Impacts of an extreme cyclone event on landscape-scale savanna fire, productivity and greenhouse gas emissions

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Abstract

North Australian tropical savanna accounts for 12\% of the world’s total savanna land cover. Accordingly, understanding processes that govern carbon, water and energy exchange within this biome is critical to global carbon and water budgeting. Climate and disturbances drive ecosystem carbon dynamics. Savanna ecosystems of the coastal and sub-coastal of north Australia experience a unique combination of climatic extremes and are in a state of near constant disturbance from fire events (1 in 3 years), storms resulting in windthrow (1 in 5–10 years) and mega-cyclones (1 in 500–1000 years). Critically, these disturbances occur over large areas creating a spatial and temporal mosaic of carbon sources and sinks. We quantify the impact on gross primary productivity (GPP) and fire occurrence from a tropical mega-cyclone, tropical Cyclone Monica (TC Monica), which affected 10 400 km\textsuperscript{2} of savanna across north Australia, resulting in the mortality and severe structural damage to \sim 140 million trees. We estimate a net carbon equivalent emission of 43 Tg of CO\textsubscript{2}-e using the moderate resolution imaging spectroradiometer (MODIS) GPP (MOD17A2) to quantify spatial and temporal patterns pre- and post-TC Monica. GPP was suppressed for four years after the event, equivalent to a loss of GPP of 0.5 Tg C over this period. On-ground fuel loads were estimated to potentially release 51.2 Mt CO\textsubscript{2}-e, equivalent to \sim 10\% of Australia’s accountable greenhouse gas emissions. We present a simple carbon balance to examine the relative importance of frequency versus impact for a number of key disturbance processes such as fire, termite consumption and intense but infrequent mega-cyclones. Our estimates suggested that fire and termite consumption had a larger impact on Net Biome Productivity than infrequent mega-cyclones. We demonstrate the importance of understanding how climate variability and disturbance impacts savanna dynamics in the context of the increasing interest in using savanna landscapes for enhanced carbon sinks in emission offset schemes.

Keywords: Cyclone Monica, MODIS, GPP, disturbance, fire, termites
1. Introduction

The impacts of climate change on ecosystem processes will arise from shifts in long term mean conditions as well as from expected increases in the variance (Scheffer et al 2001, Yi et al 2010). Disturbance is a fundamental driver of ecosystem dynamics, influencing ecosystem structure, species composition, biogeochemical cycling and productivity, regeneration as well as adaptation and natural selection (White 1979). A disturbance regime can be defined by the frequency, intensity and spatial extent of disturbance processes. Critically, extreme events may have profound influence on ecosystem structure and function yet these processes are often poorly captured or ignored by ecosystem models (Jentsch et al 2007).

Storms and cyclones (hurricanes) are important components of the natural disturbance regime of tropical ecosystems (Laurance and Curran 2008) and their ecological significance has long been recognized (Webb 1958) Forest productivity and carbon storage is severely affected following extreme cyclonic damage. For example, Hurricane Katrina killed or damaged an estimated 320 million trees in the south-eastern United States and is estimated to have released ∼0.1 Pg of carbon to the atmosphere, equivalent to the total annual terrestrial carbon sink of the all US forests (Chambers et al 2007). Previous work on cyclonic impacts on vegetation has focused on tropical forests, in particular rainforests, with less attention paid to the second largest tropical ecosystem, the tropical savanna (Franklin et al 2010).

The defining feature of savanna is the co-existence of trees and grasses (Hutley and Setterfield 2008) and disturbance plays a key role in maintaining a competitive balance between these two life-forms (Sankaran et al 2004, Van Langevelde et al 2003). Ecological models suggest that high levels of disturbance (typically fire) result in demographic bottlenecks that constrains recruitment and/or growth of woody components (Werner and Prior 2013) and as a consequence, grasses are able to persist or even dominate (House et al 2003a). With fire suppression, savanna may trend towards forest, although attaining complete canopy closure may be limited by other factors such as rainfall, soil quality or herbivory (Cook et al 2002, Murphy and Bowman 2012).

In north Australia, work has recently focused on understanding the drivers of carbon fluxes, productivity, greenhouse gas emissions and fire (Beringer et al 2011, Beringer et al 2007, Chen et al 2003, Cook et al 2005, Eamus et al 2001, Hutley et al 2005, Kanniah et al 2013, Liedloff and Cook 2011, Meyer et al 2012, Murphy et al 2010, Russell-Smith et al 2009a, Williams et al 1999, 2004). However, impact of cyclones and storms on has had less attention to date (Bowman and Panton 1994, Cook and Goyens 2008, Franklin et al 2010, Staben and Evans 2008, Williams and Douglas 1995), despite north Australia being the only major savanna biome in the world subjected to tropical cyclones. The occurrence of a number of large cyclones has had major ecological and economic impact on north Australia over the last two decades (Turton 2008). In this study, we focus on an extreme event, namely severe TC Monica, one of the largest cyclone systems ever monitored in the southern hemisphere, which cut a swath of damage across a large area of tropical savanna in northern Australia, crossing the coastline on 6 April 2006.

In this study, we quantify the impacts of a mega-cyclone event, TC Monica using a combination of data from previously published, ground based vegetation surveys post-cyclone and remote sensing of fire and MODIS GPP pre- and post-cyclone. Impacts were quantified by: (1) developing spatial maps describing the area and distribution of tree damage; (2) assessing the tree ‘isodamage’ map to quantify changes in fire occurrence and fire radiative power (FRP) pre- and post-cyclone; (3) examining spatial and temporal changes in GPP pre- and post-cyclone and (4) estimating the potential greenhouse gas emissions arising from the significant increase in fuel load post-cyclone. The analysis of a typical mega-cyclonic events, together with an understanding of their return time, allows for a long term estimate of the impact of disturbance on savanna carbon balance, the net biome productivity (NBP). We then compare this with impacts from frequent but far less severe disturbance agents, fire and termite herbivory. Firstly, how significant are these severe, extensive but infrequent events relative to these more frequent disturbance processes? Secondly, what shifts to the disturbance regime may arise from climate change and how might these changes influence savanna structure?

2. Methods

2.1. TC Monica study area

TC Monica was an intense cyclone that developed in the Coral Sea on the 16 April and tracked across north Queensland and the Northern Territory (NT) (www.bom.gov.au/cyclone/history/monica.shtml, figure 1). It was a category five system (gusts over open flat land of more than 280 km h$^{-1}$, as defined by the Australian Bureau of Meteorology) when it crossed the NT coastline, with maximum wind gusts (3 s gust speeds) of 350–360 km h$^{-1}$ just prior to landfall (Cook and Goyens 2008, NASA 2006). The cyclone crossed the coast at ∼1830 h local time, 24 April 2006, at Junction Bay, NT (11°52′45″S, 133°51′34″E), 35 km west of the small town of Maningrida. The system moved in a south westerly track at ∼15 km h$^{-1}$ towards the Jabiru NT, covering a distance of 140 km over a period of 9 h. By the time TC Monica reached Jabiru, the system had weakened with maximal gusts of 135 km h$^{-1}$ (Staben and Evans 2008). Using a combination of on-ground meteorology from the Maningrida and Jabiru Bureau of Meteorology climate stations and satellite imagery, Cook and Goyens (2008) used a logistic decay function to estimate the decline in maximum gust speeds along the cyclone path through points B and C of figure 1. Given the size and intensity of the cyclone (minimum sea level pressure at peak intensity ranged from 900 to 920 hPa, Durden 2010), it is estimated that an event of this size and intensity has a recurrence interval of between one in 500–1000 years, based on analysis of wind risk of the Northern Territory coastline of Cook and Nicholls (2009).
The impacted area is open-canopied tropical savanna woodland, with an overstorey dominated by *Eucalyptus* and *Corymbia* tree species and an understorey of C4 grasses, saplings and shrub species (Fox et al 2001). Vegetation assemblages of the impacted area include those dominated by *C. dichromophloia, E. miniata, E. tetrodonta*, with common grasses including *Triodia bitextura* and *Sorghum spp*. Other co-dominant tree species of the region include *C. foelscheana* and *C. latifolia*. Coastal mangroves occur near TC Monica’s crossing point as do wetlands (Beringer et al 2013) and associated *Melaleuca* swamp forests. The long term mean annual rainfall of the impacted area ranges from 1300 to 1580 mm (Bureau of Meteorology, Maningrida, Oenpelli and Jabiru stations), although rainfall during the study period (2001–2013) was ~150 mm above this average (figure 2).

### 2.2. Assessment of tree damage

Tree damage surveys were undertaken across the impacted area by Cook and Goyens (2008) to estimate the proportion of damaged trees (uprooted or snapped at the trunk) and the extent of defoliation. Transects were established perpendicular to the cyclone’s path at 5, 51 and 134 km from the coastal crossing point (figure 1) and both aerial surveys and on-ground belt transects (50 m × 10 m) were used to map the fraction of tree damage. In this study, these surveys and relationships between wind speed and tree damage have been extrapolated spatially to produce tree damage polygons to map damage with distance from the cyclone’s path as well as distance inland. For each polygon, the mass of tree carbon knocked down by the cyclone was calculated by multiplying tree biomass by polygon areas and fraction of damaged trees.

### 2.3. Greenhouse gas emissions

Emissions of greenhouse gases (GHG) from the resultant woody debris (fuel) following the cyclone were estimated by assuming that the dead wood was burnt over time, with fluxes of CO$_2$, CH$_4$ and N$_2$O being emitted according to the emission factors for fuel types typical of these savannas as presented by Meyer et al (2012). Savanna woodlands dominate the impacted area (Fox et al 2001) with an aboveground biomass of ~40 t ha$^{-1}$, a typical biomass for stands at this rainfall occurring on sands and sandy-loam soils.
(Cook et al. 2005, Hutley and Beringer 2011). We applied this estimate across the study area and when scaled by the fractional tree damage for each polygon, provided an estimate of the biomass on the ground or as dead standing tree stems. The overall fire frequency of the impacted area was 0.38 fires yr$^{-1}$, of which 29% were late dry season fires (LDS, August to December). We used data on burning efficiencies, fire patchiness and GHG emission factors from both coarse woody debris (CWD) and fine fuels (grasses, leaves, twigs) using Russell-Smith et al. (2009a, 2009b) and Meyer et al. (2012) to estimate the total GHG emission across the impacted area. This estimate assumes consumption was dominated by fire, with limited decomposition or consumption of the coarse woody debris by termites.

2.4. Remote sensing of productivity and fire

MODIS GPP and FRP products were used to assess the impact of the cyclone on productivity and fire severity and occurrence for 6 years pre- and 6 years post-cyclone. For pixels within each tree damage polygon, eight-day composite MODIS GPP estimates at 1 km resolution (MOD17A2) were used from January 2001 to June 2013. Both the raw data time series as well as a seasonal trend filtering algorithm were constructed for all polygons. The seasonal trend algorithm used a loess function (seasonal trend decomposition, STL, based on the Loess function) as described by Cleveland et al. (1990). This technique provides a loess smoothed trend by calculating and extracting a seasonal cycle and high frequency variability and subtracting these components from the raw signal. Time series data is decomposed into trend, seasonal and remainder components and provides seasonal adjustment to reveal significant underlying trends and is widely used in remote sensing time series (Evans and Lyons 2013, Evans et al. 2013). This provides a more reliable comparison of values at different points in time, rather than using the raw data alone. The tree damage polygons extend across the impact area and span a 300 mm rainfall range, an environmental gradient that produces spatial and temporal variability in GPP (Kanniah et al. 2010, 2013). To control for this variability in GPP, an anomaly time series for all polygons was constructed. GPP anomalies were calculated by subtracting the mean GPP for the entire period of available data (January 2001–June 2013) from each eight-day pixel value across the impact area. This approach provided raw data, seasonally detrended plus an anomaly time series to assess productivity prior to and after the cyclone. Previous work by Kanniah et al. (2009) has shown an excellent agreement between flux tower based GPP and MODIS GPP Collection 5.

The MODIS thermal anomalies products (MOD14 and MYD14, Giglio et al. 2009) were used to assess the number of fire events (hotspots) and to estimate the fire radiative power (FRP) of all significant fire events (>100 m$^2$) across the impact area. FRP is correlated with fuel consumption (Wooster et al. 2005) and Maier et al. (2013) has shown that this method can detect fires across north Australian savannas with an active flaming area of between 100 and 300 m$^2$. The annual mean FRP for each pixel within a damage polygon was calculated as was the annual number of fire detections for each year for each polygon. Total radiative energy emitted (fire radiative energy, FRE) from each polygon was calculated by multiplying the number of detections by mean FRP for each year (2003–2012). The influence of the cyclone on fire frequency was assessed using 250 m manual burnt area mapping available from the North Australia Fire Information web site (NAFI, www.firenorth.org.au/nafi2, Russell-Smith et al. 2009b). Annual totals of burnt and unburnt pixels were collated for all polygons for the pre- (2000–2005) and post-cyclone periods (2007–2012) giving fire frequency for each 6 year period for each polygon.

3. Results

3.1. Impact area

The isodamage map (figure 3) was derived from wind field analysis and tree damage surveys and consists of 17 tree damage polygons distributed in 5% brackets from 1–5%, 5–10%, to >85% tree damage. The cyclone impacted an area of 10 400 km$^2$ and tree damage extended approximately 60–70 km north and south of the crossing point at Junction Bay and ~200 km inland (figure 3). Damage was most severe in the vicinity of Junction Bay where >85% of all trees were damaged (snapped or uprooted and defoliated), an area of some 139 km$^2$ (see picture insets, figure 3). Damage was greatest east of the cyclone path (figure 3) reflecting the additional effect of the forward motion of the cyclone to winds on the east, and the reduction of that forward speed from winds on the west. At the Jabiru township, ~160 km inland, tree damage had reduced to ~20–30%. Of the total impact area, less than 10% experienced extreme tree damage (>70% damage) and the bulk of the impact area (50%) experienced 30% less tree damage (figure 4).

3.2. Fire

The annual time series of FRP for four representative tree damage polygons is given in figure 5(a). The four polygons plotted represent low impact (tree damage polygon 1–5%), moderate impact (30–35%), high impact (60–65%) and extreme (85%). A two-way ANOVA suggested mean FRP was not significantly different between years or damage classes and no influence of the cyclone was evident across these damage polygons. The total number of hotspot detections for the same four polygons for each year showed a significant spike in hotspot detections for 2006, the year of the cyclone (figure 5(b)). Also plotted are counts across all polygons. Two-way ANOVA using transformed count data (square root transform) indicated 2006 was significantly different to all other years for all damage polygons plotted (Scheffe post-hoc tests, df = 170, P < 0.001), except for the >85% class.

Histograms of annual burnt pixel counts for pre- and post-cyclone periods for the same damage polygons (1–5%, 30–35%, 60–65% and >85%, figure 6) show that the most common fire frequency was 3 out of 6 years, with a shift in fire frequency evident in the 60–65% and >80% tree damage
3.3. Gross primary productivity

Mean MODIS derived GPP over the 12 year period for the entire impact area was $20.0 \pm 2.83 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ with considerable spatial variation evident, and GPP ranged from 9.2 (60–65% damage polygon) to 40.7 Mg C ha$^{-1}$ yr$^{-1}$ (>85% polygon). The time series of the eight-day mean MODIS GPP ($\text{g C m}^{-2} \text{ ha}^{-1}$) and the STL trend line for the same four representative polygons showed strong seasonal variation in GPP, with a seasonal range of up to $5 \text{ g C m}^{-2} \text{ d}^{-1}$ from the wet season maxima (December to March) compared to dry season minima (August, September, figure 7). The more coastally distributed >85% damage polygon had the highest GPP and the most damped seasonal range and was less than $2 \text{ g C m}^{-2} \text{ d}^{-1}$. The seasonally corrected GPP trend line showed a sharp reduction in GPP during the year of the cyclone (2006) and the lowest GPP was recorded in this year, with the minima occurring in the late dry season for all polygons (August, September 2006, figure 7). The largest relative decline in GPP was in the 60–65% damage polygon, which declined 20.1% relative to the pre-cyclone mean GPP (using detrended time series). The smallest decline occurred in the 1–5% polygon (3.5%).

To better account for the spatial and temporal variability inherent across the impact area, a GPP time series anomaly was constructed for pre- and post-cyclone periods. The annual sums of the GPP anomaly ($\text{g C m}^{-2} \text{ yr}^{-1}$) for each polygon provides a measure of GPP over time relative to the 12 year mean (figure 8). Cyclonic impact was evident via 4 years of the negative annual anomaly (2006–2009) for the four damage polygons shown. The mean GPP anomaly during this post-cyclone period was $-5.6$, $-8.8$, $-10.1$ and $-7.0 \text{ g C m}^{-2} \text{ yr}^{-1}$ for the 1–5%, 30–35%, 60–65% and >85% polygons respectively. GPP anomalies pre-cyclone (2001–2005) for these polygons were closer to zero at $-0.7$, 1.9, 2.9 and $-1.8 \text{ g C m}^{-2} \text{ yr}^{-1}$ respectively. From 2010 onwards, there was a return to pre-cyclone levels, with a large positive anomaly in 2010, a record wet season (figure 2).
Figure 5. Time series of (a) mean annual FRP using the MOD14 data and (b) annual number of hotspot detections for selected tree damage polygons. Error bars are standard deviations of mean FRP calculated from the population of pixels within each polygon. Total annual fire radiative energy (FRE) was calculated for entire the impact area was calculated from mean FRP multiplied by the number of hotspot detections for each polygon.

Table 1. Potential emissions of greenhouse gases estimated from coarse and fine fuel loads resulting from damage following Cyclone Monica. The potential GHG emissions from woody debris knocked down by TC Monica is given assuming all emissions comprised CO₂, or that the wood was burnt, with the amounts of CO₂, CH₄ and N₂O released calculated according to emission factors of Meyer et al (2012) which are derived for fuel types typical of north Australian savanna.

| Species emitted | CO₂ only (Mt CO₂-e) | Combustion emissions (Mt CO₂-e) |
|-----------------|--------------------|---------------------------------|
| CO₂             | 48.4               | 47.9                            |
| CH₄             | 3.7                |                                 |
| N₂O             | 0.2                |                                 |
| Total           | 51.8               |                                 |

3.4. Greenhouse gas emissions

The potential emissions of GHG from the resultant coarse woody debris and fine fuel load were estimated by assuming all carbon was either emitted as CO₂, or that the dead wood was burnt, with the emissions of CO₂, CH₄ and N₂O being emitted according to the emission factors presented by Meyer et al (2012). Total damaged (trees uprooted or with snapped boles) biomass was ~12.7 Tg, a potential GHG emissions (CO₂, CH₄ and N₂O) of 51.8 Tg CO₂-e, with CO₂ dominating the non-CO₂ gas emissions (table 1).

Table 2. National greenhouse gas inventory for 2011 for Australia, the Northern Territory and potential emissions from Cyclone Monica.

| National GHG emissions | Mt CO₂-e |
|------------------------|---------|
| Australia—total        | 542.7   |
| Australia—agriculture  | 86.5    |
| Northern Territory—total| 29.3   |
| Northern Territory—agriculture | 6.9 |
| Potential emission—cyclone Monica | 51.8 |
| Loss of productivity (GPP) | 2.1 |

4. Discussion

Understanding tropical savannas as intrinsically unstable ecosystems maintained by disturbances such as fire and grazing, or stable systems that persist despite these disturbances, is critical to their management worldwide (Lehmann et al 2011). Northern Australia is one of the few parts of the world where cyclones regularly affect tropical savanna vegetation and Cyclone Monica was one of the most intense cyclones ever recorded in the southern hemisphere (Cook and Nicholls 2009, 2012). This extreme climatic event is likely to have a return interval of between 500 and a 1000 years, however cyclones of lesser intensity are far more common across north Australia and impact vegetation within 100 km of the coastline. Cook and Goyens (2008) list 15 cyclone events that impacted north-western NT and reported
Figure 6. Fire frequency as measured using MODIS 250 m burnt pixel counts within damage polygons for 6 years prior (2000–2005) and 6 years (2007–2012) after the cyclone for representative damage polygons (a) 1–5%, (b) 30–35%, (c) 60–65%, and (d) >80% (combined 80–85% and >85% counts). In these plots, a fire frequency of 6 is equivalent to the number of pixels within a polygon that burnt every year of the 6 year periods and a zero frequency class indicates the number of pixels that were unburnt.

significant tree damage over a 180 year period, approximately one event per decade. However, there are no records for an event of this magnitude in terms of area and tree damage, as up to 140 million trees were damaged or destroyed across a 10 400 km$^2$ area. In areas of maximal wind speeds, almost total tree destruction resulted as the photographs of figure 3 illustrate.

4.1. Impact on fire regime

Debris from the cyclone would have resulted in a significant increase in fuel load in the moderate to high damage areas. Defoliated leaves from tree and shrub canopies, plus branch, twig and bark fragments would input of between 5 and 10 t ha$^{-1}$ biomass (based on branch allometry of Chen et al 2003). This input would add to the 2–3 Mg of grassy fuel loads typically found in these savannas (Russell-Smith et al 2009a). Uprooted and snapped tree boles and large branches would add a further 20–30 Mg biomass ha$^{-1}$ in high damage areas, fuel loads typical of temperate Australian forests that are subjected to infrequent but high severity fires (Gill 2012).

The cyclone occurred at the beginning of the dry season, enabling curing over the subsequent months. Despite this potentially massive increase in fuel load (see inset image, 85% polygon area, figure 3), the impact of the cyclone on fire occurrence across the impact area as detected from MODIS hotspot detections and 250 m burnt area mapping was less than anticipated. There was no significant change in mean FRP observed pre- and post-cyclone, although there was a significant increase in the number of fire events, but this effect persisted only for the dry season after the cyclone.

Fuel mass in high impact polygons would have been dominated by coarse woody debris with fine fuels dominating moderate to low impact polygons (leaves, twigs, grass fuel). Fires would likely consume the large mass of fine fuels (grass, leaves, twigs), driving the widespread occurrence of fires (figure 5(b)) in 2006, but once the initial pulse of fine fuels were consumed, the number of fire events return to typical pre-cyclone levels. Fires in these savannas are mainly from anthropogenic ignition sources, and occur in four years out of ten. Consequently, the extensive fires are of relatively low intensity (Russell-Smith and Yates 2007) and it is possible that the MODIS hotspot detection and FRP algorithms are able to capture the grass fires (Maier et al 2013), but are
Figure 7. Time series of MODIS GPP (MOD17A2) and STL trend line for (a) 1–5%, (b) 30–35%, (c) 60–65% and (d) >85% tree damage polygons. GPP data are eight-day means and standard errors. The day of Cyclone Monica’s coastal crossing is marked by the vertical line on each panel.

Figure 8. Time series of annual MODIS GPP (MOD17A2) anomalies for the 1–5%, 30–35%, 60–65% and >85% tree damage polygons. Annual GPP anomaly was calculated by summing eight-day anomalies for each pixel across the impact area. See section 2 for further details. Error bars are standard errors. The post-cyclone period (2006 onwards) is indicated by heavy line.
less able to capture the slower burning and smouldering of the coarse fuels that would dominate the fuel loads in high damage areas. Fast moving, low intensity grass fires may not provide the required energy to ignite large tree boles and it may take several years or decades for this coarse fuel to be consumed.

Fire frequency as estimated via burnt pixel counts did suggest that in high damage areas there was an increase in fire frequency (figure 6), however the area of these polygons was low and across the entire impact area, frequency was not significantly altered. Reduction in woody cover in these high impact areas would be offset by enhanced grass growth and fuel production, maintaining similar levels of radiative emissions from resultant fires. Another factor that may have influenced observed FRP and/or frequency post-cyclone was the implementation of the Western Arnhemland Fire Abatement Scheme (WALFA) across an area of some 26,000 km² that since 2005, has been subjected to an attempt to implement a landscape-scale early dry season fire regime to reduce GHG emissions (Russell-Smith et al. 2009a, 2009b).

The WALFA area is located to the west of the cyclone impact area and there is some overlap of these two areas, although this occurs in low to moderate cyclone impact areas.

The large mass of fuel resulting from biomass destruction would eventually be consumed via fire and/or the action of decomposition and termite consumption, releasing GHG (table 1). Given the fire frequency of 0.38 yr⁻¹, 3 or more fires are likely to occur per decade across the area, and it is likely that most of this wood would be burnt within one to two decades. A cyclone emission of 51.2 Mt CO₂ is equivalent to 10% of Australia's annual accountable GHG emissions (table 2), although the duration of emission is hard to estimate and return site visits are required quantify changes in fuel composition and vegetation recovery over time.

4.2. Tree damage and recovery

The recovery of eucalypt savannas after severe storm damage is only now beginning to be understood, in contrast to their response to fire (Franklin et al. 2010). The dominant savanna Eucalyptus and Corymbia trees of this region do not maintain a seed store and regeneration from seed bank is limited (Setterfield and Williams 1996). These species are tolerant of frequent fire due to their bark thickness, resprouting ability with well-protected epicormic bud structures and rapid vertical growth during the limited fire-free growing seasons (Burrows 2013, Lawes et al. 2011). Both juvenile and mature trees are able to basally and/or epicormically resprout, with the most common tree species in the impact area, E. tetrodonta, able to sucker from roots (Burrows 2013).

Franklin et al. (2010) observed vigorous resprout rates in trees damaged by a small but intense tornado in southern Kakadu National Park, in similar landscapes to the impact area of this study. They found resprout rates of 60% for uprooted as well as tree with snapped boles. Large trees with snapped boles tended to basally resprout, whereas uprooted trees with some of the root system intact were able to regenerate via epicormic resprouts. Tree mortality close to tornado's path was higher and trees were subjected to twisting due to high wind speeds as well as turbulence and they may have experienced catastrophic internal damage to vascular systems (Franklin et al. 2010).

Staben and Evans (2008) used remote sensing to examine the loss and subsequent return of tree canopy cover following Cyclone Monica in the vicinity of Jabiru area. This area was approximately 180 km inland from the crossing point (figure 3) where winds had reduced to a category 2 system (135 km h⁻¹). Loss of canopy cover in three sub-catchments was assessed using high resolution satellite imagery and ranged from 23% to 42%. The canopy cover across the three sub-catchments was re-assessed one year after the cyclone and cover had increased between 8 and 19% from post-cyclone levels.

Hutley and Beringer (2011) examined cyclonic disturbance history in meiac savanna site within 50 km of the coast in the vicinity of Darwin, NT. Tree age and size class distribution was constructed based on tree diameter at breast height (DBH) and two recruitment events closely matched the time since the two most significant cyclones to impact this Darwin region over the last 100 years, namely Cyclone Tracy (35 years prior to measurement) and The Great Hurricane (111 years prior to measurement). This suggests that while damage to the woody components can be significant, recovery within several decades is possible and savanna vegetation is persistent, although the impact on savanna woody size class distribution and carbon sink can last for decades to centuries (Hutley and Beringer 2011).

4.3. Impact on GPP

GPP was impacted by the cyclone, with a reduction in GPP that persisted for up to four years in moderate to high damage polygons, due to the loss in woody cover, which would reduce both wet and dry season GPP. In these savannas, the tree canopy is dominated by evergreen species (Williams et al. 1997) and while LAI is reduced in the dry season, carbon uptake is maintained over the dry season (Beringer et al. 2007, Kanniah et al. 2011, Whitley et al. 2011). This loss in tree derived GPP was estimated at ~0.5 Tg C averaged across the impact area as a result of the cyclone. After four years, GPP returned to pre-cyclone rates across moderate to high damage polygons, presumable due to canopy recovery as observed by Staben and Evans (2008). GPP also recovered in high damage polygons (80%, >85%), although the composition of the canopy may consist of woody saplings and basal resprouts, shrubs and competing grasses with few mature trees surviving. Grass dominance and woody suppression in the high damage polygons would result in significant declines in dry season GPP, and this is not evident in the seasonal GPP trend lines (figure 7). This suggest some form of woody re-growth has occurred and the resprouting trait evident in savanna Eucalyptus and Corymbia trees that are an adaptation to frequent fire, also provides a recovery mechanism for windthrow, as concluded by Franklin et al (2010).

Assessing the importance of extreme weather events to ecological processes is difficult, as their impacts are...
disproportionate to their short duration (Jentsch et al. 2007). Studies of net ecosystem production (NEP, equivalent to GPP less ecosystem respiration) are typically quantified over short to medium time frames with measures of carbon fluxes made over 2–10 years, during which time extreme events are unlikely to be captured. A more useful measure of long term ecosystem source/sink dynamics is the net biome production (NBP), which is defined as NEP less carbon loss from extreme events or disturbance processes (House et al. 2003b, Schulze et al. 2000). NBP is a difficult term to quantify given uncertainty in return time for disturbance processes, but using this and other studies, it is possible to estimate the relative importance of disturbance agents particular to these savanna ecosystems, namely termite consumption of GPP, loss of GPP due to the frequent fire regime and loss due to infrequent but extreme climate events such as TC Monica.

4.4. Relative importance of disturbance agents

A simple savanna carbon balance can be constructed to assess the indicative importance of these loss processes along with their uncertainties (figure 9). Typical rates of savanna GPP are required, as are consumption or loss rates via termites, fires and cyclones, plus the return interval of these events. MODIS GPP as estimated across the impact area is consistent with tower based (Beringer et al. 2007) and inventory based (Chen et al. 2003) estimates of GPP, and is between 15 and 20 Mg C ha$^{-1}$. Beringer et al. (2007) provided typical rates of direct biomass consumption and indirect losses (loss of carbon via canopy scorching and leaf death) from fire. The magnitudes of losses are dependent on fire intensity and therefore subject to significant interannual variability. Over a 5 year period, Beringer et al. (2007) estimated direct losses from coarse and fine fuel consumption at 2.3 t C ha$^{-1}$ yr$^{-1}$ (uncertainties ± 30%) and ‘indirect’ losses as 0.7 t C ha$^{-1}$ yr$^{-1}$ (combined uncertainties ± 90%). These losses account for 15% of annual GPP over this 5 year window, with average uncertainties of ± 30% (figure 9). Within the impact area, the fire frequency is 0.38 yr$^{-1}$ and these fire losses are estimated to occur every second fire season, but are variable (±30%).

The loss of GPP from termites is a continual process and this is rather certain. However, the rate of GHG emissions is highly uncertain, due to variability between rate estimates and the difficulty in scaling from stand based measures to landscape scales. Using publishes rates of termite derived GHG emissions, we estimate the losses compared to annual GPP as 0.3% (Jamali et al. 2013), 1.3% (Sanderson 1996) to 3.0% (Cook et al. 2005). We took the loss as the average of these at 1.5%. Uncertainties also arise due to the lack of good termite biomass estimates on an area basis (±100%) and their rates of production (±100%, figure 9).

GPP losses from cyclones will be highly variable in space and time. Lower category cyclones occur far more frequently in this region than the mega-cyclone studied here, but produce less damage and over smaller areas and in this exercise, we only consider the largest cyclone category. TC Monica resulted in an emission of 51.2 Mt CO$_2$-e, which over a 5 year window is 2.9 times greater than annual GPP (figure 9). Uncertainties are high around this value (±250%) due to variability in the exact intensity of events over large impact areas. The return time of such events is assumed to be 500 years as estimated by Cook and Nicholls (2009) for the northern coastline, although this also has a large uncertainty (±200 years or ±90%). Integration of these rate processes over a 500 year time window (to account for the frequency of all disturbance agents, figure 9, inset) suggests cyclones dominates the potential for GPP consumption on an annual basis, but when integrated over the return interval (500 years), fire accounts for 63% of all GPP consumption, with termites 35% and extreme cyclones only 2%.

In conclusion, this study has examined the impacts of an extreme cyclonic event, with impacts observed at a landscape...
scale. Potential emissions of greenhouse gases are equivalent to 10% of national annual GHG emissions. Significant inputs of coarse fuels did not dramatically shift the fire regime, although there was evidence for a shift to more frequent fires in highly damaged areas. Fire radiative power was little changed across the region and fire is likely to be still dominated by the ignition and consumption of fine fuels as opposed to rapid consumption of coarse fuels following the cyclone. There is uncertainty relating to the effectiveness of satellite derived hotspot recognition of the slower combustion of coarse woody debris. This fuel type may smoulder for days or a week after the rapidly moving fire front has passed, which predominantly burns fine fuels. Nevertheless, the importance of fire was emphasized, with long term impacts on savanna carbon balance likely to be dominated by fire and termitine consumption rather than infrequent extreme mega-cyclones. At present, it is uncertain if the frequency and magnitude of mega-cyclones such as TC Monica will increase in the future (Kuleshov et al. 2010), but if climate change does reduce the return interval, the significance of such events will increase. The loss of GPP was significant and any land management activities aimed at modifying fire regimes to enhance savanna sequestration (Grace et al. 2008) would be significantly impacted by such an event. Fire regimes are also expected to change under climate change (Harris et al. 2010). Tracking the recovery of highly damaged areas to monitor the rate of fuel consumption and the rate of return of woody components is required to better understand the cyclone disturbance pathway and its impact on savanna structure and function.

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