4
EF FHS	2 (1.5–3)	2.1 (2–2.5)	3 (2–3.5)	2
OFHR	M	H	VH	VH

Symbols:
Wt Cds= Weight average damage score from individual tree cyclone damage scores
SF= Surface fuel
NSF= Near-surface fuel
EF= Elevated fuel
DWM= Downed woody material
FHS= Fuel hazard Score (Gould *et al.* 2007)
OFHR= Overall fuel hazard rating (Hines *et al.* 2010)

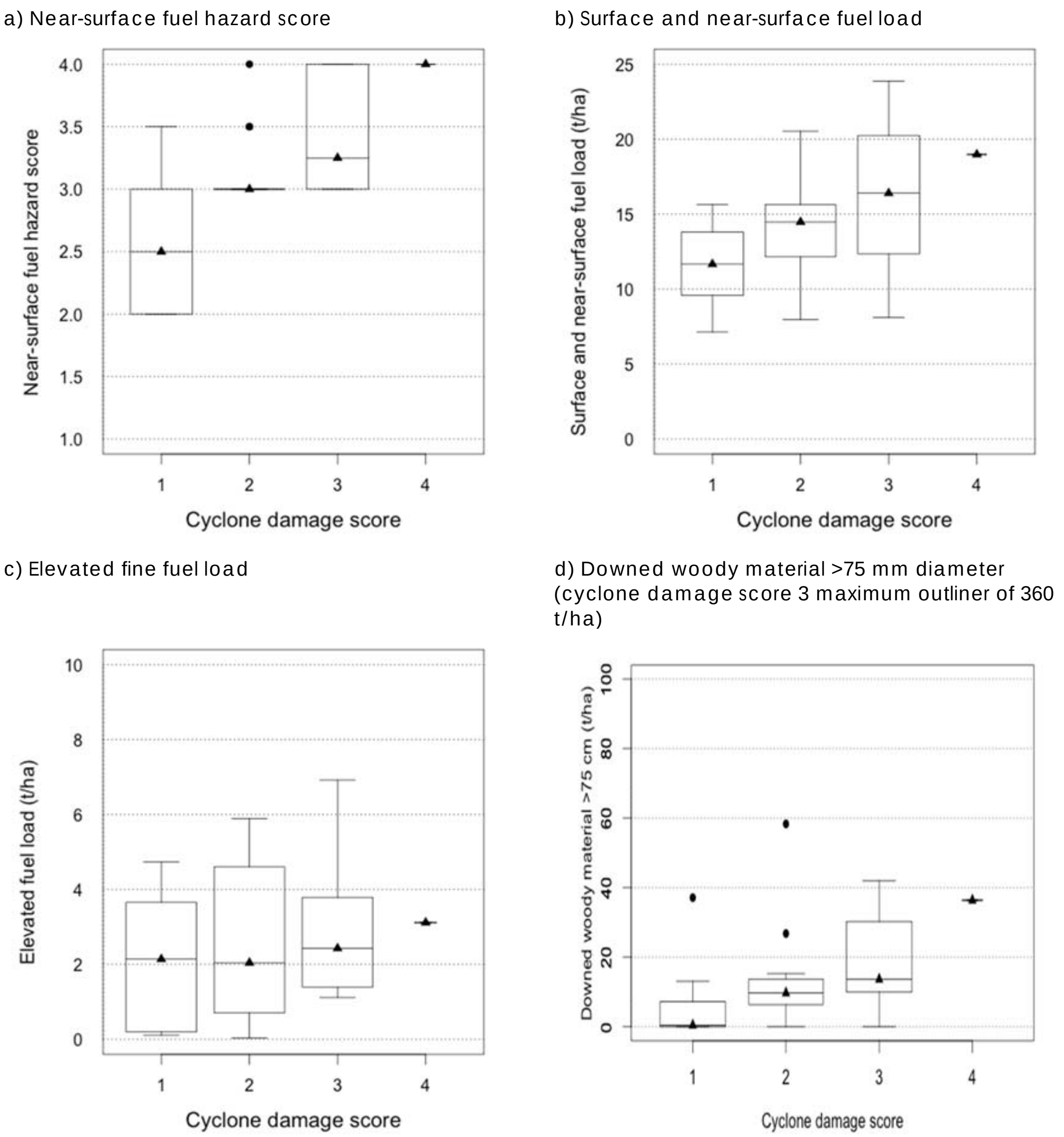

Figure 5. Variation of the different fuel parameters (a) near-surface fuel hazard score, (b) fine surface and near-surface fuel load <6 mm, (c) fine elevate fuel load <6 mm, (d) downed woody material >75 mm for the cyclone damage scores of native forest vegetation affected by Tropical Cyclone Marcia. Box-and-whisker plots shows the median value (▲), 25th and 75th quartiles (i.e. 50% of the cases have values within the box) and dot (•) represents outliers more than one box length for the 75th percentiles.

Figure 6. Cyclone damaged canopy tops adding 2 to 3 t/ha of fine fuel <6mm to the elevated fuel load

The downed woody material >75 mm rose steadily from 6 t/ha in the low cyclone damage areas up to 50 t/ha in areas with high damage (Table 4 and Figure 5d). The quantity of downed branch material (25–75 mm size class) was higher in the areas with moderate to very high cyclone damage scores compared to the areas with low damage scores. Although the downed woody branch material was higher in the areas with higher damage, the elevated fuel load did not reflect the increase in the fine fuel loads (<25 mm) of the downed branch material.

The magnitudes of change in the fuel hazard and fuel load were influenced by the cyclone damage and also by a variety of scale-dependent factors including stand structure, density and composition. The results were compiled into a set of fuel hazard and loading values by cyclone damage scores so practitioners can use them to plan and predict fire behaviour and suppression difficulties (Table 5).

Table 5. Fuel hazard and load by cyclone damage scores for native forest vegetation in central Queensland

Fuel Parameters	Cyclone Damage Score			
	1 (Low)	**2 (Moderate)**	**3 (High)**	**4 (Very High)**
SF FHS	3 (High)	3 (High)	3.5 (Very high)	4 (Extreme)
NSF FHS	2.5 (high)	3 (High)	3.5 (Very high)	4 (Extreme)
NSF Height (cm)	25	30	30	35
EF height (cm)	100	100	120	120
OFHR	Moderate	High	Very high	Very high
Fuel load (t/ha)				
SF + NSF 0–6 mm	12	14.5	16	20
EF 0–6 mm	2	3	4	5
Total fine fuel	15	17.5	20	25
DWM >25 mm	15	25	40	50
Symbols: SF= surface fuel NSF= near-surface fuel EF= elevated fuel FHS= fuel hazard score (Gould *et al*. 2007) OFHR= overall fuel hazard rating (Hines *et al.* 2010) DWM= downed woody material				

DISCUSSION

FUEL ASSESSMENT

The variability of cyclone damage vegetation is high because windstorms can be very patchy (Webb 1958). Tropical Cyclone Marcia caused large structural changes in both continuous and fragmented forested vegetation, although the amount of damage varied considerably between and within sites (Table 3 and 4). The major damage included frequent uprooting and snapping of trees some metres above the ground (Figure 3 and 4d). Therefore, defining cyclone damage by the structural damage of trees being stripped of leaves, twigs, branches, broken tops, snapped and uprooted; and employing a sampling procedure that avoided bias, provided robust estimates of cyclone damage (Table 2). This was reflected in the ability of different assessors to consistently score the same damage conditions. Also, visual estimates were similar to the overall average weight of the individual trees sampled from the optical prism sweep (Table 4). The key to consistent results was ensuring that assessors were familiar with the extreme cyclone damage score (5) as well as having an adequate number of samples to capture the variability in cyclone damaged forests. The results presented here gave estimated values of fuel hazard ratings and loads by grouping severity damage of forests into six damage classes (Table 2 and 5).

Developing a sampling design to measure the magnitude of change of fuel hazard and loading following cyclones that accurately captures the variability is difficult, as the sampling is costly and time consuming. The cyclone damage scores presented here are based on visual assessments that can be easily taught to field crews and quickly implemented, and are accurate enough to be used as input to fire models. There are a number of visual field guides that have been developed to provide a systematic method for assessing fuel hazard for suppression difficulty as well as predicting fire spread (McCarty *et al*. 1999, Gould *et al*. 2007, 2011, Hines *et al.* 2010, Cheney *et al.* 2012). These guides provide descriptions and photographs for each fuel layer and attributes to assess the fuel hazard rating. The cyclone damage scores developed in this study can be used as a supplementary guide to these existing guides to assess fuel hazard and load following cyclones. Although the damage score system is subjective, the cyclone damage scores can be related to quantitative values (Table 5) for predicting fire behaviour (McArthur 1967, Gould *et al*. 2007, Cheney *et al*. 2012) and suppression difficulty (McCarthy *et al*. 1999, Plucinski *et al*. 2007, Hines *et al*. 2010).

Appendix IV is an amendment of Table 2 to incorporate the photographic illustrations and values in Table 5 into a supplementary field guide to assess bushfire fuel hazard and load in forested area affected by cyclones. The field guide and visual assessment relies on the ability of the assessor to match the observed cyclone damage with the descriptive text and photograph which portrays an example of the damage score class. Fuel beds often contain a mixture of all fuel components and it may be difficult for the assessor to single out just one fuel component from the mixture of twigs, leaves, branches and downed woody material in the sample area. A few months after a cyclone, new growth of epicormic shoots and the development of new canopy growth may make it difficult to determine the severity of the stripped leaves and twigs. Ideally the assessment of cyclone damage forest should be conducted within three months of a cyclone.

One of the limitations of the proposed supplementary field guide is that it relies on visual assessment to obtain damage rating and fuel loading. Visual estimates of fuel hazard and loading, much like ocular estimates of vegetation cover, are subject to human error because they rely on subjective assessment with an imperfect measuring device – the eye (Muller-Dombois and Ellenberg 1974, Bonham 1989, Keane and Dickson 2007). Without a standard or benchmark, it is difficult to describe the error in a visual assessment. Thus, ocular estimates are only consistent and accurate for a single observer and often difficult to repeat with different observers. Therefore, practitioners should apply these field guides along with a good sampling design to make rapid and consistent assessment of fuel hazard ratings and cyclone damage scores with care.

EFFECTS OF CYCLONE DAMAGED VEGETATION ON FIRE BEHAVIOUR

Changes in potential fire behaviour after a tropical cyclone will depend not only on the total quantity of fuel available, but also any change in the understorey microclimate. Pohlman *et al*. (2008) found that the changes in the understorey microclimate mirrored the degree of damage to the vegetation. That is where there was very high to extreme vegetation damage, the understorey microclimate was brighter, warmer, drier and windier compared to low and moderate cyclone damaged areas (Pohlman *et al.* 2008). These changes will affect the diurnal ranges of the fine fuel moisture and the wind profile near the flaming zone. Pohlman *et al.* (2008) concluded that the understorey microclimate was approximately 5°C warmer in a rainforest after Tropical Cyclone Larry, with a 30% increase in wind speed compared to the pre-cyclone microclimate. Changes in the understorey microclimate after Tropical Cyclone Marcia are likely to be less pronounced because of the more open canopy of the forest woodland compared to the dense rainforest canopy cover.

Historic fire weather records from 1972 to 2010 indicated that the fire season would commence approximately six months after the cyclone season. Figure 7 shows the range and variation of the forest fire danger indices (FFDI, McArthur, 1967) for central Queensland. By the beginning of the fire season (early August 2015) the majority of the accumulated fine fuels (<6 mm) from Tropical Cyclone Marcia will be available for combustion and fine fuel moisture will respond to the diurnal changes to the ambient weather conditions. The combination of an increase in fuel loading with a warmer and windier understorey microclimate will mean the fire behaviour will be quite different to that observed in pre-cyclone fuel conditions.

Applying data given in Table 5 to fire behaviour models, the estimated spread rate and fire line intensity increased by 1.5 and 2.5 times respectively between the low and very high cyclone damage classes (Figure 8). These increases in fuel load and fire behaviour estimates will mostly likely be sustained for two to three years after the cyclone event. By this time the fuels will have decomposed to pre-cyclone conditions. If physical characteristics of the fuel have not been described adequately there will be insufficient data to accurately characterise a fire in terms of fire spread and fire line intensity. The data presented in Table 5 are fuel estimates for predicting fire behaviour. However, there will be conditions where the observed fire behaviour will be quite different from the predicted values using the assumed fuel conditions. This is because the spatial variability of cyclone damaged fuels at the fire front can be quite different to values given in Table 5. Fire behaviour analysts may want to predict the chances of a fire exceeding certain limits of behaviour, say 90th percentile (Figure 8). Potential overestimates of fire behaviour predictions can be easily readjusted without serious consequences. Underestimates of behaviour can be disastrous both to incident controllers and the credibility of the person making the prediction on safety warnings to fire fighters and communities.

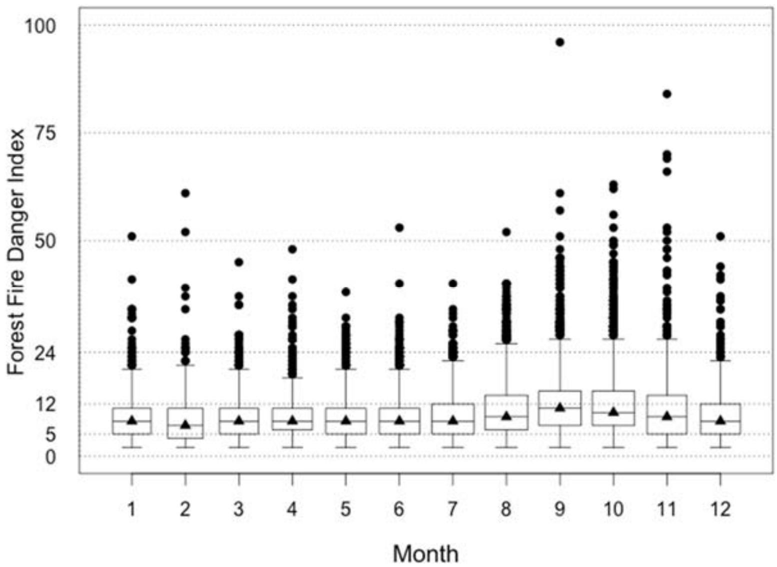

Figure 7. Range of the forest fire danger index (McArthur, 1967) between 1972 and 2010 by calendar month for central Queensland region. Box-and-whisker plots show the median value (◆), 25th and 75th percentiles (i.e. 50% of cases have values within the box) and dot (•) represents outlines more than one box length from the 25th and 75th percentiles.

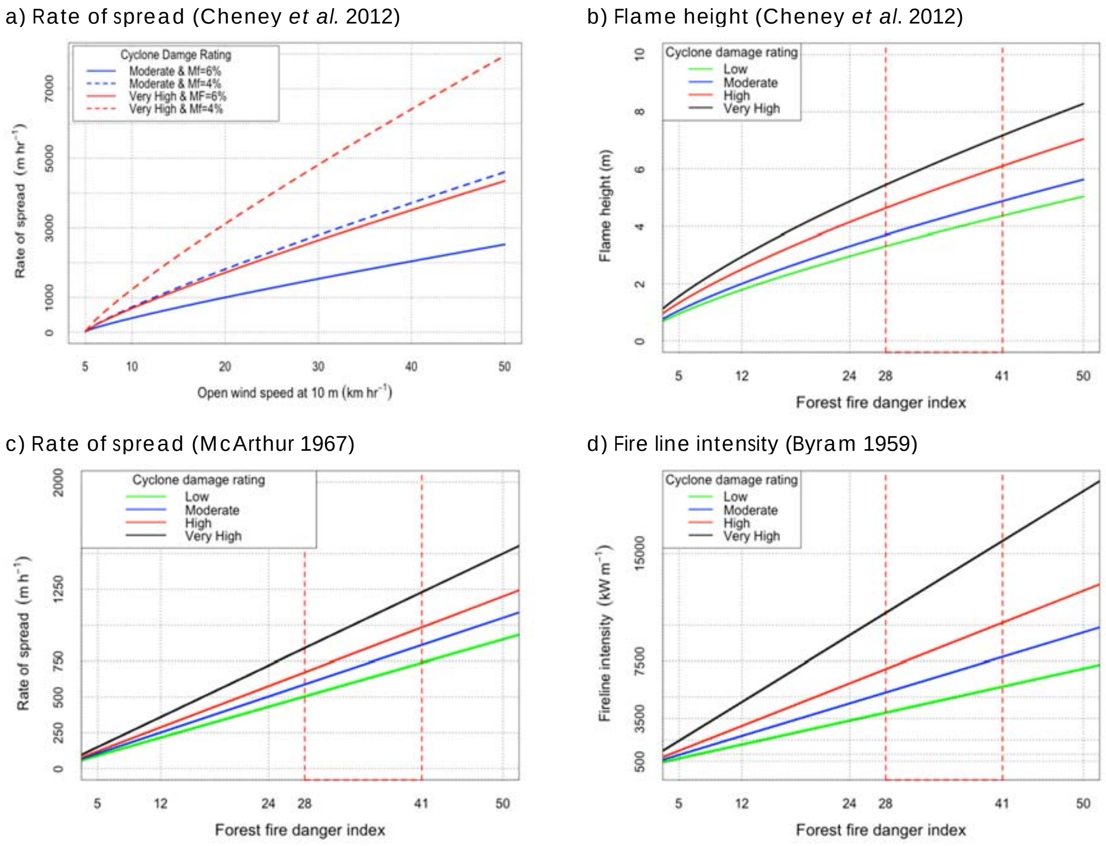

Figure 8. Fire behaviour estimates of (a) Vesta fire spread model with 95th and 99th fuel moisture content percentiles, (b) flame height, (c) McArthur 's fire spread model and (d) fire line intensity by cyclone damage ratings for the forest fire danger indices and wind speed. The vertical red dash (b, c, and d) at Forest Fire Danger Indices (FFDI) 28 and 41 represents the 95th and 99th FFDI percentile during the annual fire season between August and October in the central Queensland region.

SUPPRESSION STRATEGIES IN CYCLONE DAMAGED VEGETATION

Bushfire suppression activities aim to minimise the adverse impacts of fire on people, property and the environment. Fire fighter safety is paramount in implementing suppression strategies. This is usually achieved by minimising the area burnt through aggressive early suppression activities. These strategies are carried out in the early stages of fire development when the fire's perimeter is small and the fire intensity is low. This aggressive attack strategy maximises the likelihood of containment while minimising the area affected by fire and suppression cost (Parks 1964, Hircsh *et al*. 2004, Plucinski *et al.* 2007). The main responses to suppress fires in cyclone damaged vegetation are to firstly to stop the fire from spreading and causing damage, and secondly to keep it contained by:

- Reducing the height of flames, fire progression and ignition of dangerous trees to mitigate spotting potential
- Establishing strategic fire breaks along the outer edge of the fire perimeter, preferably mineral earth
- Mopping up persistent fires, including smouldering hotspots of large logs along the outer edge of the fire perimeter.

The rate of initial spread, acceleration and perimeter growth of a fire is highly variable and dependent on burning conditions, including topography, fuel and weather, particularly wind speed and direction (Cheney *et al*., 2012, Gould *et al*., 2007). In cyclone damaged forests, the understorey microclimate is both drier and windier, which may accelerate the rate of fire growth. Fresh large downed woody material may restrict the initial growth of fires and impede fire line access. In the years following a cyclone, the downed woody debris will become combustible and burn out slowly. This additional burning fuel can develop a convective centre behind the flame zone which will draw the local winds along the flanks and push the flames towards the burnt ground, thus restricting the lateral development of the fire and increasing the burn out time and intensity.

Impeded access onto the fire ground and increase fuel hazard in cyclone affected vegetation will limit the success of first attack. Figure 9 gives the likelihood of aerial suppression first attack success as a function of forest fire danger indices for the different cyclone damage classes. The success of aerial suppression at the 95th and 99th FFDI percentile will be 60 and 40 percent respectively in the cyclone damaged vegetation ratings of high and greater, if the first attack area is small (<0.5 ha). If the first attack is delayed and there is an increase in fire size, there is an unlikely chance (30% probability) of aerial suppression being successful in fires burning in high cyclone damaged fuel (Figure 9b). With large downed woody material impeding access onto the fire ground, it is critical that the first response in cyclone damaged vegetation is rapid and adequately resourced.

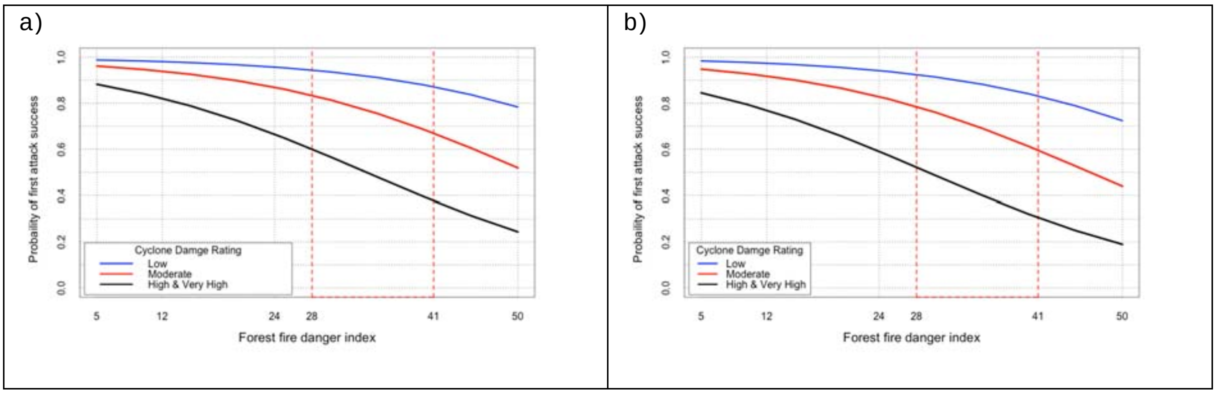

Figure 9. The effects on forest fire danger index (McArthur 1967) and the cyclone damage ratings on the predicted first attack success based on the assumption (a) 45 minutes to first aerial attack and fire is 0.5 ha on arrival; (b) 75 minutes to first aerial attack and fire is 1.0 ha on arrival. The vertical red dash at FFDI 28 and 41 are the 95th and 99th percentile of the FFDI for the central Queensland region between August and October.

CONCLUSION

Tropical cyclones are a significant natural disturbance to forest vegetation in north-eastern Australia, especially near the coast. Following cyclones, similar to Tropical Cyclone Marcia in central Queensland, defoliated, uprooted trees and snapped-off stems and branches are indicators of increased fuel load and hazard. This study developed reliable visual hazard scores to describe the cyclone damaged forest and characterise fuel hazard and fuel loading. The scores were used to determine the impact of cyclone damage on fire behaviour and suppression strategies.

Tropical cyclones lead to an increase in fuel hazard and loading which will increased the fire spread and fire line intensity by 1.5 to 2.5 times respectively and also result in impediments to suppression activities.

This supplementary field guide, along with the existing field fuel hazard guides, can be used for a variety of fire management applications.

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APPENDIX I: POST-TROPICAL CYCLONE FUEL ASSESSMENT FIELD SHEET

Area:	GPS-reference:	
Plot #:	Aspect:	Slope:
Vegetation Type:		Date: / /2015

Fuel Hazard Assessment/Destructive Sampling

Fuel Strata	Hazard score	Hazard Rating	Fuel height	Size Classes Oven Dry Weight (grams)		
				0-6 mm	6-10 mm	10-25 mm
Surface □ 0.25 x 0.25 m □ 0.5 x -0.5 m			mm			
Near-surface □ 0.5 x 0.5 m			cm			
Elevated □ 1 x 1 m			cm	0-6 dead	0-6 live	6-10 dead
Bark			m			

Forest damage assessment

Overall Visual Damage Assessment with 20 m radius of plot centre

Circle the appropriate damage category

Damage Score	Description
	Large trees: diameter 1.5 m above ground >5 cm *Small trees:* diameter 1.5 m above ground <5 cm
0	Intact: no obvious damage
1	*Large trees:* minor branch damage of <25% branch lost; *Small trees:* few trees (<10%) bent and unbroken,
2	*Large trees:* 25 – 50% branches lost, few trees (<10%) bent <45°, <10% of the trees trunk snapped off, no uprooted trees; *Small trees*: substantial part of the canopy is stripped off part of the small trees beneath other debris, 10–30% bent and unbroken
3	*Large trees:* 50–75% branches lost, >75% of the canopy leaves stripped off, 10–30 % of the trees trunk snapped off, <10% of the trees are uprooted; *Small trees:* >75% of the branches lost, no fine twigs and small branches present, >30% bent and/or snapped
4	*Large trees:* no visible signs of twigs and small branches <10 cm, scattered large branch material on the ground, 30–50% of trees trunk snapped off, 10–30% of the trees uprooted; *Small trees:* trunk snapped low to ground or 30–50% uprooted trees
5	*Large trees:* >30% of the trees are uprooted and flattened to ground; *Small trees*:>50% uprooted or snapped off

Individual Tree Damage Assessment

Prism Sweep BAF: 2M   Enter Score Damage to each "IN" tree

1		2		3		4		5		6		7		8		9		10	
11		12		13		14		15		16		17		18		19		20	
21		22		23		24		25		26		27		28		29		30	

Downed Woody Material Line Transect: 50 m

Size Classes	Number of pieces
0-6 mm (0-5m)[a]	
6-25 mm (0-10m)[a]	
25-75 mm (0-20m)[a]	
>75 mm (0-50m)[a]	Record diameter (cm)

a. distance along transect line

Photographs

Photo ID:	Description

Field Notes:

Sampling Team:

APPENDIX II: SELECTING TREES USING AN OPTICAL WEDGE PRISM

Individual trees on which to assess damage were selected using a 360 degree sweep with an optical wedge prism around a georeference sample point. A 2 M basal area factor prism (Husch *et al.* 1972) was used in the following way:

- Hold prism over the sample point at a comfortable distance from your eye, keeping the top edge of the prism parallel to the ground and the face of the prism at right angle to your line of sight.
- Closing one eye, sight through the prism to each tree at breast height (1.5 m above ground). If the tree trunk appears to overlap or just touches (Figure A2.1) the tree is selected for damage status classes listed in Table 2. If the trunk does not overlap the tree is not selected for assessment.

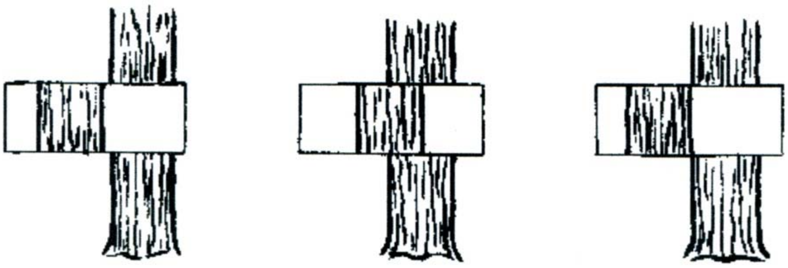

Figure A2.1. How to determine which tree to select for damage assessment from a optical wedge prism (i) left- trunk does not overlap, don't select, (ii) centre- trunk overlaps, select tree for assessment, and (iii) right- trunk borderline, select every other one

APPENDIX III: LINE TRANSECT INTERSECT PROCEDURES FOR DOWNED WOODY MATERIAL

Line transect intersect method is a point of intersection along a transect line of a given length but no width. The lines are often arranged in different orientation at a site to reduce potential for orientation bias and measurements are taken at the points of intersection. Therefore, a random orientation of the transect line will be quick to implement with the following field procedures.

1. At the sample point the assessor obtains the time second reading from a clock and multiplies by size to determine the orientation of the transect line in degrees (For example watch second reading of 24, multiply by 6 then transect line orientation will be 144 degrees). Set the compass at 144 degrees and lay out the 50 m tape on this bearing across the sample area from the plot centre.
2. Count and record the diameter of every piece of woody debris if the line transect crosses the central axis of the woody material:
    a. for straight piece of downed woody material (DWM) crosses once, the record the count or diameter at point of intersection
    b. for line transect that did not include the central axis, do not tally
    c. for a piece of woody debris crossed twice because it is branched, treat as two separate pieces, record the diameter at each point of intersection
    d. for a piece of woody debris crossed three times or more because it is crooked, record the diameter at each point of intersection (the transect line is shown as a dash line in Figure A3.1 below.

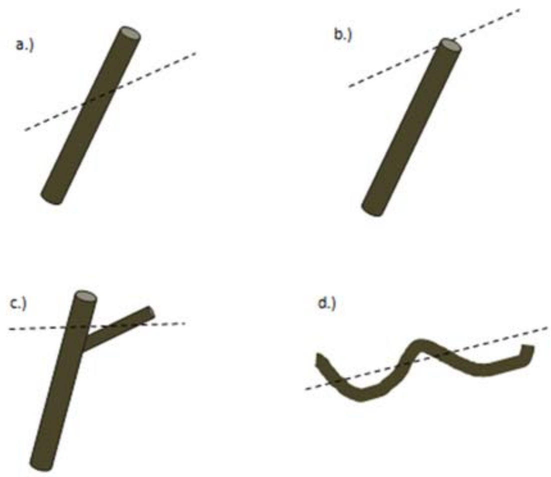

Figure A3.1. Example of the transect line intercept for different configuration of downed woody material (Gould *et al*. 2014)

3. The transect line will be divided into different distance intervals to record the different size classes of the woody material. Count the size classes <6mm, 6- 25 mm, and 25 – 75mm using the Go-No gauge calliper, then record the diameter of all the woody material >75 mm. The following distance interval to record the different size classes is illustrated in Figure A3.2:

a. Fine pieces (<6 mm) – count the number of pieces at each point of intersection between 0 and 5 metres
b. Small pieces (6–25 mm) – count the number of pieces at each point of intersection between 0 and 10 metres
c. Medium pieces (25–75 mm) – count the number of pieces at each point of intersection between 0 and 20 metres
d. Large wood (>75 mm) – record the diameter (cm) of piece at each point of intersection from 0 to 50 metres

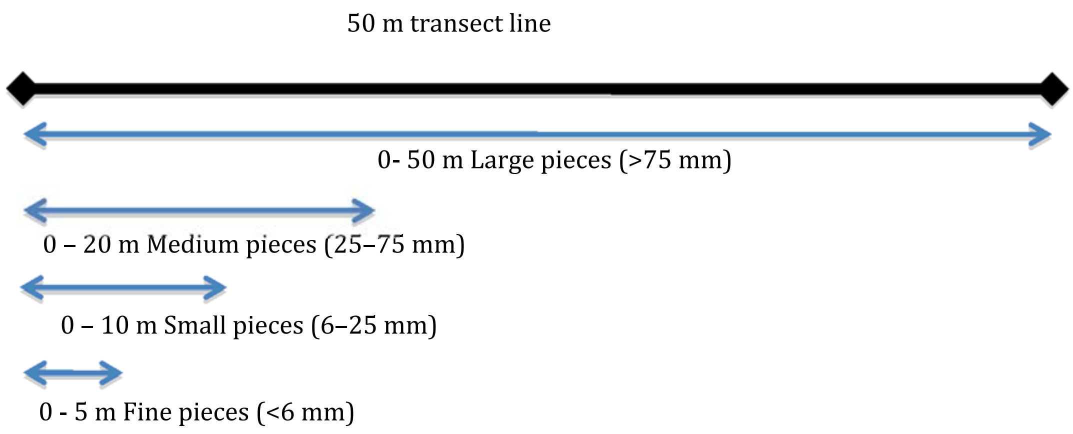

Figure A3.2. Example of a wood debris transect for sampling downed woody material in cyclone damaged vegetation using the line intersect technique

APPENDIX IV: SUPPLEMENTARY FIELD GUIDE

Supplementary field guide for assessing bushfire fuel hazard in tropical cyclone damaged forested vegetation

Photograph Examples	Cyclone Damage Score	Cyclone Damage Rating	Description *Large trees*: dbh >5 cm *Small trees (saplings)*: dbh <5 cm	Input values for fire models
	0	Nil	Intact – no obvious damage	
	1	Low	*Large trees:* minor branch damage of <25% branch lost; *Small trees*- few trees (<10%) bent and unbroken	Surface fuel hazard rating: High (3) Near-surface fuel hazard rating: High (2.5) Overall fuel hazard rating: Moderate Near-surface fuel height (cm): 25 Elevated fuel height (cm): 100 Total fine fuel load (<6mm) (t/ha): 15 Down woody material (>25 mm) (t/ha): 15
	2	Moderate	*Large trees:* 25–50% branches lost, few trees (<10%) bent <45°, <10% of the trees trunk snapped off, no uprooted tree; *Small trees:* substantial part of the canopy is stripped off part of the small trees beneath other debris, 10–30% bent and unbroken	Surface fuel hazard rating: High (3) Near-surface fuel hazard rating: High (3) Overall fuel hazard rating: High Near-surface fuel height (cm): 30 Elevated fuel height (cm): 100 Total fine fuel load (<6mm) (t/ha): 17.5 Down woody material (>25 mm) (t/ha): 25

	3	High	*Large trees:* 50–75% branches lost, >75% of the canopy leaves stripped off, 10–30 % of the trees trunk snapped off, <10% of the tree are uprooted; *Small trees:* >75% of the branches lost, no fine twigs and small branches present, >30% bent and/or snapped	Surface fuel hazard rating: Very High (3.5) Near-surface fuel hazard rating: Very High (3.5) Overall fuel hazard rating: Very High Near-surface fuel height (cm): 30 Elevated fuel height (cm): 120 Total fine fuel load (<6mm) (t/ha): 20 Down woody material (>25 mm) (t/ha): 40
	4	Very High	*Large trees:* no visible signs of twigs and small branches <10 cm, scattered large branch material on the ground, 30–50% of trees trunk snapped off, 10–30% of the trees uprooted; *Small trees:* trunk snapped off low to ground or 30-50% uprooted trees	Surface fuel hazard rating: Extreme (4) Near-surface fuel hazard rating: Extreme (4) Overall fuel hazard rating: Very High Near-surface fuel height (cm): 35 Elevated fuel height (cm): 120 Total fine fuel load (<6 mm) (t/ha): 25 Down woody material (>25 mm) (t/ha): 50
	5	Extreme	*Large trees:* >30% of the trees are uprooted and flattened to ground; *Small trees:* >50% uprooted or snapped off	Surface fuel hazard rating: Extreme (4) Near-surface fuel hazard rating: Extreme (4) Overall fuel hazard rating: Very High Near-surface fuel height (cm): 35 Elevated fuel height (cm): 120 Total fine fuel load (<6mm) (t/ha): 25 Down woody material (>25 mm) (t/ha): 80

dbh; diameter at breast height (i.e. 1.5 m above ground)