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Fire impacts on surface heat, moisture and carbon fluxes from a tropical savanna in northern Australia

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Abstract. Savannas form a large fraction of the total tropical vegetation and are extremely fire prone. We measured radiative, energy and carbon exchanges over unburned and burned (both before and after low and moderate intensity fires) open forest savanna at Howard Springs, Darwin, Australia. Fire affected the radiative balance immediately following fire through the consumption of the grass-dominated understorey and blackening of the surface. Albedo was halved following fire of both intensities (from 0.12 to 0.07 and from 0.11 to 0.06 for the moderate and low intensity sites, respectively), but the recovery of albedo was dependent on the initial fire intensity. The low intensity fire caused little canopy damage with little impact on the surface energy balance and only a slight increase in Bowen ratio. However the moderate fire resulted in a comprehensive canopy scorch and almost complete leaf drop in the weeks following fire. The shutdown of most leaves within the canopy reduced transpiration and altered energy partitioning. Leaf death and shedding also resulted in a cessation of ecosystem carbon uptake and the savanna turned from a sink to a source of carbon to the atmosphere because of the continued ecosystem respiration. Post-fire, the Bowen ratio increased greatly due to large increases in sensible heat fluxes. These changes in surface energy exchange following fire, when applied at the landscape scale, may have impacts on climate through local changes in circulation patterns and changes in regional heating, precipitation and monsoon circulation.

Additional keywords: surface energy exchanges; Howard Springs; albedo; fire intensity; eddy covariance; Northern Territory.

Introduction

Tropical savanna ecosystems account for 11.5% of the global landscape (Scholes and Hall 1996). Up to 75% of this landscape burns annually (Hao *et al.* 1990) and 50% of all biomass burning in tropical regions originates from savannas (Hao and Liu 1994). The wet–dry tropics of northern Australia feature extensive tracts of savanna vegetation which occupy ~2 million km^2. This area is equivalent to 12% of the world's tropical savanna estate, making this savanna biome of global significance. Fire is arguably the greatest natural and anthropogenic environmental disturbance in this region. Vast tracts are burnt each year by pastoralists, Aboriginal landholders and conservation managers (Russell-Smith *et al.* 2000; Williams *et al.* 2002). For example, in the relatively mild fire year of 1992, 74 000 km^2 (5.5% of the total land area) of the Northern Territory was burnt (Beringer *et al.* 1995), by far the largest proportion being savanna landscape. This 'poor' fire year consumed an estimated 29.5×10^6 tonnes of biomass and was associated with a likely release of more than 13 Tg of carbon products to the atmosphere (Beringer *et al.* 1995). Russell-Smith *et al.* (2000) provide an estimate of 244 000 km^2 and 242 000 km^2 for the total area of northern Australia (at least partially) burnt in 1997 and 1998, respectively.

While extensive, these frequent savanna fires are of relatively low intensity when compared to the infrequent but intense fires of southern Australia (Williams *et al.* 1998, 2002). Fire intensity is seasonal, with early dry season fires of low intensity (<1000 kW m^{-1}), causing minimal canopy damage, with intensity increasing as the dry season progresses and fuel load accumulates and cures. However, by the late dry season and pre-monsoonal period (August–October), fire intensity can be an order of magnitude greater (Williams

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et al. 1998) and these fires tend to burn over very large fronts and are more damaging with crown scorch of $>90\%$. The scorched canopy dramatically reduces the green Leaf Area Index (LAI) of the canopy and blackens the soil. These surface changes are likely to result in altered energy partitioning (enhanced sensible heat flux) and shifts in albedo. In addition, the aerodynamic and biological properties of the ecosystem may change, affecting surface–atmosphere coupling. For example, a fire could also cause a loss of canopy leaf area, with a subsequent reduction in canopy photosynthesis and evapotranspiration, greatly influencing post-fire fluxes of water and carbon. Information about such direct fire impacts in any environment is scarce.

At a regional scale, savanna fires may have significant impacts on the regional water, energy and carbon dioxide exchanges (e.g. Lynch and Wu 2000) and as a result are likely to have important feedbacks to the atmosphere and regional climate and hydrology. These impacts and feedbacks are not well understood and an improved understanding of them is required. At the local scale, enhanced sensible heat fluxes over patches of burnt landscape could generate mesoscale circulation systems (Knowles 1993). Variations in atmospheric heating rates above burnt and unburnt savanna and associated horizontal pressure gradients will produce atmospheric motion at a range of scales. In addition, local-to-regional scale circulation changes associated with burning may modify patterns of precipitation and could potentially affect the strength of the Australian monsoon.

Here, we examine the impact of a typical low intensity ($<1000\,\mathrm{kW\,m^{-1}}$) and a moderate intensity fire ($3600\,\mathrm{kW\,m^{-1}}$) on canopy processes such as latent (LE) and sensible (H) heat exchanges, shifts in albedo (α) and CO_2 fluxes (F_c) in a tropical savanna. The eddy covariance method was used to measure these variables before, during and after two fires, with recovery of the canopy and subsequent shifts in fluxes monitored for 2 weeks post-fire. These fire experiments were designed to answer the following questions:

(1) What are typical values of LE, H, and F_c flux and albedo from burned and unburnt tropical savanna?
(2) How does fire intensity affect these fluxes and albedo? and
(3) How does the ecosystem recover over time?

We address these questions in this paper, based on measurements made by us over open-forest savanna near Darwin during the late dry season of 2001.

Methods

Study site

Measurements were made in the Howard River catchment, located on the Gunn Point peninsula, 35 km south-east of Darwin, Northern Territory. The vegetation of the catchment and region is a mosaic of eucalypt-dominated woodland and open-forest savanna, closed forests, seasonally flooded swamps and wetlands. The open-forest savanna (*sensu* Wilson *et al.* 1990) is by far the most dominant vegetation type and all measurements were made in this vegetation type. Vegetation, soils and climate of this site have been described previously by O'Grady *et al.* (2000) and Hutley *et al.* (2000, 2001) and will be described only briefly here. Soils at the site are red earth sands (red Kandosols, after Isbell 1996) with an overstorey dominated (in terms of leaf area and biomass) by two eucalypt species, *Eucalyptus tetrodonta* F. Muell. and *E. miniata* Cunn. ex Schauer. These and other tree species form a canopy of between 14 and 15 m in height, with overstorey LAI ranging from 0.95 to 0.6 between the wet and dry seasons (O'Grady *et al.* 2000). The understorey consists of semi-deciduous and deciduous small trees and shrubs, but is dominated by the tall, C_4 annual grass, *Sorghum* sp. Understorey LAI is maximal between February and March and reaches 1.2–1.5 and rapidly declines to 0.2 with the onset of the dry season in April and May. This site is representative of frequently burnt, mesic savannas of the coastal regions of the Northern Territory, occupying an area of some $135\,000\,\mathrm{km^2}$ and occurring above the 1200 mm rainfall isohyet (Wilson *et al.* 1990). This and other closely associated eucalypt-dominated savanna types also occur in North-western Western Australia and the Gulf of Carpentaria region of northern Queensland and occupy up to $200\,000\,\mathrm{km^2}$ in northern Australia (Fox *et al.* 2001).

Previously, there has been an extensive suite of ecological (Bowman 1986), eco-physiological and flux measurements conducted at Howard Springs and similar sites in the Gunn Point region. Measurements have been made of vegetation structure and above-ground biomass (O'Grady *et al.* 2000), patterns of tree transpiration (O'Grady *et al.* 1999; Hutley *et al.* 2000), evapotranspiration (Hutley *et al.* 2000), soil water dynamics (Kelley *et al.* 2002), catchment water balance (Cook *et al.* 1998), CO_2 exchange (Eamus *et al.* 2001; Chen *et al.* 2002) and carbon balance (Chen 2002). However the impacts of fire on latent and sensible heat, and CO_2 fluxes and shifts in surface energy balance, have not been quantified.

In this study, a flux tower was instrumented at two sites, one site being subjected to a low intensity fire and the other site subject to a moderate intensity fire event. Flux measurements were made before burning, during and after these fire events. Measurements of fluxes during the actual fire will be published elsewhere. Continuous flux measurements at the moderately burnt site will be maintained for several years, providing a nearly continuous flux dataset over a series of complete wet–dry cycles.

Flux measurements and fires

Two similar savanna sites were chosen to be representative of the regional vegetation. Both sites were *E. tetrodonta*/*E. miniata* open-forest savanna and had adequate homogeneous fetch in all directions (>1 km) with slopes of less than 1°. The moderate fire intensity site (hereafter 'moderate intensity site') was located near Howard Springs at 12°29.712′S/131°09.003′E and the low fire intensity site (hereafter 'low intensity site') was located ~8 km away at 12°25.263′S/131°09.438′E.

The eddy covariance method was applied at both low and moderate intensity burn sites using similar systems. We conducted our measurements at the top of two 18 m towers over the 12–14 m tall vegetated canopy. Three dimensional wind velocities were measured using a 3-D ultrasonic anemometer (Campbell Scientific Inc., model CSAT3). Turbulent fluctuations of CO_2 and H_2O at the moderate intensity burn site were measured using an open path infrared gas analyser (Li-Cor, model LI-7500). Turbulent fluctuations of H_2O only were made at the low intensity burn site using a krypton hygrometer (Campbell Scientific Inc., model KH20). Quality control of data, data processing and corrections were applied to the data following Hutley *et al.* (2000). The energy balance closure of the processed data was generally less than 15% (data not shown) as a fraction of net radiation during the daylight hours indicating satisfactory measurement techniques and confidence in the measured fluxes (Eugster *et al.* 1997). The eddy covariance method directly measures the fluxes of sensible (H) and latent (LE) heat from the surface. The measured LE represents the net energy used in evaporation and transpiration ($\mathrm{W\,m^{-2}}$) from the canopy and can easily be converted to evapotranspiration ($\mathrm{mm\,day^{-1}}$).

The radiation balance was measured using incoming and reflected shortwave (Middleton Instruments, pyranometer model EP-07) and incoming and emitted long-wave radiation (Eppley Laboratories Inc., pyrgeometer model PIR). An independent estimate of net radiation above each surface was made using a Frischen type net radiometer (REBS, model Q*7.1).

Observations of energy and moisture exchange were made in conjunction with vegetation biomass and structure, fuel loads and fire intensities. Measurements were taken over the 2001 dry season between 30 July and 7 September. The time system used here is local Central Standard Time (CST), which is (UTC + 9.5 Hours). Throughout this paper the term daily refers to the 24-h period from midnight to midnight and daytime refers to the period when net radiation is positive (10:00–18:00). Solar noon at Howard Springs was close to 13:00 CST.

Fire occurred on day 218 (6 August 2001) at the moderate intensity site and unburned control measurements were taken from day 218 until day 238 (26 August 2001), when a fire occurred at the low intensity site. Hence, pre- and post-fire measurements from both intensity burn sites were gathered along with simultaneous burned and unburned measurements between days 218 and 238. The fire intensity at each site was estimated based on char and scorch heights using the relationship of Williams *et al.* (1997). The estimated fire intensity at the low intensity site was $600 \pm 60\,\mathrm{kW\,m^{-1}}$ and at the moderate intensity site was $3550 \pm 640\,\mathrm{kW\,m^{-1}}$ (Table 1).

Table 1. Char height, scorch height, and corresponding fire intensity, using the relationship of Williams *et al.* (1998)
Remaining ground layer biomass (i.e. unconsumed fine fuel) following each fire is also given for each site. —, not measured

	Fire intensity	
	Moderate	Low
Leaf char height (m)	2.01 ± 0.10	0.45 ± 0.03
Leaf scorch height (m)	13.5 ± 1.5	2.50 ± 0.45
Average intensity ($\mathrm{kW\,m^{-1}}$)	3550 ± 640	600 ± 60
Grassy fuel load ($\mathrm{t\,ha^{-1}}$)	1.58 ± 0.18	—
Woody fuel load ($\mathrm{t\,ha^{-1}}$)	6.38 ± 1.21	—
Grassy fuel moisture (% weight)	6.9 ± 1.5	—
Woody fuel moisture (% weight)	9.6 ± 1.7	—
Remaining biomass ($\mathrm{t\,ha^{-1}}$)	0.95 ± 0.28	1.1 ± 0.19

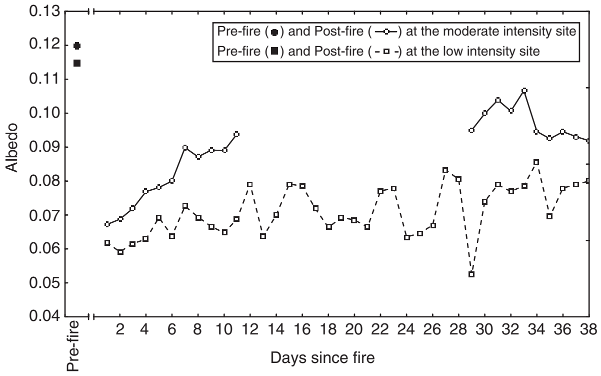

Fig. 1. Pre- and post-fire values of albedo for the low and moderate intensity fire sites. Fire occurred on day 238 (26 August 2001) at the low intensity site and on day 218 (6 August 2001) at the moderate intensity site but are shown here as days following the fire (open symbols) to emphasise the differences in albedo recovery over the 37 days following fire. Pre-fire albedos (solid symbols) are averaged for the 3 days preceding the fire.

Results and discussion

In the tree-dominated savannas of northern Australia, the most dramatic visual change resulting from fire is the consumption of the dry, grassy understorey fuel and coarse woody debris and the resultant bare and blackened surface. As shown in Fig. 1, this immediately affected the surface radiation budget through a dramatically decreased albedo. The pre-fire grassy understorey in the mid-dry season had senesced and was relatively brown and absorptive. In addition, the understorey grasses are tall (up to 1.5 m) with a high LAI (1.4) when green and, in combination with the tall scattered open-forest trees, were capable of multiple scattering and absorption of incoming shortwave radiation. Following fire, there is canopy damage and loss of canopy leaf area, which subsequently alters the radiation balance and rates of evapotranspiration and carbon flux.

Fire impacts on canopy fullness and energy partitioning

Crown fires are rare in these savanna ecosystems, due to a fire regime characterised by frequent, low intensity fires

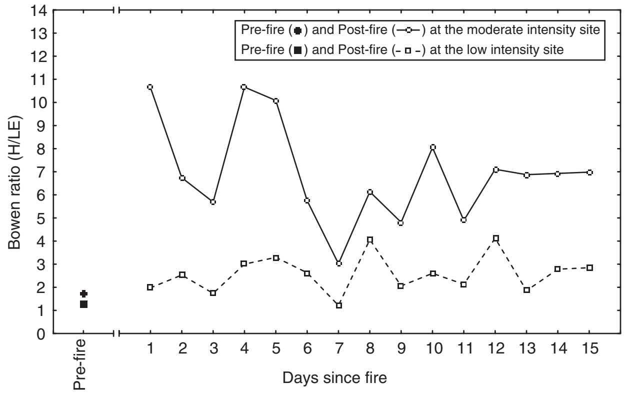

Fig. 2. Pre- and post-fire daytime Bowen ratios (H/LE) for the low and moderate intensity fire sites. Fire occurred on day 238 (26 August 2001) at the low intensity site and on day 218 (6 August 2001) at the moderate intensity site but are shown here as days following the fire to emphasise the differences in albedo recovery over the 2 weeks following fire. Pre-burn Bowen ratios are averaged for the 3 days preceding the fire. The average daily Bowen ratios for the 2 weeks following fire were 2.6 and 7.0 for the low and moderate intensity fire sites, respectively.

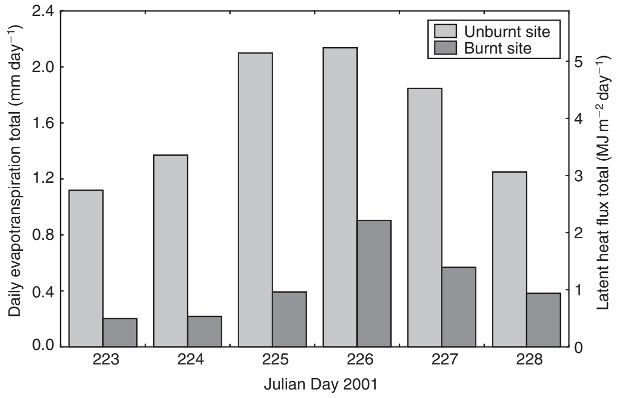

Fig. 3. A comparison of daily total evapotranspiration (ET) for the moderate intensity fire site and for an unburnt control. The fire occurred on day 218 (6 August 2001) and the data shown are for days 5 through 10 following the fire.

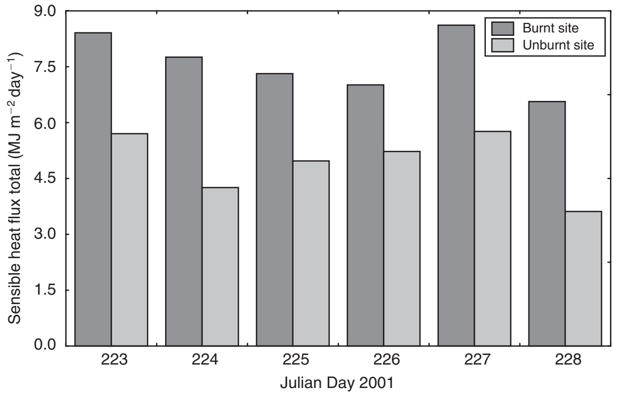

Fig. 4. A comparison of daily total sensible heat flux for the moderate intensity fire site and for an unburnt control. The fire occurred on day 218 (6 August 2001) and the data shown are for days 5 through 10 following the fire.

(Williams *et al.* 1998). However, heat from the understorey during a moderate intensity fire (ca. 3000–5000 kW m^{-1}) causes substantial canopy scorch and subsequent leaf fall from the dominant trees in the weeks following fire. Such canopy damage is likely to reduce transpiration, fundamentally changing the ratio of energy partitioned into sensible heating (H) *v.* latent heating (LE), known as the Bowen ratio ($\beta = H/LE$, Bowen 1926). Values of β near 1 indicate that equal proportions of available energy are being dissipated as H and LE. Values less than 1 indicate that the majority of energy is dissipated as evapotranspiration, while a β greater than 1 indicates a greater proportion of available energy is being dissipated as sensible heat to the atmosphere.

Mean daytime values of β 3 days before the fire were 1.4 and 1.8 for the low and moderate intensity sites, respectively (Fig. 2). These values are typical values for β for the mid dry season with low soil moisture levels and reduced canopy LAI, which reduces LE below H. Similar dry season ratios for unburnt vegetation have been reported at this site by Hutley *et al.* (2000). However fire dramatically increased values of β 2 weeks post-burn and β averaged 2.6 and 7.0 for the low and moderate intensity sites respectively (Fig. 2). This was due to enhanced sensible heating and a reduction in evapotranspiration (Figs 3 and 4).

Observations of leaf drop 2 weeks after fire showed that the canopy scorching at the low intensity site was less than 20% and, as a result, evapotranspiration was slightly reduced from 1.4 to 1.0 mm day^{-1}, 71% of pre-fire levels. The small reduction in LE caused β to increase from 1.4 to 2.6. At the moderate intensity site, canopy scorch was greater than 80% and subsequently little energy was partitioned into evapotranspiration as the functional leaf area dropped to near zero in the weeks following fire (Fig. 3). Under these conditions β was ~7.0, which is typical of desert values (Beringer and Tapper 2000).

During the dry season, surface (0–50 cm) soil water contents are typically very low (<5%) with little soil evaporation or transpiration from understorey vegetation and by the late dry season, tree transpiration accounts for 80–90% of evapotranspiration (Hutley *et al.* 2000). Therefore once the tree canopy is scorched, transpiration almost ceases with total evapotranspiration only 25% of the unburned control (1.6 mm day^{-1} in the unburnt site and 0.4 mm day^{-1} in the moderate intensity site for days 5–10 following fire; Fig. 3). This was paralleled by an increase in ground (data not shown) and sensible heat fluxes. The sensible heat fluxes during the dry season for these savanna ecosystems before fire were already moderate (5.0 MJ m^{-2} day^{-1}), due to the dry soils, low LAI, high canopy resistance and relatively large net radiation totals during the day. In the moderate intensity site, the daily sensible heat flux totals were much larger

(7.6 MJ m^{-2} day^{-1}) than the unburned control (4.9 MJ m^{-2} day^{-1}) during days 5–10 following the fire.

Recovery of albedo following fire

The pre-fire albedos of our savanna sites were 0.11 and 0.12 for the low and moderate intensity burn sites, respectively (Fig. 1). Following fire, the flat savanna surface was blackened and became highly absorptive. Albedos were reduced by almost half at both sites to 0.06 and 0.07 respectively for the low and moderate intensity sites (Fig. 1). Scholes and Walker (1993) also reported a halving of African savanna albedo to 0.06, immediately following fire, with a recovery to pre-fire values after 6 weeks. Interestingly, despite the halving of the shortwave albedo, net radiation in the moderate intensity burned plot was only 10% higher than in the unburned control (591 compared to 535 W m^{-2} at noon). The reduced albedo was partly offset by a moderate increase in outgoing long-wave radiation caused by increased short-wave absorption and increased surface radiative temperatures. Outgoing long-wave radiation was 13% higher in the moderate intensity site compared to the unburnt site (592 compared to 526 W m^{-2} at noon).

The time taken for a complete recovery of albedo, LE and H, and carbon fluxes to pre-fire levels is not well understood in these savannas. However, our observations suggest that, while initial impacts of fire in these savanna ecosystems were relatively short-lived, there was a large difference in recovery following fires of differing intensity. Despite a halving of albedo after fire to similar values at both sites, albedo at the moderate intensity site recovered to be closer to pre-burn values than at the low intensity site, 2 weeks after fire (Fig. 1). This is perhaps a counter-intuitive result, but is likely to be due to the extensive canopy scorching and leaf drop at the moderate intensity site. The transfer of a large proportion of the canopy leaf area to the ground had two likely consequences for radiative exchanges:

(1) A covering of the blackened soil with more reflective dead leaves; and
(2) Reduced canopy LAI and ability to scatter and absorb incoming radiation. These two effects combine to increase albedo relatively quickly. The low intensity site had the same initial albedo drop, due to the removal of the grassy understorey, but had reduced leaf drop, hence shifts in albedo were not as pronounced at this site with a prolonged recovery (Fig. 1). At neither site did albedos approach pre-fire values and are unlikely to do so until the grassy understorey is replaced during the next wet season.

Recovery of fluxes following fire

Energy partitioning and fluxes of carbon and water did not show the same rapid recovery that was seen in the albedo. While changes to albedo were driven by leaf scorching and shedding, recovery of the fluxes to pre-fire depends upon the development of a new flush of leaves, a process that takes much longer than the shifts in albedo. At the moderate intensity site, Bowen ratios were around 10 for several days following fire, reducing to ~7 at 2 weeks post-fire (Fig. 2). The partial recovery over time of Bowen ratios towards pre-fire values is perhaps due to the revival of any remaining undamaged or partially damaged leaves following the initial scorching. The cause of the decrease in Bowen ratio on days 2 and 3 after fire is not known but may be due to an increase in latent heat generated from an initial loss of water from the scorched leaves as they start to desiccate.

The low intensity site showed a small increase in the Bowen ratio immediately following fire due to limited canopy damage and then showed an increasing Bowen ratio over the following 2 weeks, a contrasting pattern when compared to the moderate burn site. This slow increase could be due partially to the dropping of fire-damaged leaves but could also be due to the natural shedding of leaves. These savannas show pronounced reductions in canopy cover over the dry season (Williams *et al.* 1997), resulting in ~30–40% reduction in LAI from the wet to the end of the dry season even in the absence of fire (O'Grady *et al.* 1999). Hence as leaves naturally drop, LE is reduced and the Bowen ratio may continue to increase (Hutley *et al.* 2000). As for albedo, we did not see any recovery in the fluxes to pre-fire levels in the 2 weeks following fire. We do not know how long it may take for the canopy to recover completely. However, limited observations indicate that the canopy trees will flush with green leaves ~30 days following fire (Williams *et al.* 1998; Bowman *et al.* 2003). This is believed to happen regardless of the time since the last rains and independently of fire intensity because the evergreen trees are able to access deep soil water reserves (up to 5 m depth, Kelley *et al.* 2002). This indicates that although fires are frequent, fluxes of water and energy may recover within 1 month or so of fire (Williams *et al.* 1998). However, post-fire leaves would be immature and even after a canopy flushing, recovery to pre-burn fluxes could take much longer, especially for carbon.

Our detailed assessment of fire impacts on carbon exchange is limited because only one tower was instrumented to measure CO_2 fluxes. However, we present a time series from 1 day before to 12 days after fire at the moderate intensity site. Integration of the 30-min fluxes of CO_2 over a 24-h period yields the daily Net Ecosystem Exchange (NEE). This is the net exchange of carbon between the ecosystem and the atmosphere via canopy photosynthesis and both plant and soil respiration. Pre-fire NEE values were -1.39 g C m^{-2} day^{-1} (day 216), the negative value representing a net daily uptake or sink for carbon (Fig. 5).

Following the fires and associated emissions from burning, the ecosystem became a net source of carbon to the atmosphere with an NEE of $+2.01$ g C m^{-2} day^{-1} on the day following fire (Fig. 5). This occurs, once again, because of

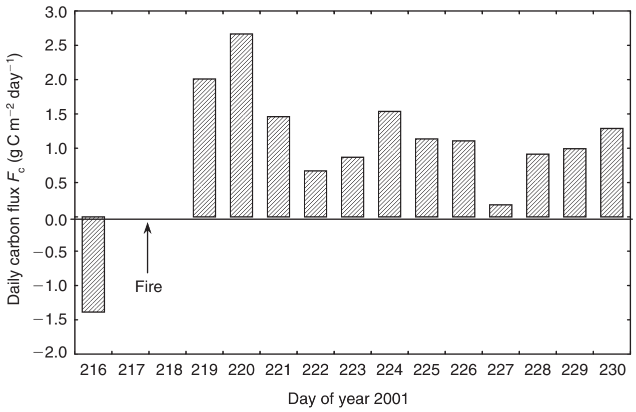

Fig. 5. Pre- and post-fire daily carbon flux for the moderate intensity fire site. Fire occurred on day 218 (6 August 2001) at the moderate intensity fire site. The savanna was a net sink of carbon before fire ($-1.39\,\mathrm{g\,C\,m^{-2}\,day^{-1}}$) but then turned into a source following fire ($+1.15\,\mathrm{g\,C\,m^{-2}\,day^{-1}}$ averaged for the 2 weeks following fire).

the canopy scorch and consequent leaf fall. Hence, photosynthesis almost ceased, with fluxes determined by plant and soil respiration. Elevated carbon emissions were sustained for a few days following fire due to smouldering woody debris and ventilation of the ecosystem. Following these processes, the average source of carbon to the atmosphere was $+1.15\,\mathrm{g\,C\,m^{-2}\,day^{-1}}$, with this rate occurring during the 2 weeks following fire (Fig. 5). There was no obvious recovery of carbon fluxes to pre-burn values over the 2 weeks and again it is uncertain as to how long complete recovery would take. Additional work is required to elucidate the dynamics of vegetation properties, energy and carbon fluxes throughout the recovery period, with fluxes measured through the following wet season. Fire impacts on canopy and carbon dynamics are further complicated by 'normal' seasonal changes in NEE, which are associated with the large changes in available soil water that occur from the wet to dry season (Eamus *et al.* 2001). The influence of fire on annual NEE measurements needs to be investigated to estimate the Net Biome Productivity (NBP), which takes into account the effects of disturbance on the annual carbon balance over longer time periods (decades). Chen (2002) estimates this to be $\sim 1.5\,\mathrm{t\,C\,ha^{-1}\,y^{-1}}$, although this estimate is based on literature values and site-specific measurements.

Potential regional-scale impacts of savanna burning on climate

Since ~30% of the savanna region of northern Australia burns each year, the post-fire impacts on the surface energy and carbon fluxes measured here are likely to be typical of the vegetation of the region (Russell-Smith *et al.* 2002). The associated 55% increase in sensible heating of $2.7\,\mathrm{MJ\,m^{-2}\,day^{-1}}$ following fire represents a large change in surface energy partitioning. Increased energy used in surface heating could have significant impacts on local to regional scale atmospheric circulations and climate. Although this study cannot elucidate any of these effects specifically, we believe it is of value to examine some possible impacts. At the local scale, depending on the aerodynamic changes to savanna vegetation following fire, enhanced sensible fluxes from patches of burnt landscape (in the order of $100\,\mathrm{km^2}$ in area) could produce localised areas of convergence and divergence and associated mesoscale circulation systems (Knowles 1993). These circulation patterns may lead to an increase in spatially fixed convective cloud development and precipitation following fire until fluxes have returned to pre-fire conditions. Tapper (1991) and Physick and Tapper (1990) have shown that landscape contrasts in albedo between salt lakes and their surrounds in Australia can produce quite strong mesoscale circulation systems. Such circulations are known to be capable of producing intense, spatially fixed cloud convection and precipitation under suitable environmental conditions (Keenan *et al.* 2000; Beringer *et al.* 2001*b*). For instance, on the Tiwi Islands north of Darwin, Australia, the contrast in albedo and heating between the land and ocean causes a thermal circulation (sea breeze) with wind flow towards the centre of the island (Beringer *et al.* 2001*a*). Given sufficient atmospheric moisture and uplift (from heating over the island) this results in thunderstorms and precipitation (Beringer *et al.* 2001*a*).

The likelihood of convection with precipitation will depend on the amount of atmospheric water vapour, which in turn varies seasonally. Hence, during the mid-dry season there may be no association with fire scars. However, by the late-dry season (September–October), when atmospheric water vapour is increasing, the generation of convection over recent fire scars may be significant. This pre-monsoonal period (August–October) is characterised by fire intensities that can be an order of magnitude greater than early and mid-dry season fires (Williams *et al.* 1998). These hotter fires tend to burn over very large fronts, are more damaging, with crown scorch of >80% and occur during periods when pre-monsoonal cloud-formation is significant. At this time, significant modification of precipitation patterns might occur.

Over the last 50–100 years or so, there has been a strong shift in the fire regime in northern Australia (Braithwaite 1991), from an Aboriginal regime characterised by early dry season (April–May) patch burning, to these more destructive late-dry season fires (Williams *et al.* 1998). Such fire-induced landscape changes, when integrated over the total area of northern Australia, might also have impacts on regional scale climate. Recent work by Beringer *et al.* (2001*b*) examined the differential heating resulting from modest albedo differences between boreal forest and tundra and its potential role in persistent large-scale circulation features in the Arctic. These workers found that springtime contrasts in heating were theoretically sufficient to alter the position of the Arctic front. We hypothesise that, in northern Australia, burning of the scale of tens of thousands of square kilometres could have similar impacts, perhaps even extending to influences on the strength and southward penetration of the Australian monsoon. For example, Johnson *et al*. (1999) argue that changes in vegetation across northern Australia resulting from human burning practices over the last 60 000 years reduced the effectiveness of the summer monsoon for central Australia. Equivalently, current burning practices along with potential changes in fire frequency as a result of climate change (Williams *et al*. 2001) could again cause widespread changes in vegetation with feedbacks to regional climate. The nature of the feedbacks between fluxes, changing fire regimes and weather under different climate/vegetation scenarios is as yet unknown, but it is potentially of great importance to landscape function, and hence land use and land management in northern Australia.

Conclusions

Fire is a frequent and extensive feature of the wet–dry tropical savannas and has been fundamental in shaping the interactions between climate, fire and vegetation. Fire has immediate impacts through smoke emissions and transport but also longer lasting effects through persistent fire scars. In these savannas, fire consumes the grass-dominated understorey with overstorey damage a function of fire intensity, which is a key variable in determining the likely impact on surface albedos and energy and carbon fluxes. Fire resulted in this savanna site becoming a significant carbon source in the short term (weeks to months). The magnitude of the carbon balance components (photosynthesis, autotrophic and heterotrophic respiration) before and after fire needs to be more thoroughly examined and further research is required to elucidate fire-induced changes at a landscape scale that might have impacts on local to regional scale climate.

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