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Quantifying the relative importance of greenhouse gas emissions from current and future savanna land use change across northern Australia

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Abstract

Clearing and burning of tropical savanna leads to globally significant emissions of greenhouse gases (GHG) although there is large uncertainty relating to the magnitude of this flux. Australia's tropical savannas occupy over 25% of the continental land mass and have a potential to significantly influence the national greenhouse gas budget, particularly because they are the focus of likely agricultural expansion. To investigate the role of deforestation on GHG emissions, a paired site approach was used. The CO_2 exchange was measured from two tropical savanna woodland sites, one that was cleared, and a second analogue site that remained uncleared for a 22 month observation period. At both sites, net ecosystem exchange (NEE) was measured using the eddy covariance (EC) method. Observations at the cleared site was continuous before, during and after the clearing event, providing high resolution data that tracked CO_2 emissions through multiple phases of land use change.

At the cleared site, post-clearing debris was allowed to cure for 6 months and was subsequently burnt, followed by extensive soil preparation for cropping. Emissions were estimated from the debris fire by quantifying the on-site biomass prior to clearing and applying savanna-specific emissions factors to estimate a fire-derived GHG emission. This was added to net CO_2 fluxes as measured by the eddy covariance tower, giving a total GHG emission of 154 Mg CO_2-e ha^{-1} from a savanna woodland with a total fuel load (above- and below- ground woody debris, course woody debris, litter plus C_4 grass fuel) of 40.9 Mg C ha^{-1}. This emission was dominated by the combustion of cleared debris which was 83% of the total emission with the remainder coming from soil emissions and decay of debris during the curing period prior to burning. Soil disturbance from ploughing and site preparation for cropping was responsible for almost 10% of the total emission. Fluxes at the uncleared site were tracked using an additional flux tower for the 22 month observation period and over this time the cumulative NEE was -2.1 Mg C ha^{-1}, a net carbon sink.

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Estimated emissions for this savanna type were then upscaled to provide estimates of the magnitude of emissions from any future deforestation. At current rates of deforestation, savanna burning is as significant a source of GHG emissions as deforestation, with fire emissions occurring every year across this savanna biome. However, expanded deforestation could exceed fire emissions and a clearing scenario was examined which suggested that clearing over and above current rates could add up to 5% to Australia's national GHG account for the duration of the clearing activities. This bottom-up study provides data that can reduce uncertainty associated with land use change for this extensive tropical ecosystem and provide an assessment of the relative magnitude of GHG emissions from savanna burning and deforestation as well as informing northern land use decision making processes.

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1.0 Introduction

An increase in greenhouse gas (GHG) emissions through human-related activities is leading to rapid change in the climate system (IPCC 2013) and it is crucial to obtain data describing net GHG balance at regional to global scales to better characterise anthropogenic forcing of the atmosphere (Tubiello et al., 2015). Emissions from land-use change (LUC) are the integral of ecosystem transformations that can include emissions from deforestation and conversion to agriculture, logging and harvest activity, shifting cultivation, as well as regrowth sinks following harvest and/or abandonment of previously cleared agriculture lands (Houghton al. 2012). At present, LUC emits 0.9±0.5 Pg C y^{-1} to the atmosphere, which is approximately 10% of anthropogenic carbon emissions (Le Quéré et al., 2014). Data sources and methods used to estimate LUC emissions are diverse. These include census-based historical land use reconstructions and land use statistics, satellite estimates of biomass change through time (Baccini et al., 2012), satellite monitored fire activity and burn area estimates associated with deforestation (van der Werf et al., 2010). In addition, there is increasing use of ecosystem models coupled with remote sensing to estimate emissions from LUC (Galford *et al.* 2011).

Emissions associated with the LUC sector have the highest degree of uncertainty given the complexity of processes involving net emissions and Houghton et al. (2012) assessed this uncertainty at ~0.5 Pg C y^{-1}, which is of the same order of magnitude as the emissions themselves. Uncertainties in estimating GHG emissions arising from savanna clearing, associated debris burning and conversion to agriculture are greater than those for tropical forests (Fearnside et al., 2009). It is important to quantify the emissions and their uncertainties in savannas particularly because tropical savanna woodland and grasslands occupy a large area globally (27.6 million km^2), greater than tropical forest (17.5 million km^2, Grace et al., 2006).

Tropical savanna woodlands and grasslands occupy a large area globally (27.6 million km^2), greater than tropical forest (17.5 million km^2, Grace et al., 2006). Deforestation and associated fire

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from these biomes are the largest contributors to global LUC emissions (Le Quéré et al., 2014). Much of these GHG emissions are from the Brazilian Amazonia, an agricultural area that has been expanding since the 1990s. However, over the last decade, the rate of tropical forest deforestation in this region has decreased from 16,000 km^2 in early 2000s to ~6,500 km^2 by 2010 (Lapola et al., 2014), but at the expense of the Brazilian cerrado, a vast savanna biome of some 2.04 million km^2, where clearing rates have been maintained (Ferreira et al., 2013, 2016; Galford et al., 2013). Given the suitability of the cerrado topography and soils for mechanized agriculture as well as potential leakage pressure resulting from declining deforestation rates of tropical forests in Amazonia, the Cerrado may become the principal region of LUC in Brazil (Lapola et al., 2014).

North Australia is one of the world's major tropical savanna regions, extending some 1.93 million km^2 across north-west Western Australia, the northern half of the Northern Territory and Queensland (Fisher and Edwards, 2015). This biome occupies approximately one third of the Australian continent and since European arrival, 5% has been cleared for improved pasture, horticulture and cropping (Landsberg et al. 2011), making it one of least disturbed savanna regions in the world (Woinarski et al., 2007). However, this small percentage equates to a substantial area of 9.2 million hectares and LUC and associated economic development in northern Australia is a government imperative and this is likely to involve expansion and intensification of grazing, irrigated cropping, horticulture and forestry (Northern Australia Committee, 2014). Drivers of this potential expansion in food and fibre production include the exploitation of growing markets of Asia as well as domestic factors such as the perception that land and water resources of north Australia can provide a future agricultural resource base to offset the expected declines in agricultural productivity in southern Australia due to adverse impacts of climate change (Steffan and Hughes, 2013).

Historically, intensive agricultural developments in northern Australia have been implemented based on limited scientific knowledge with dysfunctional policy and market settings, and as a result there has been limited success (Cook, 2009). Future expansion needs to be underpinned by sound understanding of the consequences of regional scale land transformation on carbon and water budgets and GHG emissions. Any significant expansion northern agricultural production would require significant clearance of native savanna vegetation, with unknown increases in GHG emissions. Accurate and transparent measurement of sinks and sources of GHGs has become an imperative to quantify impacts of LUC, in particular clearing and managed savanna burning, on national GHG accounts (Meyer et al., 2012).

Most LUC studies occur at catchment, regional or biome scales (Houghton et al. (2012) and are not underpinned by good understanding of underlying processes. However, there are an increasing number of plot-scale studies using eddy covariance and chamber methods to provide direct measures of net GHG fluxes from contrasting land uses (Lambin et al., 2013). These studies typically compare microclimate and fluxes of GHGs from pastures and/or crops with adjacent forest ecosystems under a range of management conditions (e.g. Anthoni et al. 2004; Zona et al. 2013) or natural grasslands and different cropping types (e.g. Zenone et al., 2011). In tropical regions, there is a focus on transitions from forest to pasture and from forest to crops for food or bioenergy production (Galford et al., 2010;Wolf *et al.* 2011; Sakai *et al.* 2004).

There are fewer studies that directly measure GHG emissions and sinks prior to, during and after LUC at one site. Land use change can involve rapid changes in net GHG emissions over varying temporal scales (minutes, hours, and seasonal cycles) and continuous flux measurements are essential to capture these events (Hutley et al. 2005). However, there are no direct observations of emissions from savanna clearing in northern Australia, contributing to the uncertainty associated with the LUC sector in Australia's national GHG accounts (Commonwealth of Australia, 2015).

Our objective is to provide a comprehensive assessment of GHG emissions associated with savanna clearing. Our aims are to 1) quantify the typical rates of CO_2 exchange of intact tropical savanna and make comparative measurements from an analogue site that was to be cleared, 2)

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quantify CO_2 fluxes before, during and after a clearing event, 3) estimate both CO_2 and non-CO_2 (CH_4 and N_2O) GHG emissions arising from burning of debris and 4) quantify ecosystem scale GHG balance for this land use conversion.

2.0 Methods

In this study we used a paired site approach, where concurrent fluxes of CO_2, water vapour and energy were measured using eddy covariance towers from an uncleared savanna woodland site and a similar savanna woodland site on the same soil type that was to be cleared, burnt and prepared for agricultural production. Fluxes of CO_2 were monitored for 161 days prior to clearing at both sites with observations continuing during the clearing event (deforestation) and for another 507 days through phases of woody debris and grass curing, burning and soil preparation through raking and ploughing. The entire observation period was 668 days. Flux observations of net CO_2 exchange were combined with on-site biomass measurements and regionally calibrated pyrogenic emissions factors to estimate emissions of CH_4 and N_2O (Russell-Smith et al., 2009b) and CO_2 (Hurst et al., 1994) from burning of the cleared debris. Fire derived emissions were combined with net CO_2 fluxes from the conversion phases to provide a total net emission in units of CO_2-e for this land conversion. In this paper, we use the term deforestation to describe 'savanna clearing'. Deforestation is defined under Australia's National Greenhouse Accounting system, as the loss of forest/woodland cover due to direct human-induced actions and fail to regenerate cover via natural regrowth or restoration planting (Commonwealth of Australia, 2015).

2.1 Study sites

Both savanna woodland sites were located within the Douglas-Daly River catchment approximately 300 km south of Darwin, Northern Territory (Fig. 1). Both sites are OzFlux sites (www.ozflux.org.au), with flux observations ongoing at the uncleared (UC) savanna since 2007 (Beringer and Hutley, 2016; Beringer et al., 2011; Hutley et al., 2011). OzFlux is the regional Australian and New Zealand flux tower network that aims to provide continental-scale monitoring

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of CO_2 fluxes and surface energy balance to assess trends and improve predictions of Australia's terrestrial biosphere and climate (Beringer et al., 2016). The UC site is broadly representative of Australian tropical savanna woodland found on deep, well drained sandy loam soils at ~1000 mm annual rainfall (Table 1). The cleared savanna site (CS) cleared was carefully selected to ensure the vegetation and soils were as similar to the UC site as possible, and with topography suitable for eddy covariance measurements.

Both sites were classified as savanna woodland type 4B2 using Northern Territory Government vegetation mapping (Aldrick and Robinson 1972, 1:50,000 mapping), equivalent to the 'Eucalypt woodland' Major Vegetation Group (MVG) of the National Vegetation Information System (NVIS, Commonwealth of Australia, 2003). The sites were dominated by an overstorey of *Eucalyptus tetrodonta* (F. Muell.), *Corymbia latifolia* (F. Muell.) and *Erythrophleum chlorostachys* (F. Muell.) with a mid-storey of small deciduous trees and shrubs and an understorey of C4 grasses (*Sorghum, Heteropogon spp*. dominated). Soils at both the UC and CS sites were red kandosols of the haplic mesotrophic great group (Isbell, 2002), characterised as deep, sandy-loams (Table 1). The long-term mean annual (± sd) rainfall at the UC site was estimated at 1180 ± 225 mm (1970-2012, Australian Water Availability Project (AWAP), www.csiro.au/awap), similar to the CS site at 1107 ± 342 mm (1985-2013, Bureau of Meteorology station, Tindal, NT).

Both UC and CS sites had a flat topography (slopes of < 2%) with a consistent savanna woodland fetch of ~1.5 km at the UC site, and ~1 km at the CS site. At both sites 23 m guyed masts were installed to support eddy covariance instruments at 21.5 m at both sites. The tower at the CS site was moved three times to ensure adequate fetch was maintained according to seasonal wind direction during clearing and phases of land use change as well as the height of the canopy surface post-clearing and during the soil tillage phase (Table 2). Instruments were mounted at the top of the tower during these phases (7 m and 3 m).

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Remotely sensed fire scar history is available across north Australia at 250 m resolution (North Australian Fire Information system (NAFI), www.firenorth.org.au) indicating that fires had occurred within the flux footprint of the UC flux tower in 5 out of the last 13 years (2000-2013), whereas no fires had occurred within the footprint of the CS site. The average fire return time for the entire Australian savanna biome is one in 3.1 years (Beringer et al., 2015).

2.2 Land use conversion

Conversion of woodland to agricultural land in northern Australia involves pulling trees over using a large chains dragged between two bulldozers, followed by the mechanical stockpiling of woody debris to decay and cure prior to burning. This is followed by raking and stock-piling of any remaining debris and re-burning. Finally, there was mechanised ripping of soil to remove remaining coarse root material to 60 cm depth. These processes result in the removal of all above-ground and most of the below-ground biomass, such that the soil was ready for tillage and cultivation. These phases result in a series of events that may lead to short-term, pulsed GHG emissions that would otherwise be missed or greatly under-estimated by episodic measurements taken at a weekly or monthly frequency after an initial tree felling event (Neill et al., 2006; Weitz et al., 1998). The CS site was cleared between 2 and 6 March 2012, which is towards the end of the wet season; 737 mm of rainfall had fallen since the end of the preceding dry season. Over this five day period, 295 ha of savanna were cleared. The specific sequence and timing of clearing, burning and land preparation phases is given in Table 2.

2.3 Flux measurements and data processing

Eddy covariance systems at both sites consisted of 3-D ultrasonic anemometers (Campbell Scientific Inc., model CSAT3) and a LI-7500 open-path CO_2 / H_2O analysers (Licor Inc., Lincoln, USA). Flux variables were sampled at 10 Hz and covariances stored every 30 minutes. The LI-7500 gas analysers were calibrated on an approximately six monthly interval for the duration of the data collection period and were highly stable. Daily rainfall, air temperature, relatively humidity, soil

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heat flux (Fg, W m^{-2}) and volumetric soil moisture (θ_v, m^3 m^{-3}) from surface to 2.5 m depths were measured at both sites. The radiation balance was measured using a net radiometer (Rn, W m^{-2}) (model CNR4, Kipp and Zonen, Zurich).

Thirty minute covariances were stored using data loggers (CR3000, Campbell Scientific, Logan) and data post processing and quality control was undertaken using the OzFluxQC system as described by Isaac et al. (2016). In this system, data are processed through three levels; Level 1 is the raw data as collected by the data logger, Level 2 are quality-controlled data and Level 3 are post processed and corrected but not gap-filled data. Quality control measures at Level 2 include checks for plausible value ranges, spike detection and removal, manual exclusion of date and time ranges and diagnostic checks for all quantities involved in the calculations to correct the fluxes. Quality checks make use of the diagnostic information provided by the sonic anemometer and the infra-red gas analyser. Level 3 post processing includes 2-dimensional coordinate rotation, low- and high-pass frequency correction, conversion of virtual heat flux to sensible heat flux (Fh, W m^{-2}) and application of the WPL correction to the latent heat (Fe, W m^{-2} and CO_2 fluxes (Fc) (Isaac et al., 2016). Level 3 data also include the correction of the ground heat flux for storage in the layer above the heat flux plates (Mayocchi and Bristow, 1995).

Gap filling of meteorology and fluxes along with flux partitioning of net ecosystem exchange (NEE) into gross primary productivity (GPP) and ecosystem respiration (Re) was performed on the Level 3 data using the Dynamic INtegrated Gap filling and partitioning for Ozflux (DINGO) system as described by Beringer et al., (2016). In summary, DINGO gap fills meteorological variables (air temperature, specific humidity, wind speed and barometric pressure) using nearby Bureau of Meteorology (www.bom.gov.au) automatic weather stations that were correlated with tower observations. All radiation streams were gap-filled using a combination of MODIS albedo products (MOD09A1) and Bureau of Meteorology gridded global solar radiation and gridded daily meteorology from the Australian Water Availability Project (AWAP) data set

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(Jones et al. 2009). Precipitation was gap-filled using either nearby Bureau of Meteorology stations or BoM AWAP. Soil temperature and moisture were filled using the BIOS2 land surface model (Haverd et al., 2013a) run for each site forced with BoM AWAP data. Energy balance closure was examined using standard plots of (Fh+Fe) vs (Fn-Fg) using 30 minute flux data. Day time and night time data were grouped according to each of the seven LUC phase periods, plus a further plot using data pooled across all phases (Fig. 2). Data from the UC site is also plotted using 30 minute data for 2007-2015.

Gap filling of fluxes was undertaken using DINGO that uses an Artificial Neural Network (ANN) model following Beringer et al. (2007). Model training uses gradient information in a truncated Newton algorithm. NEE and fluxes of sensible, latent and ground heat fluxes were modelled using the ANN with incoming solar radiation, VPD, soil moisture content, soil temperature, wind speed and MODIS EVI as inputs. The ustar threshold for each site was determined following Reichstein *et al.* (2005) and night time observations below the ustar threshold were replaced with ANN modelled values of Re using soil moisture content, soil temperature, air temperature and MODIS EVI as inputs. The ANN Re model was then applied to daylight periods to estimate daytime respiration and GPP was calculated as the difference between NEE and Re.

2.4 Leaf area index

Canopy leaf area index (LAI) at the CS site in the surrounding intact savanna was measured using a 180^{o} hemispherical lens (Nikon 10.5 mm, f/2.8) after Macfarlane et al. (2007). Three savanna transects were photographed seasonally on 9 occasions over 2.1 years from the pre-clearing phase (October 2011) to December 2013. Along each 100 m transect, 11 hemispherical pictures were taken at 10 m intervals (33 photos for each measure occasion). At both sites the LAI was also estimated using MODIS Collection 5 LAI (MOD15A2) for a 1 km pixel around each tower. The 8-day product was interpolated to daily time series using a spline fit. Only MODIS values with a quality flag of 0 for FparLai_QC were used in the estimate indicating the main algorithm was used (lpdaac.usgs.gov/sites/default/files/public/modis/docs/MODIS-LAI-FPAR-User-Guide.pdf).

2.5 Emissions from debris burning

Emissions of CO_2, CH_4 and N_2O from the debris burning were estimated following the approach as outlined in the IPCC Good Practice Guidelines (IPCC 2003), which uses country or region specific emission factors for fire activity (as indicted by burnt area) and the mass of fuel pyrolised to estimate the emission of each trace gas. This approach is well developed for north Australian savanna (Murphy et al., 2015a) for a range of fuel types (grasses, fine and coarse woody fuels, Russell-Smith et al. 2009). Fuel load (biomass) estimates are essential to this approach and was quantified for four fuel types prior to clearing: 1) above-ground woody biomass, 2) below-ground biomass, 3) surface coarse woody debris (CWD), and 4) grass biomass. Emissions estimates were based on fuel mass per area for each fuel type, carbon content (%), elemental C:N ratios and Australian savanna combustion emissions factors for CH_4 and N_2O (0.0035, 0.0076 respectively, Russell-Smith et al., 2009b) and CO_2 (0.87, Hurst et al., 1994).

To quantify above-ground biomass, pre-clearing, eight 50 x 50 m plots were established within the 295 ha clearing area and all woody plants >1.5 m in height were identified to species with stem diameter at 1.3 m (DBH) and total tree height measured. Savanna specific allometric equations are available (Chen 2002; Williams et al., 2005) and these were used to estimate above-ground biomass for each individual tree and shrub, based on stem DBH and height measurements for all stems in each plot. Below-ground biomass was calculated using the root:shoot ratio estimate of Eamus et al. (2002) for these savannas which was 0.38. These savanna trees have no dominant tap root, but large lateral roots in the top 30 cm of soil and up to 90% of root biomass occurs in the top 50 cm (Eamus et al. 2002). As such, we assumed that chaining and bulldozer clearing of all above-ground biomass and soil ripping (ploughing) to 60 cm soil depth, plus mechanised removal of root biomass associated with tree bole, resulted in a near-complete removal of both above- and below-ground

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woody biomass pools. This debris was subsequently stockpiled for curing over the dry season and then burnt (Table 2).

The CWD pool was defined as any fragment with a diameter >6 mm and was estimated using a line intercept method (Woldendorp et al., 2004). Six 100 m transects, randomly located across the cleared block, were established and along each transect the length and diameter of all intersected CWD fragments were recorded. Large fragments (>100 mm diameter) are frequently hollowed from the action of termites and fire, and the diameter of the annulus and fragment were measured to estimate this missing biomass.

Five rot classes were adapted from Rice et al. (2004) and assigned to all measured CWD fragments. Rot classes (RC) captures the decay gradient of CWD fragments and were defined as recently fallen, solid wood (RC1), solid wood with or without branches present but with signs of aging (RC2), obvious signs of weathering, still solid wood, bark may or may not be present (RC3), signs of decay with the wood sloughed and friable (RC4) and severe decay with little structural integrity remaining (RC5). A wood density was assigned to each rot class after Rose (2006) to provide an accurate estimate of CWD that included hollowing. Grass biomass was estimated using a grassy fuel loads guide developed for north Australian savanna (Johnson, 2001), which was applicable given soil type and annual and perineal grass mixture of both sites. The biomass per area from the four pools was added to give a total fuel load.

Debris from the March 2012 clearing event was allowed to cure for months through the dry season to ensure a high fire intensity (>5 MW m^{-1}) and combustion efficiency. This period is of similar duration that fuels can naturally cure in this landscape, enabling the application of the regional savanna emission factors as defined by Russell-Smith (2009b). Burning of stockpiled debris lasted approximately 10 days in August 2012, the late dry season (Table 2), a period of high winds and low daytime relative humidity (10-20%). Debris that did not burn was stock-piled for a second time and burnt to ensure all biomass was consumed with ~10% remaining as ash and

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charcoal, a typical fraction from high severity fires (Russell-Smith et al. 2009b). Fine ash blew away and surface charcoal fragments were incorporated into the top soil on ploughing.

Emissions from the debris burning (CO_2 and non-CO_2) were combined with NEE data from the post-clearing period to give a total emission in CO_2-e for this LUC. This estimate included CO_2 fluxes as captured by the flux tower plus CO_2 and non-CO_2 (CH_4, N_2O) emissions from debris burning.

2.6 Emissions from deforestation and savanna burning at regional scales

The impact of any future expansion of deforestation across north Australian savanna landscapes was assessed relative to historic rates and GHG emissions. These emissions were also compared to prescribed savanna burning, a land management activity that contributes ~1.5% to Australia's national GHG emissions and is 25% of the Northern Territory's annual emissions (Commonwealth of Australia, 2015). Annual emissions from these activities (historic and future savanna deforestation and prescribed burning), were estimated at three scales; catchment, state/territory and regional. Emissions estimates from deforestation and savanna burning were compiled for the Douglas-Daly River catchment (area 57, 571 km^2), the savanna area of Northern Territory (856,000 km^2) and for the savanna region of north Australia (1.93 million km^2) as defined by Fox et al. (2001, Fig. 1, insert).

Historic deforestation emissions from the Douglas-Daly catchment were estimated using satellite-derived clearing areas (1990-2013) for the catchment as reported by Lawes et al. (2015). These annual deforestation areas were combined with our estimate of GHG emissions from the CS site to give a mean annual estimate in Gg CO_2-e y^{-1}. To estimate GHG emissions from savanna deforestation at state/territory and regional scales, data for the Northern Territory and the north Australian savanna region were taken from the reported emissions under Activity A.2 under the Land Use, Land-Use Change and Forestry sector of State and Territory Greenhouse Gas Inventories

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(Commonwealth of Australia, 2015). Annual reporting of these GHG emissions is state based, not biome based, and for the regional savanna estimate, data for Western Australia, the Northern Territory and Queensland were used but included only the area within each state that was as defined as savanna after Fox et al. (2001, Fig. 1) and emissions from each state were summed to give the north Australian savanna regional estimate.

To estimate the GHG emissions from future expanded deforestation across north Australia, we upscaled our estimate of deforestation emissions per hectare using the areas identified as having future clearing potential following the land use assessment of north Australian catchments by Petheram et al., (2014). This preliminary assessment identified catchments to be cleared based upon surface water storage potential and proximity of land resources suitable clearing for irrigation development to enable high-value farming such as irrigated agriculture, horticulture or improved pasture. Using these criteria, suitable catchments in Western Australia (Fitzroy River, Ord Stage 3; 75 000 ha potential area), the Northern Territory (Victoria, Roper Rivers, Ord Stage 3, Darwin-Wildman River area; 114, 500 ha) and Queensland (Archer, Wenlock, Normanby, Mitchel Rivers; 120 000 ha) were selected. This gives a projected savanna clearing area of 311, 000 ha, equivalent to an additional 16% of cleared land over and above the 1,886,512 ha that has been cleared across the savanna biome since 1990 (Commonwealth of Australia, 2015). Projected emissions calculations included emissions from historic emissions plus additional emissions estimates from the expanded deforestation areas. Emissions from the expanded deforestation areas were calculated assuming any such clearing would occur over a five year period. This filter provided identical areas for comparison of mean annual savanna deforestation and prescribed burning emissions.

For savanna burning, CH_4 and N_2O emissions were calculated using the on-line Savanna Burning Abatement Tool (SAVBat2, www.savbat2.net.au), where an area is defined using satellite derived burnt area mapping (www.firenorth.org.au) and pre-defined Vegetation Fuel Types (VFTs) mapping (Fisher and Edwards, 2015; Thackway, 2014). In accordance with IPCC accounting rules,

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only non-CO_2 fluxes are reported for savanna burning, as it is assumed that CO_2 emissions from dry season burning is entirely offset by growth of vegetation (mostly C_4 grasses) in subsequent wet season(s) (IPCC, 1997). To estimate emissions, SAVBat2 uses satellite derived burnt area mapping as generated by the North Australia Fire Information (NAFI) system (www.firenorth.org.au), following methods described by. These estimates were compiled for the three savanna areas of interest; the Douglas-Daly River catchment, the Northern Territory and the north Australian savanna region. Mean annual burning emissions for 1990-2013 were calculated and are reported as non-CO_2 only (CH_4, N_2O) and total emissions (CO_2, CH_4 and N_2O) in Gg CO_2-e.

3.0 Results

3.1 Pre-clearing site comparisons

Comparisons between the two sites were made using pre-clearing meteorology, flux observations and energy balance closure (Figs. 2, 3) to ensure the CS and UC sites were comparable. Table 3 provides NEE, Re and GPP for each LUC phase for each site in Mg ha^{-1} per month. Flux measurements prior to clearing (intact canopy phase) were made for 161 days, a period spanning the late dry to early wet season transition (September-December) through to the mid-wet season (January-February, Table 2). Energy balance closure was high at the CS site with a regression of the energy balance components giving a slope of 0.91 for this site (Fig. 2, Phase 1). At the UC site this slope was 0.87 using all available data (2007-2015). Seasonal patterns of T_{air}, VPD (Fig. 3b), LAI (Fig 3c) and C fluxes (NEE, GPP, Re, Fig 3d) were similar when both sites were intact, although rainfall was 340 mm higher at the UC site (Table 3). At both sites, NEE shifted from being a weak sink of less than -1 µmol CO_2 m^{-2} s^{-1} during the late dry season, to a net source of CO_2 during the early wet season (Fig. 3d). During this period, Re increased rapidly from +2 µmol m^2 s^{-1} to +5 µmol m^2 s^{-1} in early October with the onset of wet season rain, but then remained relatively constant for the remainder of the wet season.

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As the wet season progressed, temporal patterns of GPP were similar at both sites and steadily increased to -6 to -7 µmol m^{-2} s^{-1} and remained at this rate until cleared (March 2012). Re was relatively stable during this period and NEE increased to -2 µmol m^{-2} s^{-1} through the wet season (December to February). Despite the higher rainfall received at the UC site, mean monthly NEE, GPP and R_e differed by <10% (Table 3, intact canopy phase). Normalising fluxes by MODIS LAI for each site further reduced differences to 2% (data not shown), suggesting site differences were small and the UC site provides a suitable control for the CS site.

3.2 Fluxes following clearing

Clearing of the 295 ha block commenced on 2 March 2012 and the bulldozers reached the footprint of the flux tower at ~0900h local time on 6 March (Fig. 3a,b). The four day clearing event occurred during relatively high soil moisture conditions, with surface (5 cm depth) θ_v ranging from 0.08 to 0.10 m^3 m^{-3} and sub-soil θ_v (50 cm depth) ranging from 0.12 to 0.14 m^3 m^{-3}. As a result, pre-clearing fluxes were high and NEE reached -15 µmol CO_2 m^{-2} s^{-1} during the middle of the day (Fig. 4). Mean daily NEE for the week prior to clearing was a net CO_2 sink of -0.60 ± 0.63 µmol m^{-2} s^{-1}, and was not significantly different to mean daily NEE at the UC site of -0.80 ± 0.93 µmol m^{-2} s^{-1} (ANOVA, $P<0.03$). For the three weeks following clearing, the CS site rapidly became a net source of CO_2 with a mean daily NEE of +4.38 ± 0.24 µmol m^{-2} s^{-1}, with a much reduced diurnal amplitude and no response to rainfall events (Fig 4a,b).

Table 3 provides values of rainfall and monthly NEE, Re and GPP for the remaining seven LUC phases following clearing, namely debris decomposition and curing (153 days), burning (22 days), wet season regrowth (80 days), followed by soil tillage and preparation of irrigated raised soil beds (181 days). For each phase, the comparable flux estimate from the UC site is estimated for all post clearing phases and for the entire observation period (Table 3). Following clearing GPP at the CS site was reduced by a factor of 3.5 when compared to the UC for the same period (March 2012 – January 2013, Table 3). While greatly reduced, GPP still occurred at the CS site during this

13.7 month period (-0.38 Mg C ha^{-1} month^{-1}), via re-sprouting of felled overstorey and sub-dominant trees and shrubs, as well as grass germination and growth stimulated by early wet season rainfall (November 2012-January 2013, 361 mm, Table 3). Ecosystem respiration during this period was higher at the UC site (+1.12 Mg C ha^{-1} month^{-1}) when compared to the CS site (+0.82 Mg C ha^{-1} month^{-1}) and given the large decline in GPP, the CS site was a small net C source at +0.51 Mg C ha^{-1} month^{-1}, as compared to the UC site which was a weak sink of -0.03 MG C ha^{-1} month^{-1}.

Cumulative NEE over all the post-clearing LUC phases was +7.2 Mg C ha^{-1} at the CS site as compared to a net sink of -0.78 Mg C ha^{-1} at the UC site (Table 3). The temporal dynamics of cumulative NEE across all LUC phases (note differences in phase duration) is summarised in Fig. 5, which compares fluxes from both sites for the complete observation period. Three significant periods of C emission are evident in Fig. 5. Firstly, the clearing event and the subsequent switch from a C sink to a net source of 1.9 Mg C ha^{-1} due to soil disturbance and the decomposition of biomass. Secondly, this was followed by a reduction in source strength over the dry season of 2012, attributable to a reduction in Re during the dry season (2012 dry season pre-burn phase, Table 3). Thirdly, there were other major emissions attributed to soil tillage and bed preparation in the wet and dry seasons of 2013, a cumulative net emission of +2.75 Mg C ha^{-1} that occurred over the final six months (Fig. 5) in preparation for cropping.

3.4 Emissions from debris burning

At the CS site, the fuel distribution of cleared debris was dominated by heavy fuels (> 6 mm diameter, as defined by Russell-Smith et al., 2009), with a mean (±sd) above-ground biomass of 27.9 ± 7.5 Mg C ha^{-1} and a range of 14.4 to 39.3 Mg C ha^{-1} across the eight biomass plots. The mean coarse root biomass was estimated at 10.6 ± 2.9 Mg C ha^{-1}. The CWD pool was assessed using six transects and was spatially variable, with mean CWD of 1.5 ± 1.8 Mg C ha^{-1}. Grass biomass was assessed at 0.9 Mg C ha^{-1}. The total biomass from the four pools was estimated to be 40.9 Mg C ha^{-1} which became the fuel load following clearing, soil ripping and lifting of tree stumps and associated root mass, 5 months of dry season curing and stocking piling. We assumed 90% of all coarse fuels were consumed with 10% ash and charcoal remaining as observed by Russell-Smith et al. (2009b) for late dry season fires. Using this biomass data with savanna emission factors for CO_2, CH_4 and N_2O, the estimated emission from debris burning totalled 128.0 Mg CO_2-e ha^{-1}.

3.5 Total GHG emission

Emissions derived from debris burning needs to be combined with the post-clearing NEE as measured by the EC system to provide a total GHG emissions estimate from this LUC in units of CO_2-e. The LUC phases following clearing spanned a 502 day period (Table 3), and NEE was +7.2 Mg C ha^{-1} (Table 3), which is in units of CO_2-e +26.4 Mg CO_2-e ha^{-1}. In comparison, NEE from the UC site over the same period was -0.78 Mg C ha^{-1} or -2.9 CO_2-e ha^{-1}. Adding emission from debris burning to NEE gave a total emission of +154.4 Mg CO_2-e ha^{-1} for the CS site, although the fire-derived non-CO_2 emission was only 3% of this total. The CO_2-only emission from fire plus NEE was +150.9 Mg CO_2 ha^{-1} which was a flux 50 times larger than the observed savanna CO_2 sink at the UC site over this post-clearing period.

3.6 Upscaled and projected emissions from deforestation and savanna burning

Table 4 provides mean (±sd) emissions estimates for the two of the most significant GHG burning and deforestation for 1990-2013. At all spatial scales, burnt area dwarfed the land area deforested. For the Douglas-Daly catchment area, reportable non-CO_2 emissions from savanna burning were 577±124 Gg CO_2-e y^{-1}, almost four times larger than emissions from the mean annual savanna deforestation rate of 163±162 Gg CO_2-e y^{-1}. For the Northern Territory savanna, annual burning emissions were an order of magnitude larger than deforestation (Table 4) and two orders of magnitude larger if CO_2 emissions were included. At the regional scale of the northern Australian savanna, the deforestation rate was 16,161±5,601 Gg CO_2 y^{-1}, with emissions from Queensland savanna area dominating this amount at 15,762±5,566 Gg CO_2 y^{-1}. This is an emission double that of the reportable savanna emission of 6,740±1,740 Gg CO_2 y^{-1} (Table 4).

Emissions estimates that include future deforestation rates would be equivalent to savanna burning, at least for the duration of the additional clearing. For the Douglas-Daly catchment, this future emission is estimated at 781 Gg CO_2-e y^{-1} and across the Northern Territory savanna area, this would be 3,574 Gg CO_2-e y^{-1}, similar to current savanna burning emissions for the Douglas-Daly catchment and the Northern Territory (Table 4). Emissions that include future deforestation rates for the northern Australian savanna region were estimated at 24,769 Gg CO_2-e y^{-1} and would be ~30% in excess of current regional savanna burning emissions.

4.0 Discussion

Australia has lost approximately 40% of its native forest and woodland since colonisation (Bradshaw, 2012), with most of this clearing for primary production in the eastern and south-eastern coastal region. Attention has now turned to potential development of the largely intact northern savanna landscapes, which will involve trade-offs between management of land and water resources for primary production and biodiversity conservation (Adams and Pressey, 2014; Grundy et al., 2016). Globally and in Australia, savanna fire ecology and fire derived GHG emissions have been reasonably well researched (Beringer et al., 1995; Cook and Meyer, 2009; Livesley et al., 2011; Meyer et al., 2012; Walsh et al., 2014; van der Werf et al., 2010) and the impacts of fire on functional ecology of Australian savanna has been recently reviewed by Beringer et al. (2015). In this study, we have focussed upon savanna deforestation and land preparation for agricultural use.

Eddy covariance measurements

We used the eddy covariance methodology as it provides a direct and non-destructive measurement of the net exchange of CO_2 (and other GHG gases) at high temporal resolution, ranging from 30-min intervals to daily, monthly, seasonal and annual estimates. It is a full carbon accounting tool as all exchanges of CO_2 from autotropic and heterotrophic components of the ecosystem undergoing change are quantified. This makes it a useful tool for bottom-up GHG and carbon accounting studies as micrometrological conditions and associated fluxes can be tracked through time for the duration of a land use conversion (Hutley et al., 2005).

At the CS site, burning of post-clearing debris of comprised 83% of the total emission of 154.4 Mg CO_2-e ha^{-1} (0.154 Gg CO_2-e ha^{-1} y^{-1}), with the remainder attributed to the net ecosystem exchange of CO_2 as measured by the flux tower. This comprised significant CO_2 losses via respiration of debris, enhanced soil CO_2 efflux from soil disturbance and tillage, which was partially offset by net uptake of CO_2 from woody re-growth, re-sprouting, grass germination and growth (Fig. 5). Soil disturbance via ripping, tillage and preparation was responsible for almost 10% of the CO_2 emission from the conversion. The EC flux tower was operational during the clearing event, demonstrating the utility of this method as the switch of the ecosystem being a net CO_2 sink to being a net source occurred over a few hours of the clearing event completing (Fig. 3). During the LUC phase changes, there was little evidence of major pulses of CO_2 flux, instead there was a rapid transition to a new diurnal pattern following management events, such as the clearing (Fig. 4) or the commencement of soil preparation (data not shown). This is in contrast to non-CO_2 fluxes emissions, in particular N_2O, with short term emissions often follow disturbance (Grover et al., 2012; Zona et al., 2013).

The net CO_2 source as measured by the flux tower represents an emission that would be missed if vegetation biomass density alone was used to estimate LUC emissions, the approached used in current remote sensing studies for regional and national accounting purposes. As such, the emission associated complete oxidation of biomass by fire would be more comparable to reported deforestation emissions. The total GHG emission we report in this study is more accurately described as a land conversion, as it includes the oxidation of biomass plus emissions associated with soil disturbance and tillage required for a conversion to a cropping or grazing system.

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The emission estimate from this study does not include non-CO_2 soil derived fluxes of CH_4 and N_2O, which can be significant for LUC events in certain ecosystems (Tian et al., 2015). Grover et al. (2012) compared soil CO_2 and non-CO_2 fluxes from native savanna with young pasture and old pastures (5-7 and 25-30 years old) in the Douglas-Daly River catchment. Soil emissions of CO_2-e were 30% greater on the pasture sites as compared with native savanna sites, with this change being dominated by increases in CO_2 emission and soil CH_4 exchange shifting from a small net sink to a small net source at the pasture sites. Non-CO_2 soil fluxes were generally small, especially N_2O emissions, although these measurements were made many years after the LUC event and there is uncertainty as to their relevance for a recently deforested and converted savanna site. An additional pathway for CH_4 and N_2O emissions in these savannas is through termite activity (Jamali et al., 2011a, 2011b), and in our study, termite mounds were abundant across the CS site, but were largely destroyed by clearing and soil preparation, potentially reducing net non-CO_2 emissions. Further work is required to quantify these fluxes and refine our total emission estimate for this LUC event.

This land conversion represents the loss of decades of carbon accumulation in this mesic savanna (>1000 mm MAP), ecosystems which are currently thought to a weak carbon sink (Beringer et al., 2015). The 8-year ensemble mean NEE for the UC site was -0.11 ± 0.16 Mg C ha^{-1} y^{-1} and is representative of a savanna site at or near a near-equilibrium state in terms of carbon balance, given the moderate fire frequency (1 in 5 years, Table 2) with high severity fires uncommon (1 in 8 years of measurement). The annual increase in tree biomass at this UC site is 0.6 t C ha^{-1} y^{-1} (Rudge, Hutley, Beringer unpublished data), suggesting a regeneration period of approximately four decades after stand replacing disturbance event (extreme fire, cyclone, flood, harvest). Even after the large pool of carbon is lost following oxidation of biomass, carbon loss will continue on cleared land via continued soil carbon mineralisation leading to a slow decline in soil carbon storage that is frequently reported for forest to cropping LUC systems (Jarecki and Lal, 2003; Lal and Follett, 2009). Conversion of forest or woodland to improved pasture grazing may result in either increases or decreases in soil carbon (Sanderman et al., 2010). Alternatively, it is possible that carbon sequestration may occur post-clearing via woody regrowth if a cleared site is abandoned and not further prepared for cultivation. This has actually been a relatively common transition and a significant sequestration pathway that needs to be included in savanna LUC assessments (Henry et al. 2015). Admittedly, if savanna cleared land does fully transition to a cropping system, some fraction of the lost carbon could also be replaced or sequestered by the new agricultural or horticultural land use.

There are few detailed, plot scale studies of GHG emissions from savanna clearing in north Australia. Several studies (Law and Garnett 2009, 2011) used the Full Carbon Accounting Model (FullCAM Ver 3.0, Commonwealth of Australia, 2015a; Richards and Evans, 2004) to generate spatial maps of above- and below-ground biomass and soil organic carbon pools across the NT. The FullCAM model uses spatial and temporal soil, climate, rainfall data with NVIS major vegetation classes to simulate carbon losses (as GHG emissions) and uptake between the terrestrial biological system and the atmosphere. Land use change scenarios can be run within the model and Law and Garnett (2009) examined deforestation emissions from the Eucalypt woodland NVIS vegetation class, as per UC and CS site classification. Modelled emissions were 136±42 Mg CO_2-e, comparable to the deforestation (fire only) estimate of 128 Mg CO_2-e reported in our study.

Henry et al. (2015) used a life cycle assessment approach to quantifying GHG emissions from LUC associated with beef production in eastern Australia. Australia's major beef producing areas across central and southern Queensland and northern central New South Wales were classified into 11 bioregions, with the northern most bioregion, the northern Brigalow Belt, falling within the savanna biome. Vegetation biomass from this bioregion was estimated at 84.7±7.1 Mg ha^{-1} or ~41.4 Mg C ha^{-1}, with an emission estimated at 129 Mg CO_2-e (Henry et al., 2015), almost identical to the woodland biomass density and resultant emission with deforestation (fire derived emission) from the CS site of this study.

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Our emissions estimate is robust for this vegetation class and can be upscaled and as such can be compared and upscaled with other land sector activities, such as prescribed savanna burning. At a regional scale, current levels of savanna burning dominate emissions compared to land clearing rates (Table 4). The cumulative deforestation across the savanna region since 1990 (1,886,512 ha) is 17 times smaller than the annual savanna burn area as approximately 30 to 70% of the savanna area is burnt annually (Russell-Smith et al., 2009a). Modelling NEP for savanna biome for 1990-2010 (Beringer et al., 2015; Haverd et al., 2013), suggests the north Australia savanna is near carbon neutrality, or is a weak source of CO_2 to the atmosphere once regional scale fire emission are included. As such, the IPCC assumption that CO_2 emissions from the previous year's burning are recovered by the following year's wet season growth may have some validity for regional scale GHG accounting. This assumption at plot to catchment scales may not be valid, as localised interannual variability in rainfall, site history and fire regimes may result in either net accumulation or loss of carbon (Hutley and Beringer, 2011; Murphy et al., 2014, 2015). Assuming year to year CO_2 loss from burning is re-sequestered, assessment of the non-CO_2 only emissions from savanna burning with clearing is useful. This comparison suggests projected deforestation emissions (24,769 Gg CO_2-e y^{-1}, Table 4) could be well in excess of current annual burning emissions, at least for the period of enhanced clearing, which in this study, we assume to be five years.

In 2013, Australia's total reported GHG emission was 548,440 Gg CO_2-e and the impact of expanded savanna deforestation on the national emission can be estimated using data in Table 4. Table 4 provides the mean annual emission rate from an annual deforested area, giving a mean annual deforestation emission per ha averaged for the entire savanna area, which is 221±50.8 Mg CO_2-e ha^{-1} using 1990 to 2013 data (Commonwealth of Australia, 2015). This value represents a spatially averaged emission as it is derived from the full range of savanna vegetation types and above-ground biomass, which across the Northern Territory savanna area ranges from 10 to 70 Mg C ha^{-1} (Law and Garnett, 2011). Assuming this emission per ha, an additional 311, 000 ha of

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savanna deforestation, cleared over a five year period, adds 12,099 Gg CO_2 y^{-1}. For the duration of the expanded deforestation, this is a 2.2% increase to Australia's nation emission over and above the historic LUC emissions, which are 2.9% of national emissions. Using our finding that a land conversion (deforestation followed by site tillage and preparation for cultivation) adds an additional 17% of GHG to a deforestation event, northern land development could increase Australia's GHG by ~6% per annum for the duration of the expanded deforestation period.

This assessment is subject to a number of uncertainties. Firstly, a component of our emissions estimate is based on eddy covariance measurements of CO_2 flux, which typically have an error of 10-20% (Aubinet et al., 2012). In this study, energy balance closure suggested fluxes were underestimated by up to 19% across the entire observation period (Fig. 2). Energy balance closure ranged from <10% flux loss during the intact canopy phase to >20% error during the final three LUC phases when the flux instruments were at 3 m height measuring net soil CO_2 emissions from the smoothed, vegetation-free ploughed soil surface during preparation.

Secondly, it is difficult to predict the nature of future deforestation (rate, area and specific location) and development across the savanna region and the emissions comparison presented here is indicative only. Catchments selected by Petheram et al. (2014) regarded as suitable or with potential to be cleared in the future and were based on biophysical properties and were unconstrained by the regulatory environment and they did not account for conservation and cultural values placed on identified land and water resources. In addition, challenges to agricultural expansion in northern Australia include uncertain land and water tenure, high development costs and lack of existing water infrastructure, logistics and technical constraints, lack of human capital and distance to market, are all factors that are likely to restrict land clearing. It is well understood that the availability and cost of water for irrigated, or irrigation assisted agriculture is critical for viable agriculture in northern Australia (Petheram et al., 2008, 2009). Australian government policies currently support small-scale, precinct or project scale approaches, based on well-

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understood water and soil resources, where water allocation is capped. The current policy and market instruments are likely to ensure that development remains measured and restricted, unlike development of previous decades in other regions of eastern and southern Australia.

As a result we used a conservative estimate of potential land suitability area (311, 000 ha over a five year clearing period), as estimates of assumed clearable area range up to 700,000 ha (e.g., Douglas-Daly catchment, Adams and Pressey, 2014) or over 1 million ha across north Australia (Petheram et al. 2014), areas that may be unlikely given capital investment requirements as well as conservation and cultural considerations. Our comparison with burning emissions is also influenced by the clearing period we assume. This was based on patterns of historic rates of clearing as there are periods when deforestation rates have easily exceeded 311,000 ha over five years periods, particularly in Queensland (Commonwealth of Australia, 2015), but longer clearing duration reduces the annual totals and impact on the national GHG account.

5.0 Conclusions

While GHG emissions from savanna deforestation are dominated by debris burning, emissions from soil tillage and soil bed preparation is likely to be 20% of the total emission, suggesting satellite-based emissions based on oxidation of cleared vegetation alone do not capture all phases of LUC prior to cultivation. Savanna burning using the area as defined in this study was 1.5% of Australia's national GHG emissions and is of similar magnitude to emissions associated with historic savanna deforestation. However, for the deforestation scenario as described in this study (an addition of 311 000 ha of deforestation over five years), Australia's GHG emissions could increase by between 5 to 10% for the duration of the expansion, depending on the area deforested. These are indicative estimates only, but suggest that the impacts of northern agricultural development will have some impact on the national GHG budget and will need to be considered in northern land use decision making processes. These considerations are also particularly relevant given the emission reduction targets set by Australia following the 21st Conference of Parties to the UN Framework

Convention on Climate Change (COP21 / CMP11) to reduce GHG emissions by 26 to 28% of 2005 by 2030.

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Table captions

Table 1 Site characteristics for the uncleared savanna (UC) and cleared (CS) sites. Site soil orders are given as per Isbell (2002) with savanna vegetation classified using Fox et al. (2001). Fire frequency was estimated from fire mapping taken from the North Australian Fire Information system (NAFI, www.firenorth.org.au) for 2000-2013. Basal area and stem density is provided for all woody stems >5 cm DBH at both sites CS sites. Mean site LAI for UC is from Hutley et al. 2011 and for the CS site, it was estimated from canopy hemispherical photos, see text for details.

Table 2 Characteristics of land conversion phases during the 668 day observation period at the savanna clearing site (CS). Also given are the canopy heights following LUC phases and flux tower heights that were adjusted following clearing, burning and then soil preparation phases.

Table 3 Mean rainfall, NEE, Re and GPP for each of the land use change phases at the CS site as measured by the eddy covariance tower. Comparative fluxes are given for the UC site for the identical periods. On the days of ignition during the debris burning phase, flux data at the CS site were excluded. Integrated fluxes are given for the post-clearing period (507 days) and the entire observation period (668 days) for both sites.

Table 4 Greenhouse gas emissions for 1990-2013 from prescribed savanna burning and savanna deforestation at catchment (Douglas-Daly River), state/territory (Northern Territory savanna area) and regional scales (north Australian savanna area, Fig. 1). For savanna burning, burnt area and associated mean annual emissions (± sd) are given for both reportable non-CO_2 (CH_4, N_2O) and total emissions (CO_2, CH_4 and N_2O). For the identical areas as used for savanna burning, mean annual GHG emissions from deforestation (± sd) are given. For the Douglas-Daly River catchment, deforestation area was taken from Lawes et al. (2015) and combined with deforestation emissions from the CS site. Deforestation emissions (1990-2013) for the NT and the north Australian savanna area are taken from the State and Territory Greenhouse Gas Inventories (Commonwealth of Australia, 2015). In bold text are the emissions associated with the current deforestation rate plus expanded deforestation areas as identified by Petheram et al. (2014), which are combined with emissions from the CS site to give an upscaled estimate of potential emissions with agricultural development at the three spatial scales.

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Table 1

Site	*UC*	*CS*
Location	14°09'33.12"S, 131°23'17.16"E	14°33'48.71"S, 132°28'39.47"E
Soils	Red Kandosol (Blain)	Red Kandosol (Blain)
	Woodland savanna	Woodland savanna
Vegetation type, dominant species	Map unit **D4**. *E. tetrodonta, C. latifolia, Terminalia grandiflora, Sorghum spp, Heteropogon triticeus*	Map unit **D4**. *E. tetrodonta, Erythrophleum chlorostachys, C. bleeseri, Sorghum spp, H. triticeus*
Map unit area **(**km^2)	59,986	59,986
Fire frequency (y^{-1})Error! Hyperlink reference not valid.	0.3	0
Basal area (m^2 ha^{-1})	8.3	6.8
Canopy height (m)	16.4	14.2
Stem density (ha^{-1})	330 ± 58	643 ± 102
Overstorey LAI (wet/dry)	n/a / 0.8	0.9 / 0.5
MODIS LAI (wet/dry)	1.5 / 0.9	1.6 / 1.0
MAP (mm)	1372[a] /1180[b]	1107[c]
Max T_{air} (°C)	37.5 (Oct) / 31.2 (Jun)	37.5 (Oct) / 29.7 (Jun)
Min T_{air} (°C)	23.8 (Jan) / 12.6 (Jul)	25.0 (Nov) / 13.7 (Jul)

[a]On-site observations, 2007-2012, [b]gridded rainfall (AWAP, 1970-2012), [c]Tindal BoM station (14.52S, 132.38E, data from 1985-2013).

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Table 2

Season	*Period*	*LULUC phases*	*Canopy height (m)*	*Tower height (m)*
Late dry season	Sep - Oct 2011	Intact savanna	16	23
Wet season pre-clearing	Oct 2011 - Feb 2012	Intact savanna	16	23
Wet season clearing	Mar - May 2012	Savanna cleared using bulldozers, followed by debris decomposition, understory grass germination	2-4	7
Dry season pre-burn	May - Aug 2012	Vegetation debris curing, understorey grass growth	2-3	7
Debris burning	Aug 2012	Debris and grasses burnt then stockpiled, re-burnt	0	7
Dry season post-burn	Aug - Nov 2012	Vegetation removed, followed by grass and shrubs germination and resprouting	0-1	7
Early wet season	Nov 2012 - Jan 2013	Site cultivation removal remaining below-ground biomass. Rainfall stimulation of grass, shrubs and trees germination and growth	1-3	7
Wet season	Jan - Mar 2013	All regenerated vegetation removed via soil cultivation	0	3
Dry season	Apr - Jul 2013	Soil cultivation in stages	0	3

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Table 3

LULUC phases	*Period*	*CS*				*UC*			
		Rainfall	*NEE*	*Re*	*GPP*	*Rainfall*	*NEE*	*Re*	*GPP*
	(d)	*(mm)*	(Mg C ha^{-1} $month^{-1}$)			*(mm)*	(Mg C ha^{-1} $month^{-1}$)		
Intact canopy cover	161	736.6	-0.23	1.57	-1.79	1076.8	-0.25	1.45	-1.70
Clearing event	4	59.4	0.23	1.95	-1.73	59.8	0.38	1.80	-1.50
Wet-dry debris curing, decomposition	59	143.2	0.98	1.39	-0.41	412.0	0.32	1.53	-1.22
Dry season pre-burn	94	0	0.34	0.57	-0.23	2.4	0.15	0.94	-0.79
Fire emissions late dry	22	0	0.90	0.76	0.0	0.0	-0.01	0.71	-0.72
Dry season post-burn	67	2.2	0.31	0.37	-0.06	64.4	-0.28	0.64	-0.91
Early wet regrowth	80	361.0	0.03	0.99	-0.96	345.8	-0.32	1.80	-2.12
Wet season site prep	91	701.7	0.62	0.99	-0.37	914.4	-0.20	1.67	-1.88
Dry season final bed prep. and cultivation	90	0	0.29	0.32	-0.02	10.8	0.06	0.91	-0.85
Total post-clearing	507	1267.5	7.2	12.8	-5.6	1809.6	-0.78	20.7	-21.5
Total all phases	668	2004.1	6.0	21.2	-15.2	2886.4	-2.1	28.5	-30.6

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Table 4

Savanna region	*Savanna burning*			*Savanna deforestation*			
	Burnt area[a]	Emissions non-CO_2[a]	Emissions total[a]	Deforestation area	Emissions total	Expanded deforestation area[d]	Expanded emissions total[d]
	(ha y^{-1})	(Gg CO_2-e y^{-1})	(Gg CO_2-e y^{-1})	(ha y^{-1})	(Gg CO_2-e y^{-1})	(ha)	(Gg CO_2-e y^{-1})
Douglas-Daly River catchment	2,482,100 ±490,400	577 ±124	14,270 ±3064	1275 ±454[b]	163 ±162[b]	**20,000**	**781**
Northern Territory	13,419,410 ±487,300	3,490 ±922	86,255 ±22,880	1,717 ±611[c]	398 ±128[c]	**114,500**	**5,949**
North Australian	32,249,254 ±11,176,004	6,740 ±1,729	166,586 ±42,725	78,605 ±34,976[c]	16,161 ±5601[c]	**311,000**	**28,260**

[a]Burnt area and emissions data estimated using the on-line Savanna Burning Abatement Tool (SAVBat2), 1990-2013
[b]Deforestation area data taken from Lawes et al. (2015), upscaled using the emissions from the CS site from this study, 1990-2013
[c]Deforestation area and emissions data taken from the State and Territory Greenhouse Gas Inventories (Commonwealth of Australia, 2015), 1990-2013
[d]Expanded deforestation area data taken from catchments as identified by Petheram et al. (2014), upscaled using the GHG emissions from the CS site from this study and added to historic emissions

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Figure captions

Figure 1 Location of the uncleared site (UC) and the cleared savanna (CS) sites south of Darwin, Northern Territory. The inset figure shows the distribution of the savanna biome across northern Australia as defined by Fox et al. (2001).

Figure 2 Energy balance closure plots using 30 minute flux data from the CS and UC sites. For the CS site, data were grouped according to the LUC phase periods using pooled day time and night time data. Plots are arranged clockwise and labelled ‘Phase 1’ through to ‘Phase 7’, with a further plot of all data pooled from all phases (‘All Phases’). The final plot is the long-term UC site is also plotted using 30 minute data for 2007-2015. Statistical data for each regression is given for each plot.

Figure 3 Comparative meteorology and fluxes for the uncleared (UC) and cleared savanna CS sites prior to the clearing event. Data spans the late dry season (September 2011) through to the mid-wet season prior to the clearing event of 2-6 March 2012. Plots include a) daily rainfall (black bars UC site, grey bars CS site), mean daily T_{air} (black lines UC, grey CS), b) mean daily VPD (dashed lines; black UC, grey CS), c) interpolated 8-day MODIS LAI (black UC, grey CS), d) NEE (black UC, grey CS) partitioned into R_e (red UC, pink CS) and GPP (dark green UC, pale green CS).

Figure 4 a) Daily rainfall and b) diurnal patterns of NEE at the CS site for the week prior to the clearing event of 2-6 March 2012 (vertical bar) and three weeks post-clearing.

Figure 5 Cumulative NEE from the CS (red line) and UC sites (black line) for each land use phase (see Table 2 for details) over the entire observational period, September 2011 to July 2013. The UC site is a long-term savanna site of the Australian flux network (OzFlux, see Beringer et al. 2016) and using the sites’ 8-year flux record (2007-2013), the long-term cumulative mean NEE is plotted for each land use phase of (grey line; ± 95% CI). The dashed line indicates zero net CO_2 flux.

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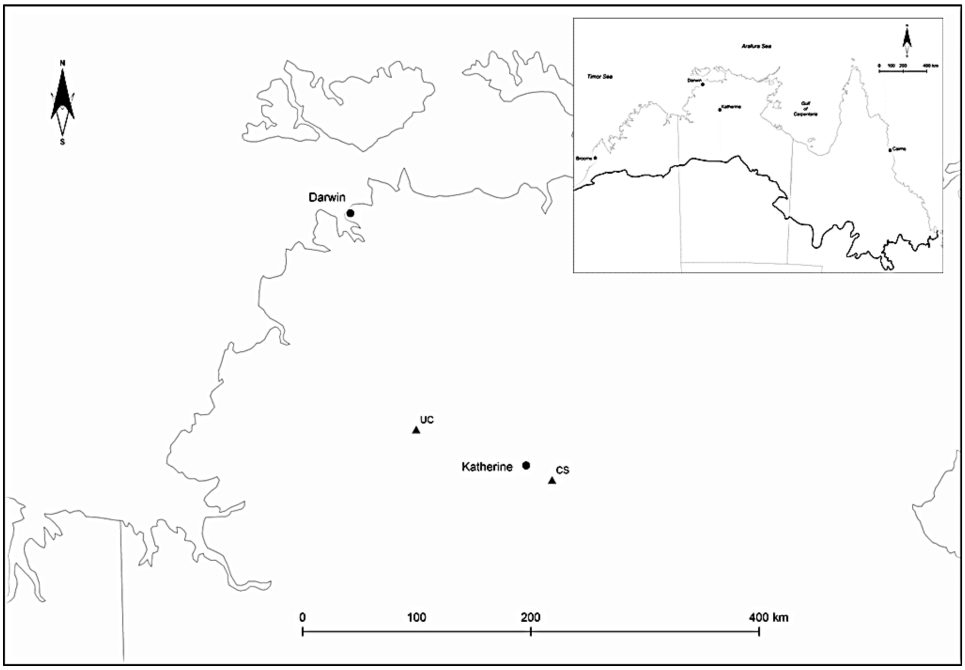
Figure 1



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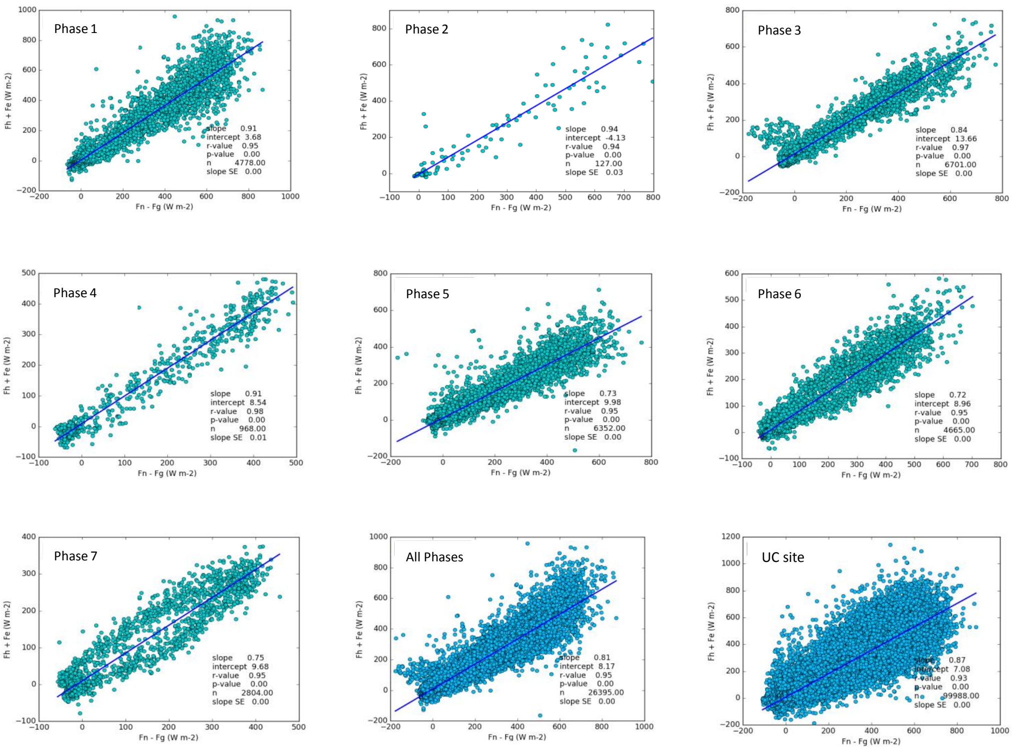
84 Figure 2



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86 Figure 3

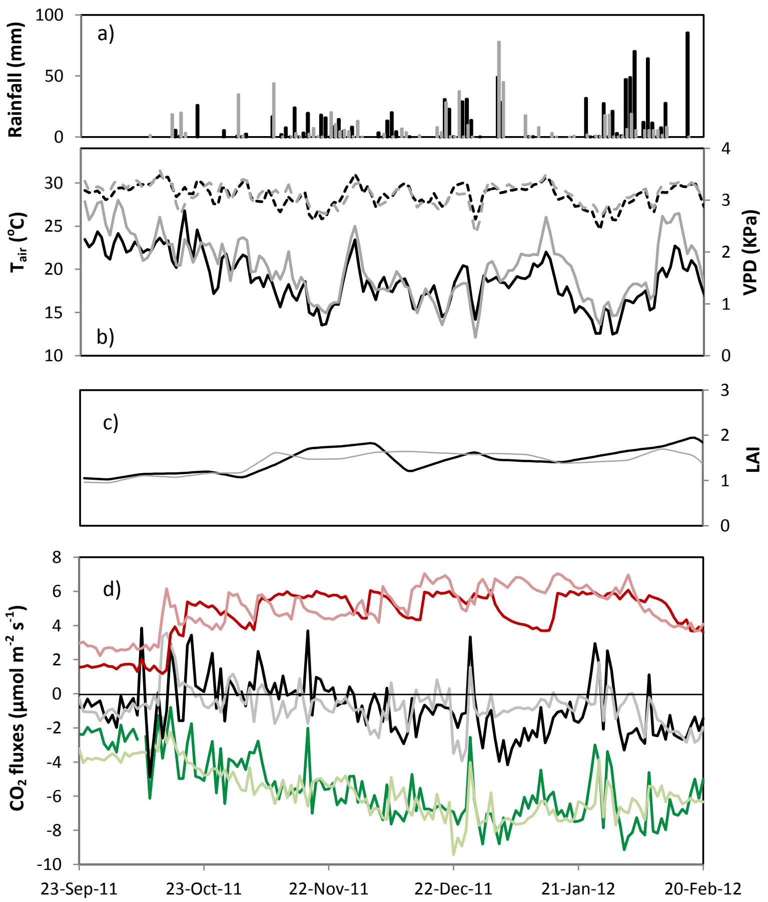
87 

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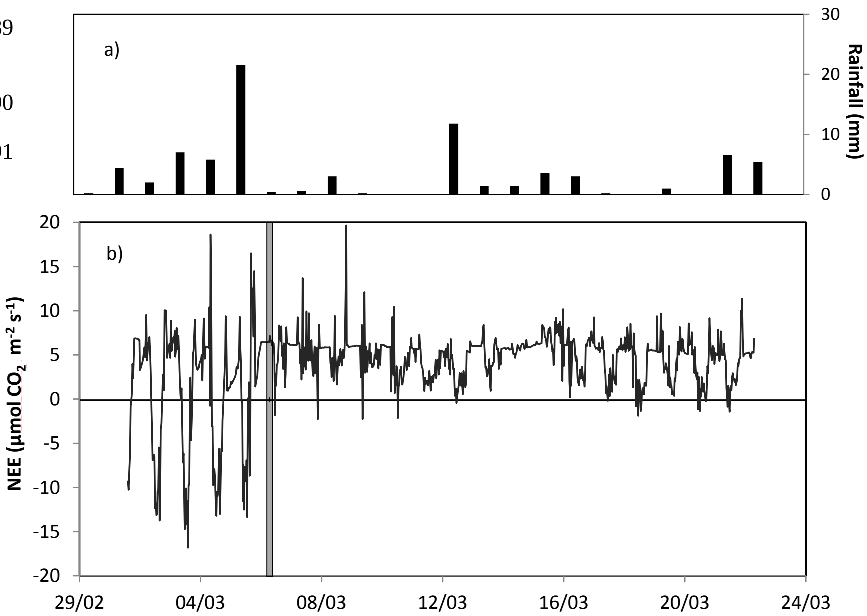
Figure 4



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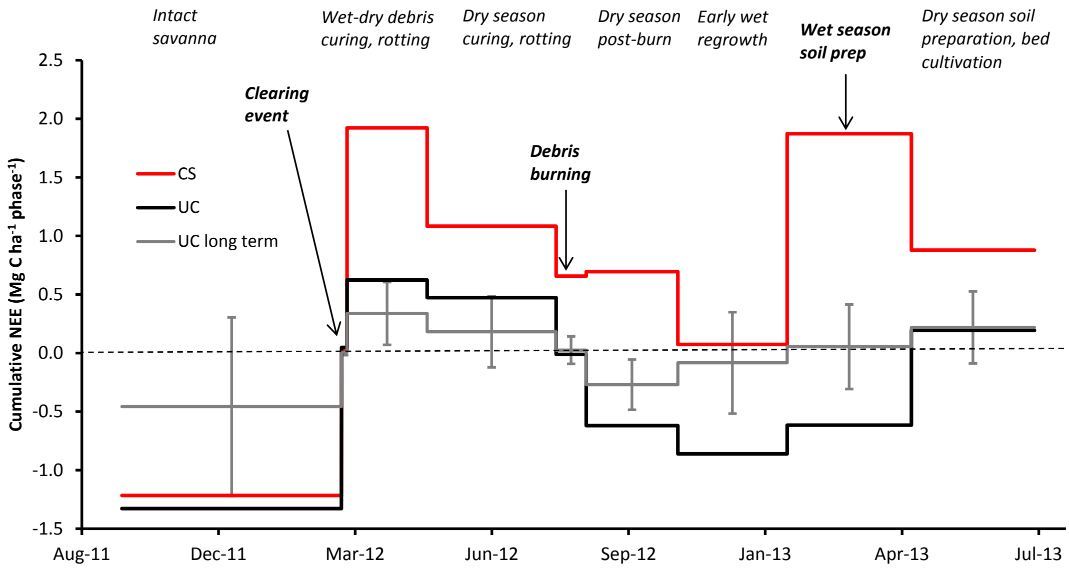
92 Figure 5



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