Developing a savanna burning emissions abatement methodology for tussock grasslands in high rainfall regions of northern Australia

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Abstract

Fire-prone tropical savanna and grassland systems are a significant source of atmospheric emissions of greenhouse gases. In recent years, substantial research has been directed towards developing accounting methodologies for savanna burning emissions to be applied in Australia's National Greenhouse Gas Inventory, as well as for commercial carbon trading purposes. That work has focused on woody savanna systems. Here, we extend the methodological approach to include tussock grasslands and associated *Melaleuca*-dominated open woodlands (<10% foliage cover) in higher rainfall (>1,000 mm/annum) regions of northern Australia. Field assessments under dry season conditions focused on deriving fuel accumulation, fire patchiness and combustion relationships for key fuel types: fine fuels − grass and litter; coarse woody fuels − twigs <6 mm diameter; heavy woody fuels − ≥6 mm diameter; and shrubs. In contrast with previous savanna burning assessments, fire treatments undertaken under early dry season burning conditions resulted in negligible patchiness and very substantial consumption of fine fuels. In effect, burning in the early dry season provides no benefits in greenhouse gas emissions and emissions reductions in tussock grasslands can be achieved only through reducing the extent of burning. The practical implications of reduced burning in higher rainfall northern Australian grassland systems are discussed, indicating that there are significant constraints, including infrastructural, cultural and woody thickening issues. Similar opportunities and constraints are observed in other international contexts, but especially project implementation challenges associated with legislative, political and governance issues.

Resumen

La quema de sabanas y pastizales tropicales es una fuente significativa de emisión de gases con efecto invernadero. En Australia, un número considerable de proyectos de investigación recientes ha sido orientado hacia el desarrollo de metodologías para cuantificar la emisión de gases ocasionada por las quemas, para el Inventario Nacional de Gases de Invernadero ('National Greenhouse Gas Inventory') y con propósitos de comercio de carbono. Esas investigaciones estaban enfocadas en sistemas de sabanas con presencia de especies leñosas en regiones con 500−700 mm de precipitación anual. En el presente trabajo extendimos la metodología para incluir tanto pastizales con especies de crecimiento en matojos ('tussocks grasslands') como los asociados bosques abiertos (<10% de dosel arbóreo), caracterizados por alta presencia de *Melaleuca*, los cuales predominan en regiones de pluviosidad más alta (>1,000 mm/año) en el norte de Australia. Las evaluaciones durante la estación seca se orientaron a la acumulación de material combustible, la heterogeneidad de sitios de fuego y las relaciones con combustión para 4 tipos clave de combustibles: combustibles finos (gramíneas y hojarasca); combustibles leñosos finos tales como chamizas y ramas pequeñas (trozos <6 mm de diámetro); combustibles leñosos gruesos (≥6 mm de diámetro); y arbustos. En contraste con evaluaciones previas de quemas en sabanas, en esta investigación los tratamientos de quema al comienzo de la época seca resultaron en una heterogeneidad insignificante de fuego y en un muy alto consumo de los combustibles finos. En consecuencia la quema en esta época no trae beneficios en la emisión de gases de invernadero; la reducción de gases por quemas en pastizales que crecen en matojos ('tussock grasslands') sólo es posible reduciendo la extensión de las quemas. Se discuten las

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implicaciones prácticas de la reducción de las quemas en áreas de mayor pluviosidad en el norte de Australia y se señala la existencia de importantes limitantes incluyendo infraestructura, la formación de matorrales espesos y aspectos culturales. Se señala, además, que similares oportunidades y limitantes existen en otros países tropicales donde, sin embargo, los retos para implementar proyectos de reducción de quemas son más que todo de índole legislativa, política y de gobernanza.

Introduction

It is widely recognized that, together with interactions with seasonal moisture availability, nutrients and herbivory, fire regimes play a critical role in modifying the floristic composition, vegetation structure and dynamics of tropical savanna and associated grassland systems (Scholes and Archer 1997; Bond 2008; Lehmann et al. 2011). For example, reduced incidence and intensity of burning in northern Australian grazing management systems, as a result of either deliberate fire exclusion or a reduction in the capacity of grassy fuels to support intense fires through heavy grazing pressures, can allow woody plants to become firmly established in grasslands (Noble and Grice 2002; Myers et al. 2004). As a consequence, it is recognized that fire regimes in tropical savanna and grassland systems have substantial effects on carbon stocks and dynamics in living biomass components and associated dead fractions (e.g. Williams et al. 2004; Liedloff and Cook 2007; Bond 2008; Murphy et al. 2010; Smit et al. 2010; Ryan and Williams 2011), and possibly also in soils (Coetsee et al. 2010; Cook et al. 2010; Richards et al. 2011).

In addition to effects of fire regimes on biomass/carbon stocks, fire-prone savanna and grassland systems are a globally significant source of annual greenhouse gas (GHG) emissions. During 1997−2009, fires in savannas (incorporating grassland, open savanna and woodland) were estimated to account for 60% of total global fire emissions; estimates indicate such fires also accounted annually for 36% of methane (CH_4) and 58% of nitrous oxide (N_2O) emissions from fire sources globally (van der Werf et al. 2010). In recognition of the significance of this emissions source, the Kyoto Protocol requires participating Tier 1 (developed economy) countries, where pertinent, to account for emissions of GHGs (specifically CH_4 and N_2O) from "prescribed burning of savannas" (UNFCCC 1998: Article 3, Annex A). Australia, as the only Tier 1 country with substantial savanna coverage, includes savanna burning emissions in its National Greenhouse Gas Inventory (NGGI); typically accountable GHG emissions annually contribute ~3% of Australia's NGGI (ANGA 2011). In accord with international accounting rules, Australia's NGGI does not account for CO_2 emissions from savanna burning on the assumption that CO_2 emissions in one burning season are negated by growth of vegetation in subsequent growing seasons (IPCC 1997). Accountable greenhouse gas emissions from Australian savanna burning are predominantly associated with anthropogenic ignition sources (Russell-Smith et al. 2007).

In accord with other provisions of the Kyoto Protocol (Article 6), which establish a framework for developing market-based instruments to address anthropogenic sources and sinks of GHG emissions, Australia has also established a formal offsets mechanism, the Carbon Farming Initiative (CFI), which "allows farmers and land managers to earn carbon credits by storing carbon or reducing greenhouse gas emissions on the land" (refer CFI website: www.climatechange.gov.au/cfi). One of the first GHG emissions reduction methodologies developed for the CFI has been a savanna burning methodology focusing on higher rainfall regions (>1,000 mm/annum) for fire-prone northern Australia (Russell-Smith et al. 2009; DCCEE 2012; Meyer et al. 2012). An essential premise underlying that methodology is that reductions in fire frequency and intensity result in reduced GHG emissions, because more of the fuel biomass (mostly grass and leaf litter) is decomposed biologically through pathways that, compared with savanna fires, produce lower relevant emissions per unit biomass consumed (Cook and Meyer 2009). The recently approved accounting methodology for savanna burning (DCCEE 2012) establishes strict accounting protocols, prescribing all methodological and calculation procedures, vegetation-fuel type and fire mapping requirements, and use of requisite parameter values, satellite imagery and acceptable data sources.

In this paper, we report research undertaken to extend the current savanna burning methodology (DCCEE 2012) to include an additional fuel type, and associated fuel accumulation (FA) and burning efficiency (BEF) parameters, relating to tropical tussock grasslands under higher rainfall (>1,000 mm/annum) conditions.

While tussock grasslands in northern Australia occur mostly on heavy-textured soils under lower seasonal rainfall conditions (generally ~500−700 mm/annum), and generally support highly productive grazing systems (especially for beef cattle production: Tothill and Gillies 1992; Noble and Grice 2002; Myers et al. 2004), extensive tussock grasslands occur in some higher rainfall savanna regions, especially on western Cape York Peninsula, Queensland. In these latter situations, beef cattle production is generally economically marginal, given mostly infertile soils, limited infrastructure, restricted seasonal access and remoteness from markets (e.g. refer to notes concerning Cape York pastoral industry on the Tropical Savannas Cooperative Research Centre's Savanna Explorer website at www.savanna.org.au/qld/cy/cygrazing.html). In such situations, and in combination with very frequent and extensive late dry season wildfires (Felderhof and Gillieson 2006), market opportunities afforded through savanna burning offsets may provide useful additional economic opportunities.

Tussock grassland (and *Melaleuca* open-woodland) communities occupy 48,600 km^2, or 10.6% of the 456,800 km^2 higher rainfall (>1,000 mm/annum) savanna region, based on Australian National Vegetation Information System (NVIS) mapping (National Vegetation Information System: www.environment.gov.au/erin/nvis/mvg/index.html#mvg30), with the great majority (76%, or 37,000 km^2) occurring on Cape York Peninsula (Figures 1A, 1B). When intersected with available annual fire extent mapping derived from MODIS imagery for the period 2000–2012, 74.7% of Cape York tussock grasslands had burnt at frequencies of 0.3 or greater (i.e. 4 or more times), 48.2% had burnt at frequencies of 0.58 or greater (i.e. 7 or more times) and 6.2% remained unburnt.

In this paper, we: (1) address parameter values required for developing a modified higher rainfall savanna burning abatement methodology addressing tussock grassland conditions; and (2) consider potential benefits and challenges for such a methodology to contribute to grazing and land management enterprises in Australia's higher rainfall savannas.

Materials and Methods

Savanna burning methodology

Components of the currently approved savanna burning methodology are set out in detail in Russell-Smith et al. (2009), DCCEE (2012) and Meyer et al. (2012). Essentially, savanna burning emissions are calculated as the product of the mass of pyrolized fuel and the emission factor (EF) of respective accountable GHGs (CH_4, N_2O). Pyrolized fuel is the product of: the area exposed to fire (derived from satellite mapping sources), taking into account spatial patchiness (calibrated from field studies), x the accumulated fuel load (FA) x the burning efficiency (BEF), defined as the mass of fuel exposed to fire that is pyrolized. Both FA and BEF are determined from field observations.

The methodology takes into account that, in savanna fires, different percentages of combustible fuels (grass, litter, twigs, logs, shrubs) are combusted in different major fuel types (e.g. open-forest, woodland) under different fire intensity conditions. In the current absence of available reliable fire intensity mapping surfaces for northern Australia, and as surrogate for fire intensity, the methodology differentiates between fires of generally lower severity, occurring in the early dry season (before August), and fires of generally higher severity, occurring in the late dry season (typically August−November) (Williams et al. 2003; Russell-Smith and Edwards 2006). A useful description of fire behavior in Australian grasslands is given in Cheney and Sullivan (2008).

The current burning methodology for higher rainfall savanna recognizes 4 major savanna fuel types: open-forest, with woody foliage cover (FC: sensu Specht 1970) of 30−70%; sandstone woodland (FC, 10−30%), typically over hummock (*Triodia* spp.) grasses; woodland (FC, 10−30%), typically over tussock grasses; and shrubby heath, typically with hummock grasses (FC, <30%).

This study addresses adding a fifth broad fuel type, tussock grassland, with woody FC <10%. Under higher rainfall northern Australian conditions, such grasslands may include scattered trees and shrubs, characteristically comprising *Melaleuca* spp. and allied myrtaceous taxa (e.g. *Asteromyrtus*). Under current fire and grazing situations in northern Australia, *Melaleuca* is recognized as being a significant invader of former open (non-woody) grasslands (Garnett and Crowley 1995; Myers et al. 2004; Crowley et al. 2009). The definition of 'tropical grassland' adopted here, allowing for a small component of woody cover (<10%) and recognizing that tropical grasslands occupy one end of the savanna vegetation continuum, is consistent with that used in other international settings (Olson et al. 1983; Scholes and Hall 1996; White et al. 2000; Lehmann et al. 2011).

Methods

Extending the current higher rainfall savanna burning abatement methodology to include tussock grasslands essentially requires obtaining additional data specifically describing grassland pre-fire (FA: fuel accumulation with time) and post-fire (BEF: fire patchiness, combustion efficiency) relationships. Pertinent data for other requisite parameters (e.g. emission factors for CH_4 and N_2O from combustion of fully cured grassy fuels) are already available from the literature.

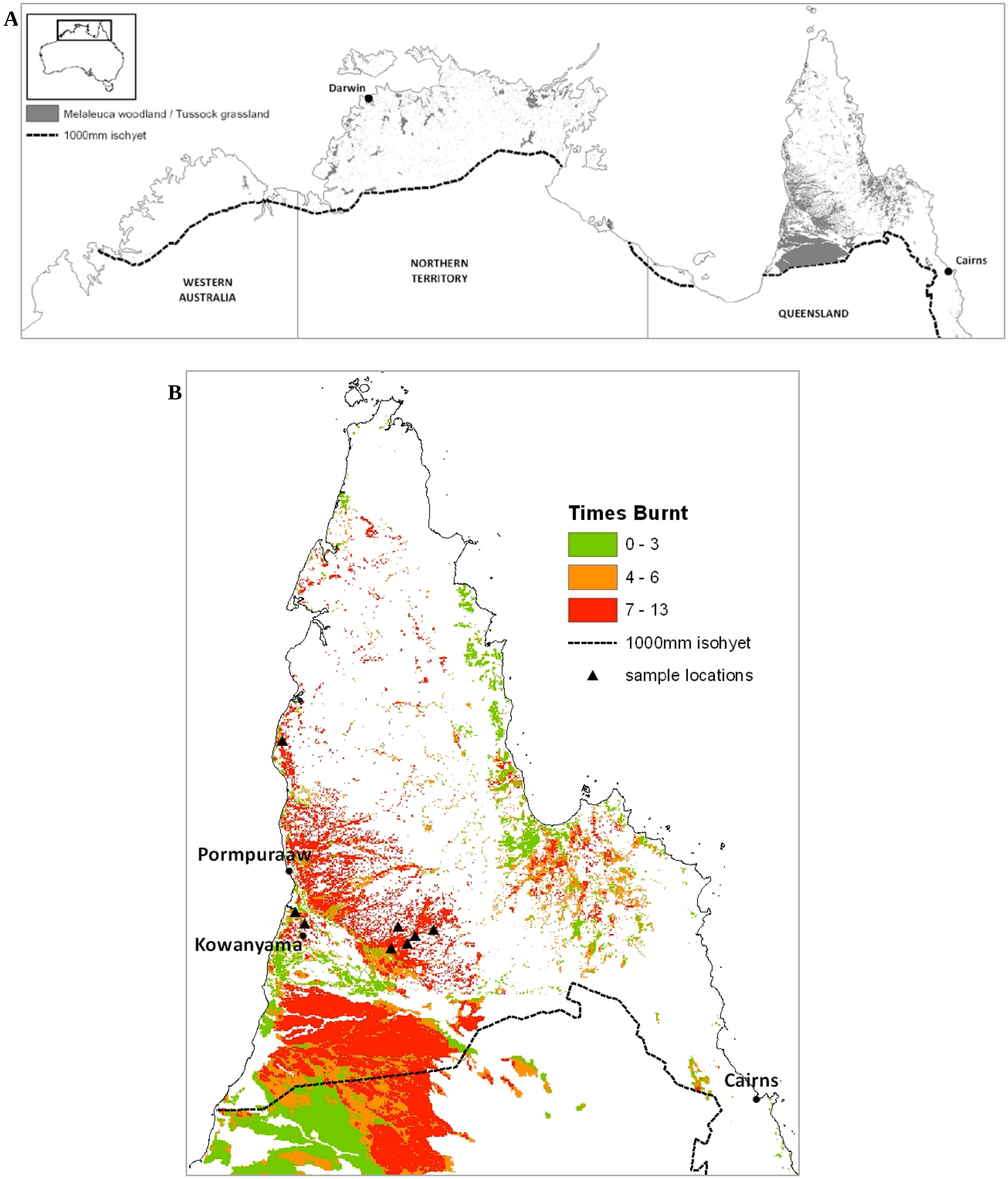

Figure 1. Distribution of tussock grassland (including *Melaleuca* open-woodland) communities: (A) in Australian higher annual rainfall (>1,000 mm) savanna region; and (B) on Cape York Peninsula, with recent fire frequency superimposed. Refer text for details concerning mapping surfaces.

Field sampling to assess pre- and post-fire conditions in typical higher rainfall (>1,000 mm/annum) grassland settings was undertaken at 2 sampling periods (see below) in the 2012 dry season, focusing on western Cape York Peninsula, given the significant extent of tussock grassland and open woodland in that region (Figure 1A). For consistency, applied field assessment methods followed, with noted exceptions, those described by Russell-Smith et al. (2009).

As a basis for sampling pre-fire fuel accumulation components, available fine-scale (1:100,000) vegetation mapping of grassland and associated open-woodland communities in the focal region (Queensland Herbarium 2009) was intersected using standard GIS (Geographic Information System) procedures with monthly/annual fire extent mapping derived from MODIS imagery (250 m pixels), for the period 2000−2012 (North Australia Fire Information website: www.firenorth.org.au/nafi2).

Given the very high fire frequencies prevalent in this region, including in target grassland and open-woodland communities (Figure 1B), accessing suitable areas that had remained unburnt for more than 1 or 2 years presented challenges. As such, the field program concentrated largely on a single region (in the vicinity of the township of Kowanyama: Figure 1B) with a mix of fuel ages (times-since-burnt) largely associated with fire-refugia − typically islands in braided stream channels. Identified suitable sites were accessed mostly by helicopter.

Pre-fire assessments. These were undertaken at 90 sites (transects of 10 m x 100 m) established in homogeneous tussock grassland or *Melaleuca* open-woodland communities, and homogeneous time-since-last-fire mapping units. Following the methodological approach outlined by Russell-Smith et al. (2009), time-since-fire (in years) was established for each site as identified through GIS analysis.

As well as information collected for descriptive purposes (e.g. tree stem density and height, species identification), sampling focused on assembling fuel accumulation data for the following classes: (a) fine fuel (grass plus litter <6 mm diameter); (b) coarse woody material (≥6 mm–5 cm diameter); (c) heavy fuel (≥5 cm diameter); and (d) shrub fuel with diameter at breast height (DBH) <5 cm, in 3 height classes per species (<50 cm, 50−200 cm and >200 cm). All field measurements and subsequent corrections for dry weight were undertaken using procedures as outlined in Russell-Smith et al. (2009).

Simple linear regression was used to examine relationships between accumulation of fuel load components (i.e. grass, litter, coarse fuels, heavy fuels, shrubs) and time-since-fire. Regressions for respective fuel components were expressed over the full 10-year time-since-fire sampling period, although, in many relatively long unburnt samples, no fuels were recorded for most fuel components. We note that, while this approach is consistent with Russell-Smith et al. (2009), under idealized experimental conditions fine fuel accumulation may be represented by a logarithmic function, which approaches a maximum value, theoretically reflecting a site-specific equilibrium between annual input and decay (Olson 1963). In northern Australian savanna woodlands with a tussock grass understory, the steady-state equilibrium for fine fuel accumulation may be attained within 5 years following fire (Cook 2003).

Given that savanna fires do not consume all available fuel components, for t_0 we included measurements of post-fire fuel components derived from fire treatments (see below). Following Russell-Smith et al. (2009), natural log-transformation was applied to both fuel load response (given strong positive skews for most observations) and time-since-fire (given apparent non-linearity). For time-since-fire, t_0 was given as the natural logarithm of 0 plus 1 day (i.e. 1/365). Where no coarse, heavy or shrub fuels were observed in sampling at respective plots, we assumed a small value (i.e. 0.001 t/ha) prior to natural log-transformation.

Following the methodology outlined in DCCEE (2012), we derived time-since-fire fuel component parameter values for years 1–5, and >5 years, as follows: Where significant ($P<0.01$) accumulation was observed for fuel load components with time-since-fire, we derived respective time-since-fire values for years 1–5, and maximum fuel load (>5 years) based on the derived regression value for year 6, utilizing the full 10-year expression equation. Truncating the maximum fuel component parameter value in this manner offers a conservative solution, as it fits with our observations (see Results), as well as partially addressing potential annual fire mapping errors, which compound over time (Russell-Smith et al. 1997). In other instances where non-significant relationships were observed between fuel load components and time-since-fire, we assumed that fuel load was best described by a simple mean, calculated using untransformed values, so as to not unduly weight the effects of large numbers of zero observations.

All plots were accessible to grazing by cattle and native herbivores (e.g. kangaroos and wallabies). In the field, sampling plots were located in fully cured grasslands, at sites away from intensively grazed or disturbed permanent watering points. We note that free surface water was very restricted at our study locations at the time of sampling; hence fuel loads were assessed under realistic ambient landscape-scale field conditions, including grazing utilization.

Post-fire assessments. These assessments comprised 2 components:

(1) Combustion efficiency: Immediately following the pre-fire assessments above, 24 plots were burnt under noon–early afternoon hot and typically gusty conditions in order to undertake measurements of post-fire fuel components. Post-fire measurements were undertaken within 6 h after the burn. Post-fire measurements generally followed the procedure given by Russell-Smith et al. (2009), with the exception that post-fire ash was sampled in each plot with 5 systematically placed quadrats, each 1 m x 1 m.

(2) Patchiness (percent burnt): Assessments of percent burnt were undertaken at both established plots at the time of post-fire assessments (above) on transect sections (1 m x 100 m) and at other recent extensive fires in tussock grassland and open-woodland vegetation types in random 1 m x 100 m areas within larger burnt patches as in Russell-Smith et al. (2009).

The applied methodology differed from that outlined in Russell-Smith et al. (2009), as separate assessments were not undertaken under both early dry season (EDS: pre-August) and relatively severe late dry season (LDS: post-August) fire-weather conditions. Russell-Smith et al. (2009) observed marked seasonal differences in fuel consumption and patchiness, while we observed that even EDS fires in tussock grasslands resulted in almost complete fine-fuel consumption and negligible patchiness, mitigating the need to undertake a separate LDS assessment. Additional sampling in the LDS was undertaken, however, specifically targeting pre-fire assessments of fuel accumulation at hitherto under-represented longer-unburnt sites.

Results

Pre-fire assessments

Commonly occurring graminoids in the 90 sample plots included the grasses *Eriachne* spp., *Aristida* spp., *Heteropogon triticeus*, *Panicum* spp. and *Whiteochloa airoides* and the sedges *Eleocharis* spp., *Fimbristylis* spp. and *Rhynchospora* sp. (Figure 2). Sample plots were dominated by perennial graminoids (Figure 2), characteristic of open grassland systems in Cape York Peninsula (Queensland Herbarium 2009). Shrubs (<5 cm DBH) occurred at 60 plots, and tree stems (≥5 cm DBH) at 41 plots, at overall (n = 90) mean densities of 99.9 shrubs/ha and 47.4 trees/ha. *Melaleuca* spp. comprised 78.2% of all shrubs, and 98.2% of all tree stems (Figure 3A). The great majority of tree stems were <20 cm DBH and <10 m tall (Figures 3A, 3B). These small stem sizes are indicative of relatively recent stand development/invasion within the last 2 decades. Even at highest sampled stem densities, tree foliage cover was <10%, given typically small crown sizes ≤2 m diameter.

Available fuels were dominated by fine fuels, which comprised a mean 88.3% of total fuel mass in years t_0–t_{10} (n = 118). Mean (± s.e.; n = 118) fuel loads for respective components were: fine fuels, 2.6 ± 0.19 t/ha; coarse fuels, 0.12 ± 0.03 t/ha; heavy fuels, 0.17 ± 0.05 t/ha; and shrub fuels, 0.05 ± 0.01 t/ha. These values are much lower than the mean values for 219 fuel component samples for more wooded vegetation types during the early dry season under equivalent higher rainfall conditions: fine fuels, 4.16 t/ha; coarse fuels, 0.16 t/ha; heavy fuels, 1.35 t/ha; and shrub fuels, 0.62 t/ha (Russell-Smith et al. 2009). On average, under grassland/open-woodland conditions, 23 ± 7% of fine fuels was litter, and 18 ± 7% of litter was leaf and twig components.

Fuel accumulation relationships with time-since-fire are given for the 4 fuel classes in Figure 4. The linear regression [Ln(fuel component) with Ln(time-since-fire)] for fine fuel loads was highly significant ($P<0.001$, R^2(adj.)= 0.94). Modelled regression values for fine fuel accumulation with time, and mean values for coarse, heavy and shrub fuel components, are given in Table 1.

Post-fire assessments

Fire treatments undertaken at 24 plots were generally of low-to-moderate severity, as evidenced by relatively low impacts on shrub size classes; consumption of shrub biomass at the 24 plots in the <0.5 m height class was 18.3%, and 8.2% in the 0.5–1.0 m height class.

Of the remnant post-fire debris, a mean of 21.3 ± 3.8% was ash. Mean consumption, corrected for remnant ash, which was applied equally to all fuel classes following Russell-Smith et al. (2009), was 99.9 ± 0.02% for fine fuels, 71.9 ± 12.6% for coarse fuels, 14.9 ± 9.8% for heavy fuels and 7.3 ± 3.2% for shrub fuels (Figure 5).

Based on assessments of post-fire patchiness undertaken at 112 transect segments (each 1 m x 100 m), the mean burnt proportion was 95.8 ± 1.3%.

Discussion

This assessment provides a robust basis for parameterizing a savanna burning greenhouse gas emissions abatement methodology for Australian tropical tussock grasslands and *Melaleuca* open-woodland communities under relatively high rainfall conditions. The essential framework for that methodology is set out in DCCEE (2012). Key parameters and variable values required for propagating that framework, derived mostly from observations presented here but also from other pertinent studies, are summarized in Table 1.

By contrast with the earlier higher rainfall savanna burning abatement methodology focusing on woody systems (Russell-Smith et al. 2009; DCCEE 2012), particular features of the present study concern: (1) distinct differences in fuel accumulation and fuel consumption parameters for different fuel type components; and (2) the absence of seasonal variation in all parameters studied. While the latter issue (see below) somewhat clouds direct comparison between the 2 studies, suffice to say that, in grasslands, on average: (1) accumulation of fine fuels is less (given small leaf and twig litter inputs) than in woody systems, and accumulation of coarse, woody and shrub fuel components is much lower; (2) fuel consumption is greater for fine fuels, double that for coarse fuels, and substantially less for heavy and shrub fuel components; and (3) given these relationships and the much higher emission factors derived from woody fuel components (DCCEE 2012), resultant emissions per unit area burnt are substantially lower for grasslands than for woody savannas.

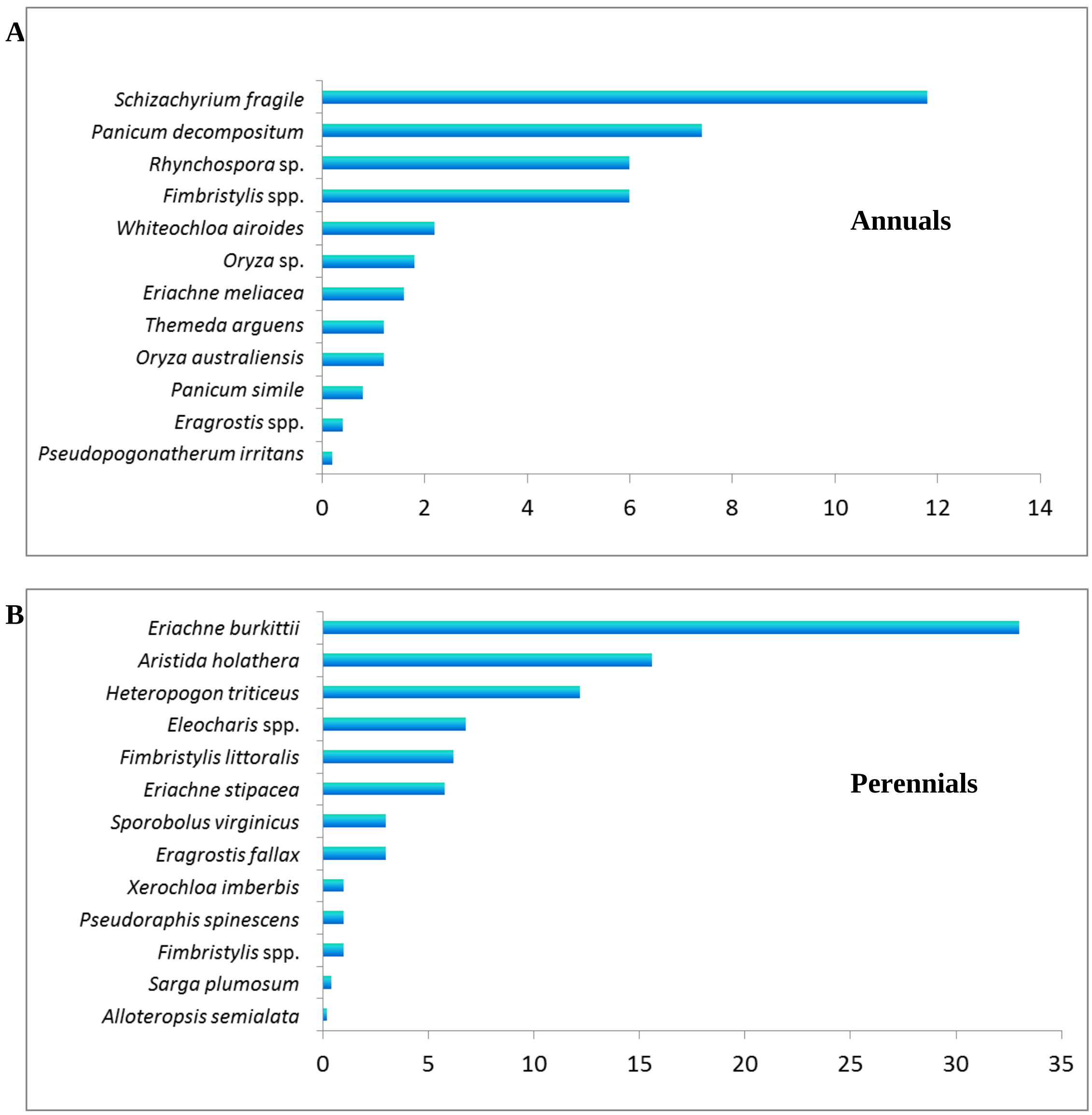

Figure 2. Sampled frequency of common graminoid taxa at 90 sample plots for: (A) annuals; and (B) perennials.

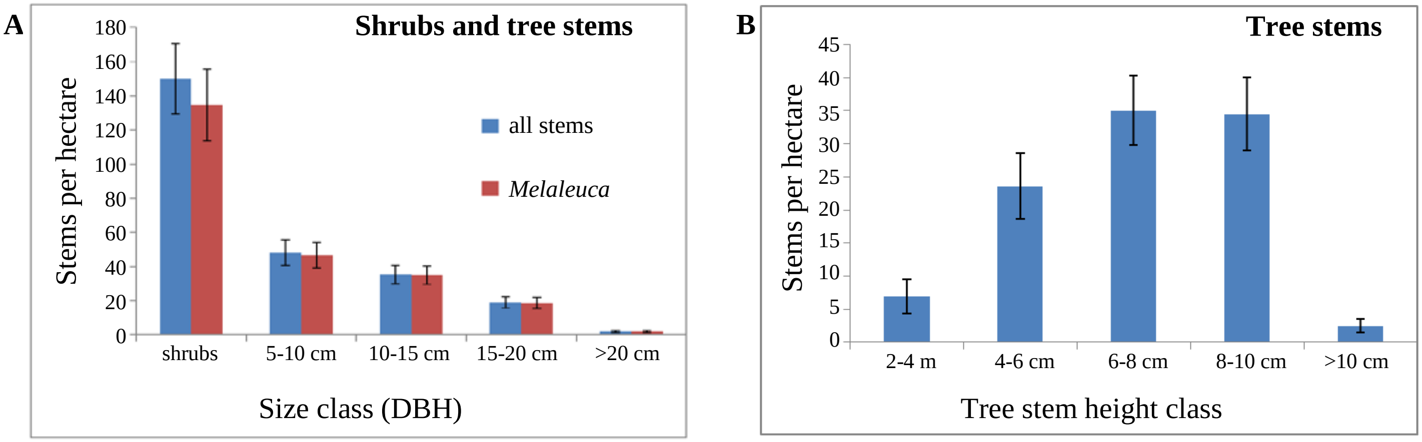

Figure 3. Mean density (± s.e.) of: (A) shrubs and tree stems in DBH classes; and (B) tree stems in height classes, where n = 60 for shrubs and n = 41 for tree stems.

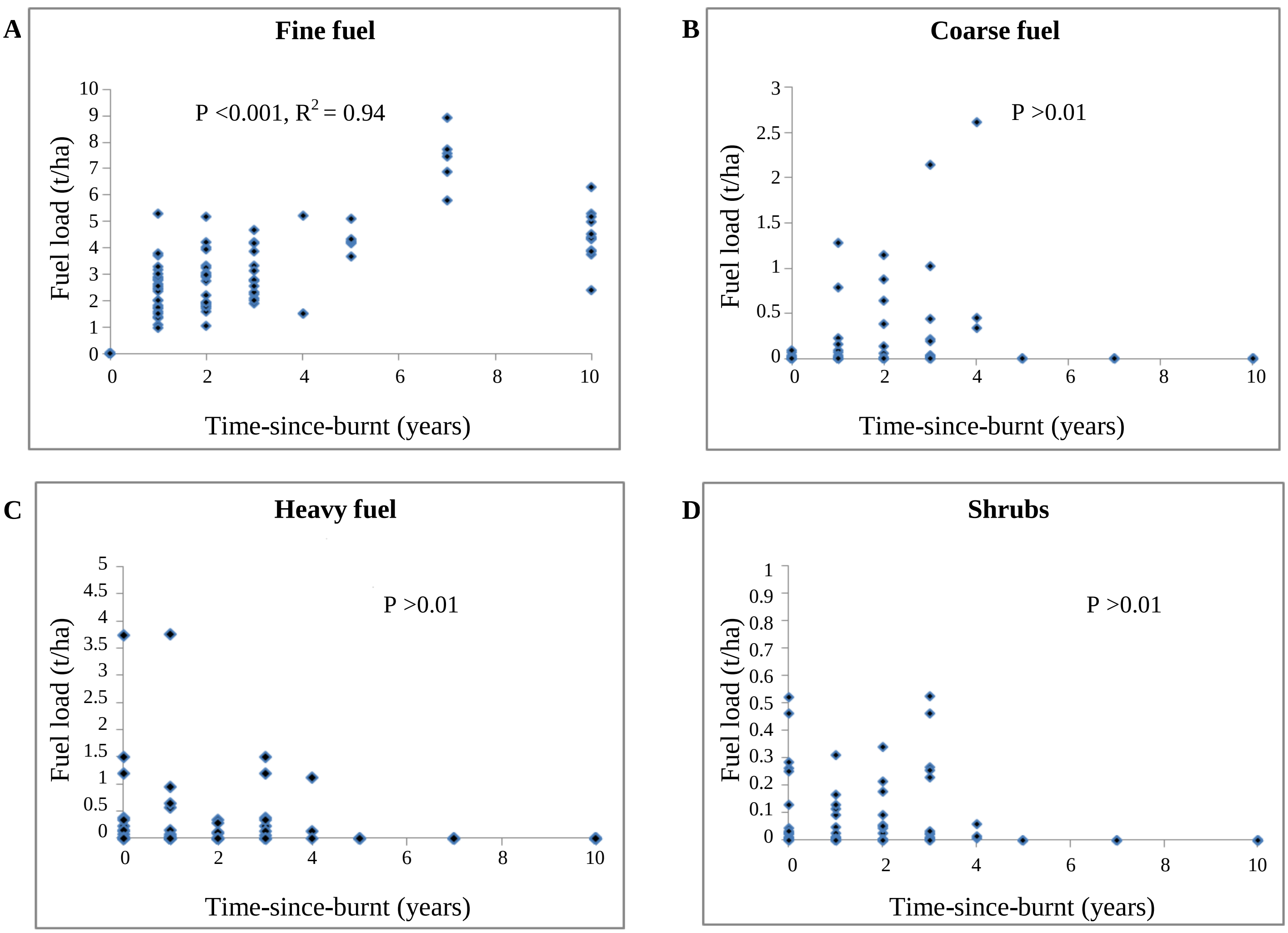

Figure 4. Relationship between accumulation of respective fuel components and time-since-fire. P and, where given, R^2 values, refer to the results of linear regressions of fuel load (natural log-transformed) vs. time-since-fire (natural log-transformed). Refer text for additional details.

Table 1. Summary of parameters required for deriving emission estimates from tussock grasslands under higher annual rainfall (>1,000 mm) conditions.

Parameters and variables	Values	Comments	References
***(a) Fuel accumulation* (n = 90)**		Assumes insignificant seasonal (EDS vs. LDS) differentiation, especially of leaf and twig litter input, given small contributions of these components in litter (see below)	Refer Russell-Smith et al. (2009); this study
Fine fuels (t/ha)	Ln(fine fuels) = 0.06 + 1.027*Ln(time-since-fire, in years) Yr 1 = 1.06 t/ha Yr 2 = 2.16 t/ha Yr 3 = 3.28 t/ha Yr 4 = 4.41 t/ha Yr 5 = 5.54 t/ha Yr 5+ = 6.68 t/ha	Adequately described by this relationship	This study
- Proportion of litter (detached grass, leaves, twigs) in fine fuels	23.7%	Adequately sampled	This study
- Proportion of leaves and twigs in litter	18%	Small component, and highly variable depending on woody plant density	This study
Coarse fuels (t/ha)	0.12 ± 0.03	Relatively small component, and variable	This study
Heavy fuels (t/ha)	0.17 ± 0.05	Relatively small component, and variable	This study
Shrub fuels (t/ha)	0.05 ± 0.01	Relatively small component, and variable	This study
***(b) Fire patchiness* (n = 112)**		Assumes insignificant seasonal differentiation in cured grasslands, based on low fire patchiness (high % burnt) under EDS conditions	This study
Proportion of area burnt	95.8%		This study
(c) Burning efficiency factor (n = 24)			
Pyrolysis efficiency (proportion of fuels pyrolized)		Assumes insignificant seasonal (EDS vs. LDS) differentiation in fuel consumption, especially given almost complete consumption of fine fuels (see below). Further work required to address possible effects of differential fire intensity	Refer Russell-Smith et al. (2009); this study
- Fine fuels (n = 24)[1]	99.87% (99.84%)[2]	Adequately sampled	This study
- Coarse fuels (n = 12)[1]	71.89% (71.88%)[2]	Adequately sampled	This study
- Heavy fuels (n = 12)[1]	14.87% (14.87%)[2]	Adequately sampled	This study
- Shrub fuels (n = 12)[1]	7.25% (7.24%)[2]	Adequately sampled	This study
Residual ash − proportion of consumed biomass			
Proportion of remnant fine fuel fraction comprising ash (n = 24)[1]	21.3%	Adequately sampled	This study
(d) Emission factors		Detailed studies already undertaken for high rainfall savannas, including grassland fuels. Note that no seasonal differentiation in emission factors is observed under fully cured conditions	Meyer and Cook (2011); DCCEE (2012); Meyer et al. (2012)
Methane (CH_4)			
Fine fuels	0.0015	Adequately sampled	Refer above
Coarse fuels	0.0015	Adequately sampled	Refer above
Heavy fuels	0.01	Adequately sampled	Refer above
Shrub fuels	0.0015	Adequately sampled	Refer above
Nitrous oxide (N_2O)			
Fine fuels	0.0066	Adequately sampled	Refer above
Coarse fuels	0.0066	Adequately sampled	Refer above
Heavy fuels	0.0036	Adequately sampled	Refer above
Shrub fuels	0.0066	Adequately sampled	Refer above

[1]While total sample size = 24 plots, the number of plots referred to here relates to the number of observations made for respective fuel components, e.g. n = 12 refers to number of plots where coarse or heavy fuels were sampled both in pre- and post-fire treatments.
[2]Values given in parentheses are the proportion of fuels pyrolized (as measured in post-fire assessments), corrected for the proportion of ash remaining in situ. These corrected values are used for estimating emissions. In the absence of other data, we assumed that the in situ ash conversion rate was proportionately the same for all fuel components.

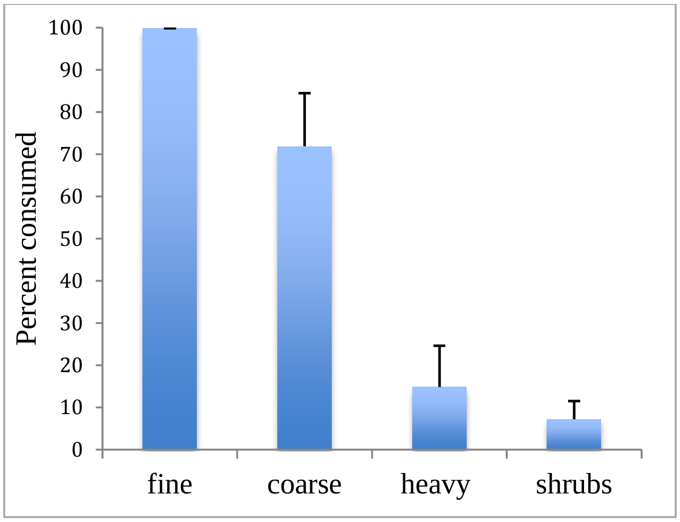

Figure 5. Mean consumption (± s.e.) of respective fuel components, from 24 post-fire assessments.

These observations imply that fire-related emissions characteristics in grassland systems differ fundamentally from those in more woody savannas. This applies particularly to seasonal characteristics. Considering fuel accumulation for example, while seasonal litter-fall in woody savannas can result in significantly greater availability of fine fuels in the LDS (Cook 2003; Williams et al. 2003), we contend that this is unlikely to be a significant factor in these grasslands, especially given that shrub fuels comprised only 1.1% of total available fuels.

At the outset of the program, we anticipated undertaking fire treatment assessments under both typical EDS and LDS conditions. However, under EDS conditions, where fine fuels were mostly to fully cured and continuous, and even where fire treatments were of low-to-moderate severity (sensu Williams et al. 2003; Russell-Smith and Edwards 2006), effectively full combustion of fine fuels and negligible patchiness resulted (Table 1). Any fire patchiness occurred typically in association with seasonal drainage features, and was thus applicable generally to both EDS and LDS conditions. On the basis of these observations, we considered it unwarranted to implement the potentially hazardous LDS fire treatment, or to apply differential seasonal parameters to our emissions estimates.

In woody savanna situations under LDS conditions, Russell-Smith et al. (2009) observed that consumption of heavy fuels was double, and shrub fuel components 5 times, those reported here for grasslands. Assuming that combustion of heavy and shrub fuel components in grasslands in LDS might reflect these differentials, as a sensitivity exercise it is useful to consider the net effect on emissions estimates. Thus, (1) taking into account data presented here describing untransformed mean fuel accumulation for all fuel components, and doubling that of heavy fuel consumption, and multiplying by 5 that for shrub fuel consumption, and (2) applying the methodological approach outlined in DCCEE (2012) for calculation of CH_4 and N_2O emissions from equivalent grass-dominated fuel types, (3) we estimate that the resultant seasonal difference in LDS emissions would be 2.5% greater than that under EDS conditions. Use of natural log-transformed mean fuel accumulation data reduces the seasonal differential even more substantially.

Management implications

Fire mapping data for Cape York Peninsula indicate that, on average, 47.4% of tussock grasslands and *Melaleuca* open-woodlands was burnt annually over the period 2000−2012. Applying parameter values developed here to the emissions calculation framework outlined in DCCEE (2012), average annual GHG emissions from Cape York grassland communities for the 5-year period 2008–2012 would be 174,288 t CO_2-e (range: 136,340–204,180 t CO_2-e). Reducing mean annual fire extent by 30%, in line with conservative experience in savanna woodlands elsewhere (Russell-Smith et al. 2013), would reduce emissions by 52,290 t CO_2-e.

Such an emissions abatement project would be eligible under the CFI and would permit the sale of carbon credits into Australia's Carbon Pricing Mechanism (CPM). The CPM started in July 2012 with a fixed price of AU$23 per tonne, rising at 2.5% per year until 2014/15, when it will be linked with the European Union Emissions Trading Scheme and the price will be set by the market (see www.cleanenergyfuture.gov.au/clean-energy-future/carbon-price/). At the time of writing it is uncertain what policy direction will be taken in Australia concerning carbon pricing arrangements. The future European carbon price is also uncertain and, while there are some efforts to attempt to address recent price volatility, a stable future price to 2015 and beyond is unlikely to materialize for some time (see www.bloomberg.com/news/2013-03-28/carbon-in-worst-quarter-since-2011-set-for-rescue-vote.html).

Currently, most fires on Cape York Peninsula occur in the LDS period, typically as extensive wildfires (Felderhof and Gillieson 2006). As demonstrated by landscape-scale fire management projects currently being undertaken in various northern Australian regions, it is feasible to reduce the incidence of LDS fires and overall fire extent through strategic EDS fire management practices (e.g. Legge et al. 2011; Russell-Smith et al. 2013). However, whether such strategic fire management is practically transferable to relatively productive grassland settings is uncertain.

For example, in addition to infrastructural and capacity issues, there are significant constraints to implementing strategic EDS management programs in Cape York grasslands. There is potential for extensive woody thickening, especially *Melaleuca* invasion, associated with inappropriate fire regimes (Crowley 1995; Crowley et al. 2009). *Melaleuca* invasion can impact on both pastoral production and ecological values (Garnett and Crowley 1995; Myers et al. 2004; Crowley et al. 2009). Crowley et al. (2009) demonstrated that annual to triennial burning of grassland systems in the 'storm burning season' (i.e. after the first rains have commenced late in the year) can effectively control the height escape of suckers of *Melaleuca* and other woody species and hence maintain open-grassland conditions. On the negative side, undertaking burning under moist fuel conditions results in significantly elevated methane emissions per unit area burnt (Meyer et al. 2012).

In addition, most tussock grasslands on Cape York Peninsula and in other higher rainfall regions of northern Australia occur on lands owned and/or managed by Aboriginal people. In these situations, customary obligations and responsibilities typically involve requirements for implementing fire management extensively throughout the year, in essence, progressively burning the landscape as it dries (e.g. Thomson 1939; Chase and Sutton 1981; Yibarbuk 1998). Today, however, most Aboriginal land owners and managers have limited infrastructure (e.g. all-weather tracks) and means to access their lands, especially at appropriate times of the year, when it is feasible to implement effective fire management (see Altman and Kerins 2012 for detailed regional examples).

The potential carbon market benefits of applying strategic fire management in higher rainfall tropical grassland settings may thus seem small, when compared with contemporary infrastructural, cultural and land management tensions. At the enterprise level, however, strategic burning of grasslands may augment larger benefits realized through savanna burning activities undertaken in more woody settings, and by maintaining more pasture for cattle production purposes.

The emissions accounting methodology developed for northern Australia has general application in other tropical savanna regions, but substantial further work may be required to (a) access or develop reliable seasonal fire, and vegetation/fuel-type, mapping surfaces, (b) calibrate or determine appropriate parameter (e.g. fuel accumulation and combustion; emission factors for CH_4 and N_2O) estimates for regional conditions, (c) help develop technical capacity (remote sensing; Geographic Information System, GIS) and associated infrastructure. Particular methodological challenges are to ensure that the application is supportive of local cultural practices and requirements, and that mitigating early dry season fire management activities actually reduce emissions, i.e. are conducted when fuels are fully cured rather than still being moist, which would result in higher CH_4 emissions (Meyer et al. 2012). A first step therefore is to work with local communities to assess the applicability of, and where practicable appropriately modify, the model.

In a recent assessment focusing on savanna burning opportunities in southern African and South American savannas, where savannas occupy 10 Mkm^2 and 26.9 Mkm^2, respectively, Russell-Smith et al. (2014) observed that, although such projects are likely to be technically and operationally feasible, the associated legislative, political and governance issues typically are significantly more complex. Such opportunities include fire management projects in higher rainfall grassland/forest ecotonal settings, but with the caveat that carbon credits derived from (a) emissions abatement in fire-prone grasslands, and (b) associated biosequestration in adjoining woody vegetation, may be small in comparison with derived livelihood benefits (Bilbao et al. 2010).

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