Potential for Indigenous fire management in central Australia to reduce greenhouse gas emissions and increase biosequestration

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Executive Summary

Flammable spinifex grasslands occupy about 2.1 million km^2 of the Australian continent, about 40% of which is on Aboriginal lands. For thousands of years, Aboriginal people skillfully managed fire in these landscapes, maintaining a stable mosaic of mostly small, low intensity and patchy fires. With the cessation of traditional burning following European settlement, the fire regime quickly changed to one of large, intense lightning-caused hot season wildfires. A return to traditional Aboriginal fire management, resulting in smaller, patchier fires lit in the cool season, provides an exciting but challenging opportunity for remote desert communities to contribute significantly to reducing Australia's greenhouse gas emissions, to increasing carbon stocks, to conserving biodiversity and to improving ecosystem health. In addition to environmental benefits, substituting wildfires with traditional fire management has significant social and cultural benefits. Done at appropriate scales, good fire management can also provide training, employment and economic opportunities.

This feasibility study found that changing the fire regime from predominantly high intensity, hot season wildfires to predominantly low intensity, cool season managed fires, analogous to the traditional Aboriginal fire regime, can result in a 24% reduction in greenhouse gas emissions and a significant (but difficult to quantify) increase in woody biomass carbon stocks through the persistence of mulga (*Acacia aneura* and it close relatives). However, because of the relatively low productivity of these arid landscapes, large areas will need to be managed to realize significant benefits. An estimate based on best available information suggests that to generate 100,000 tonnes of CO_2-equivalent abatement per annum from a 500,000 km^2 'project area' of central Western Australia would require about 30% of the total area burnt each year, to be burnt in the cool season. This equates to a mean annual burning program of ~1 million ha, or ~2% of the 'project area'. In addition to greenhouse gas abatement, good fire management will also increase carbon stocks in long-lived woody biomass such as mulga. Based on limited data, and some assumptions that remain to be tested, this could be as much as 5 million tonnes per annum for the project area. Large scale fire management will also have significant social, cultural, economic and environmental benefits. In higher rainfall, more productive regions of central Australia, smaller areas could be treated at lower cost to realize these benefits.

While challenging, achieving multiple benefits through large scale fire management is possible by building capacity in remote communities, building strong partnerships with other fire and land management agencies and by the application of technology such as remote sensing and aerial burning. In partnership with others, Aboriginal communities have expressed a strong interest in being involved in an expanded fire management program to deliver multiple benefits, conditional on being adequately consulted and provided with appropriate training and resourcing. This will build on recent experiences many communities have with blending traditional and contemporary fire management practices. However, to manage fire at the scales necessary to make a difference will require a substantial medium to long term development and capacity-building program.

1. **Introduction**

Spinifex grasslands are characterised by the dominance of perennial hummock grasses, primarily of the genus *Triodia*. They occur over a diversity of landforms including sand plains and dune fields, gibber plains and rocky hills in the semi-arid and arid regions of the remote and sparsely populated central, western and northern parts of Australia (Figure 1). Spinifex grasslands cover about 2.1 million km^2 (~27%) of the continent, of which about 800,000 km^2 (~40%) is on Aboriginal land (Allan and Southgate 2002). The climate is arid or semi-arid with annual average rainfall ranging from about 225 mm to 350 mm. Typical of desert climates, rainfall is highly variable and long periods of drought are not uncommon. The summers are long and hot and winters cool and mild. Spinifex grasslands are generally structurally simple, with a discontinuous ground cover of *Trioda spp.* (spinifex) hummocks to a height of 30-50 cm. Scattered low shrubs and trees usually grow in association with spinifex (Suijdendorp 1981). Notable tree and mallee form genera sometimes associated with spinifex include *Eucalyptus*, *Allocasuarina*, *Acacia*, *Callitris*, *Hakea* and *Grevillea*.

The combination of accumulations of flammable vegetation, the physical structure of the hummocks and the often extreme fire weather conditions makes spinifex grasslands highly flammable (Griffin 1984; Burrows and Christensen 1990; Allan and Southgate 2002; Marsden-Smedley *et al*. 2012). Historically, lightning and deliberate burning by Aboriginal people were the main causes of fire. Today, most fires are started by lightning, although human-caused ignitions are significant near settlements and along vehicle travel routes. While most *Triodia* species are fire sensitive (readily killed by fire, regenerate from seed), spinifex grassland communities are fire dependent; fires at appropriate temporal and spatial scales are essential for their persistence and health (Burbidge 1944; Suijdendorp 1981).

Under traditional law and custom, Aboriginal people inherit, exercise and bequeath customary responsibilities to manage their traditional country. The relatively recent exodus of Aboriginal people from parts of central Australia (Davenport *et al*. 2005), has coincided with an alarming decline in native mammals and some birds, and a contraction of some fire sensitive plant communities. Proposed causes of these changes include an altered fire regime resulting from the departure of traditional Aboriginal burning, predation by introduced carnivores and competition with feral herbivores (Johnson *et al.* 1989; Burbidge and McKenzie 1989; Morton 1990; Latz 1995). While knowledge of fire effects in hummock grasslands is incomplete, there is evidence of dramatically changed fire regimes in many areas since the decline of traditional Aboriginal burning practices. There has been a reduction in diversity of fire regimes (frequency, season, intensity and scale), and an increase in the intensity and scale of hot summer wildfires. This has resulted in a shift from a pyrogenic fine-grained habitat mosaic to pyrogenic homogenization (Burrows and Christensen 1990; Allan and Southgate 2002; Burrows *et al*. 2006; Bliege Bird *et al*. 2013).

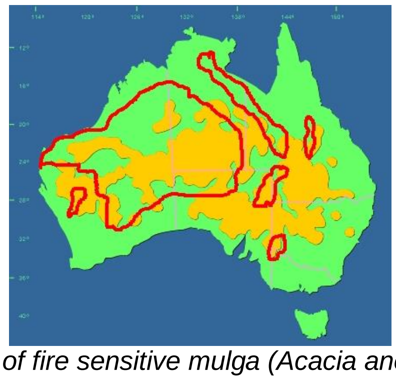

Figure 1: Approximate distribution of fire sensitive mulga (Acacia aneura and close relatives) (yellow) and flammable spinifex (Triodia spp.) (boundary in red) (source: mulga - Bruce Maslin pers. comm.; spinifex – adapted from Allan and Southgate 2002).

1.1 Altered fire regimes

While there is considerable anecdotal evidence of changed fire regime following the departure of traditional Aboriginal burning in much of the spinifex grasslands (e.g., Bolton and Latz 1978; Latz and Griffin 1978; Latz 1995; Bowman *et al*. 1995), the most compelling and quantifiable evidence comes from black and white aerial photography taken by the Australian military over a remote area of the Great Sandy Desert in 1953 at a time when Aboriginal people were living a traditional lifestyle, more than a decade before European contact (Davenport *et al.* 2005). Burrows and Christensen (1990) and Burrows *et al*. (2006) studied a sample of the aerial photography covering about 250,000 ha and it revealed a mosaic of numerous small burnt patches. The mean burnt patch size was about 60 ha, with most (75%) of the burnt patches being less than 32 ha and 50% less than 5 ha (Burrows *et al*. 2006). About 20% of the area was burnt by fires < 100 ha and ~36% by fires > 1 000 ha; the largest fire being about 6,000 ha. Burrows *et al*. concluded that based on fire shape and on information provided by desert Aborigines, the burnt patches were consistent with having been lit by people, who burnt the spinifex for a myriad of reasons but primarily for acquiring food. The fire regime dominated by Aboriginal burning contrasts sharply with the more recent fire regime following the exodus of people and /or the cessation of traditional burning from much of these lands. By the mid-1970s, some 15-20 years after the cessation of traditional Aboriginal burning, the fire regime had changed. Satellite imagery revealed that the mosaic of small, low intensity (cool) fires evident on the 1953 photography had been replaced by large, intense (hot) summer wildfires primarily ignited by lightning.

As with the reported case study (Burrows *et al*. 2006) the fire regime in most of spinifex-dominated central Australia has changed from a stable pattern of numerous small, cool fires to an unstable pattern of large, hot summer wildfires followed by intervening periods of few fires because of lack of vegetation to burn, culminating in large hot wildfires once the fuel has re-accumulated. For example over the period 2000-2002, ~500,000 km^2 of spinifex grassland was burnt by wildfire (Wright and Clarke 2007) and hot summer wildfires commonly exceed 200,000 ha (Haydon *et al*. 2000; Allan and Southgate 2003; Burrows *et al*. 2009). This 'boom and bust' fire regime is now largely driven by rainfall, which drives the rate of fuel accumulation (Griffin *et al*. 1983; Allan and Southgate 2002), with lightning as the dominant ignition source, whereas for thousands of years, deliberate burning by Aboriginal people was the dominant influence on the fire regime.

Recently, Bliege Bird *et al*. (2012) working with Martu Aborigines in the Great Sandy Desert reported that where contemporary Aborigines hunted with fire, usually within about 50 km of their settlements, the fires were smaller, more tightly clustered and importantly, remained small even when wet periods were followed by very large fires in areas beyond where Aboriginal people were actively burning. They demonstrated that Aboriginal patch burning significantly buffers the 'boom and bust' fire cycles associated with rainfall variation in the absence of Aboriginal burning. Furthermore, Bliege Bird *et al*. proposed that the mitigating effect of Aboriginal hunting fires on large summer wildfires reduces the mortality on small mammal populations, enhancing their persistence in these landscapes.

As well as being implicated in the decline of medium-size arid zone mammals, there is evidence that large and intense hot season wildfires are adversely impacting on fire sensitive plant communities associated with or adjacent to hummock grasslands, such as mulga and cypress pine (*Callitris* spp.) (e.g. Start 1986; Griffin *et al.* 1990; Bowman and Latz 1993; Latz 1995; van Leeuwen *et al*. 1995; Allan and Southgate 2002; Bowman *et al*. 2009; Marsden-Smedley *et al*. 2012; Ward *et al*. 2014). 'Mulga' is the general name applied to the woody perennial tree species *Acacia aneura* and its close relatives (Maslin and Reid 2012). Like spinifex, mulga is widespread throughout the arid zone occupying about 1.5 million km^2 (~ 20%) of the continental land surface (Figure 1). Mulga occurs in a variety of habitats, including co-occurrence with spinifex, which, given the flammability of spinifex and the fire sensitivity of mulga, presents an ecological conundrum (e.g., Start 1986; van Leeuwen *et al*. 1995; Hodgkinson 2002; Nano and Clarke 2008; Nicholas *et al*. 2009; Murphy *et al*. 2010). There is also concern, and growing evidence, that the contemporary fire regime of large, regular intense summer wildfires is reducing the extent of mulga in these landscapes (Griffin and Hodkinson 1986; Start 1986; Latz 1995; Allan and Southgate 2002; Smyth and James 2004; Bowman *et al.* 2009; Ward *et al*. 2014).

In addition to ecological and cultural consequences of altered fire regimes resulting from the reduction in anthropogenic burning following the departure of Aboriginal people and their burning practices throughout most of the desert, there are likely to be significant environmental consequences, including increased greenhouse gas (GHG) emissions and a reduction in biosequestration associated with the contraction of mulga and other fire sensitive and potentially long-lived woody vegetation.

Therefore, appropriate fire management of the spinifex grasslands, including the broadscale re-introduction of the fire regime known to be in existence prior to European settlement and industrialization (the 'natural' fire regime), may have multiple environmental and ecological benefits. If it can be demonstrated that the natural fire regime also reduces GHG emissions and increases biosequestration, then there may exist significant social and cultural benefits, including providing a culturally appropriate sustainable economic activity for remote desert Aboriginal communities.

The purpose of this study is to explore the feasibility of whether good fire management on Aboriginal lands in the spinifex-dominated landscapes of central Australia can reduce GHG emissions and increase biosequestration. This builds on the successful savanna burning for GHG abatement in northern Australia (Russell-Smith *et al*. 2009; Russell-Smith *et al.* 2013). Specifically, the current feasibility study aims to address the following key technical questions:

1. What is the abatement and sequestration potential (tonnes CO2-equivalent per annum) from both mulga and spinifex components under a typical range of rainfall and landscape conditions?
2. Can 'natural' (pre-European settlement), or traditional Indigenous fire regimes deliver effective biomass accumulation (hence biosequestration) and GHG abatement at landscape scales?

In addition, this study briefly considers the support and capacity-building in remote desert Aboriginal communities to enable them to implement traditional burning practices at the appropriate scales to make a difference by addressing questions such as:

1. What additional resources would be required for Aboriginal communities to deliver effective fire management?
2. Under what conditions would effective fire management be economically sustainable?
3. What is the level of Indigenous community interest in this proposition?

Finally, this study flags research required to improve estimates of spinifex grasslands burning emissions for greenhouse accounting (biomass modeling over a range of sites/rainfall zones; mapping fuel/vegetation classes; mapping mulga; assessing fire kill of mulga) and capacity building and governance arrangements to enable appropriate fire management.

The fundamental premise is that abatement and sequestration will be improved by re-instating traditional Aboriginal burning practices, which means using prescribed fire to:

- Reduce the total area (of a defined project area) that is burnt each year.
- At the burnt patch scale, increase the amount of unburnt vegetation within a burnt area (fire scar) (intra-scar patchiness);

- At the landscape scale, increase the amount of unburnt vegetation between fire scars (inter-scar patchiness);
- Reduce the extent of mulga (and its close relatives) killed and/ or extirpated by fire each year.

These benefits can be achieved by ensuring that a greater proportion of the landscape is burnt by prescribed / managed fires and shifting the season of fires away from late spring/summer and early autumn (hot fires) to late autumn, winter and early spring (cool fires). Cool season fires are characterised by being relatively small, of low intensity, less plant ‘killing power’, more patchy, a greater propensity to self-extinguish, and reduced total fuel/biomass consumption. On the other hand, hot season fires are characterised by large, high intensity fires, reduced patchiness, higher levels of fuel consumption and high mortality to mulga stands and other plants.

The proposition is that shifting the regime from hot season fires to cool season fires will result in a net reduction in area burnt and fuel consumed and increased survival and growth of mulga, resulting in a reduction in carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_20) emissions and increased biosequestration.

1. Methods

In relation to technical or biophysical issues concerning the potential for significant GHG abatement and biosequestration resulting from good fire management, both existing and new data were collated and analysed to address these issues.

2.1 Greenhouse gas abatement

Fire management for GHG abatement is based on developing and implementing the fire regime that retains the highest level of plant biomass at the landscape scale in perpetuity. In vast, remote flammable environments such as the spinifex grasslands of central Australia, fire exclusion or fire suppression strategies alone are not feasible and the ‘do nothing’, unmanaged approach to fire, which currently applies over much of the spinifex grasslands for various reasons, is resulting in large, intense lightning-caused hot summer wildfires. In this study, traditional Aboriginal fire management (the natural fire regime) is compared with the ‘unmanaged’ fire regime with respect to GHG emissions and carbon sequestration.

The GHG emissions from burning natural vegetation are primarily a function of the total mass of vegetation / fuel burnt and its composition. The mass of fuel can be calculated from the dry weight of fuel per unit area, the area burnt and the burning efficiency, or patchiness, or proportion of the total fuel mass that actually burnt (Russell-Smith *et al*. 2009). Currently, there are no data on the GHG emissions from the burning of spinifex grasslands and associated vegetation, so data from the savanna burning methodology are used, which are likely to be similar. For a given vegetation type or fuel class, emissions are directly proportional to the biomass or amount of fuel that is combusted (Cook and Meyer 2009) so vegetation biomass removed or retained can be used is a surrogate for greenhouse gas emissions and carbon sequestration. In addition to understanding combustion efficiency, or burn patchiness, modeling post-fire biomass accumulation with time since last fire (usually expressed as t/ha) is crucial for estimating the total amount of vegetation available for burning. This, together with measures of patchiness (proportion of vegetation / fuel that actually burnt) and the areal extent of burnt and unburnt vegetation, emissions can be estimated.

2.2 Modelling post-fire fuel accumulation

Existing data were used to model post-fire fuel biomass accumulation for three broad fuel classes. A space-for-time method was employed with sampling initially classified according to broad desert regions of Western Australia. IBRAs (Thackway and Creswell 1995) reflect broad intra-regional biophysical similarities such as climate and landforms likely to influence plant productivity, structure, composition and combustion. Three WA desert IBRAs were sampled, being the Great Victoria Desert, the Great Sandy Desert, and the Gibson Desert. Fuel accumulation data were also gathered from Lorna Glen, a former pastoral lease on the southern edge of the Little Sandy Desert, but technically in the Murchison and Gascoyne IBRAs (Figure 2). Within each IBRA, a chronosequence of satellite imagery was used to determine fire history (fuel age), which formed the basis for biomass sampling. Thus, a fuel age within an IBRA formed a sample site. In all, data were gathered from 100 sites following the methodology described by Burrows *et al.* (2009). Briefly, this amounted to measuring fuel structure (height and cover of spinifex and other species), ground cover (bare ground, leaf litter, coarse woody debris, etc.) and oven dry fuel biomass, which was determined by harvesting all fuel/vegetation from 10 x 1 m^2 quadrats. In all, almost 1,000 x 1 m^2 quadrats were sampled. In most cases, all vegetation within the sample quadrats was fuel – i.e., live and dead material <=4 mm and <=6 mm in diameter respectively.

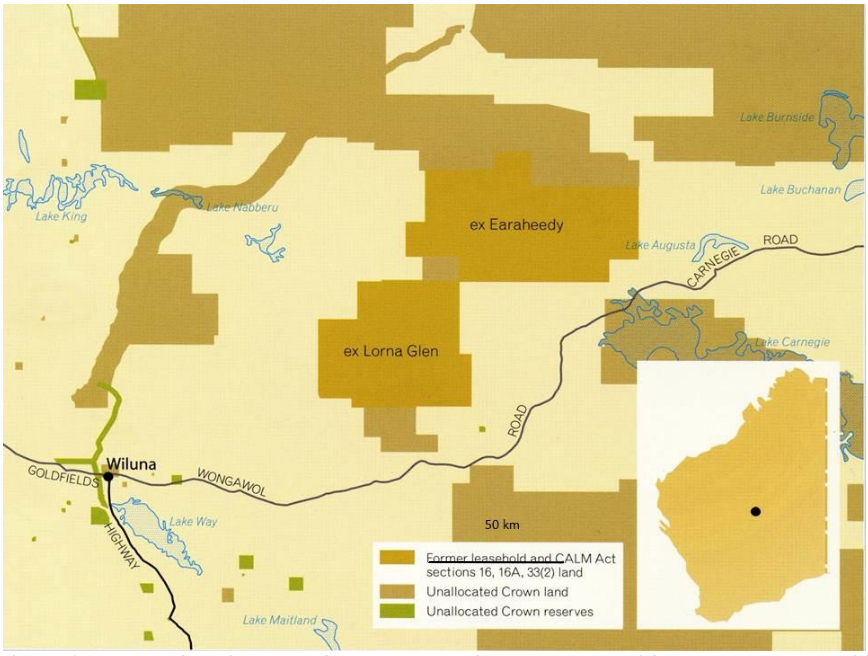

Figure 2: Location of Lorna Glen (Matuwa), a 245,000 ha ex-pastoral lease now owned by Martu.

2.3 Measuring area burnt

Existing data acquired as part of a separate project reporting on fire history and extent in the 20 million ha Martu Determination and Birriliburru Lands in the Western Desert (Burrows *et al*. 2013) were used to quantify the proportion of a 20 million ha project area burnt each year. The project area was classified and mapped into two 'fire management' zones, or landscapes, based on the prevalence of contemporary Aboriginal (Martu) verses lightning ignition sources. Most fires in the Martu zone were lit for hunting during the cooler months, whereas fires in the lightning zone mostly burnt during the hotter months.

An annual sequence of Landsat satellite imagery with five Landsat scenes covering ~11 million ha was acquired, interpreted, digitised, mapped and analysed to monitor trends in the temporal and spatial scales of fires over a 17 year period (1997-2013, except for 2007 as no imagery was available). Mapping fire scars in spinifex grasslands from satellite imagery is relatively straightforward compared with some other vegetation types such as tropical savannas or tall forests (Burrows *et al*. 2009). Boundaries of fire scars that were clearly visible on an annual time sequence of medium resolution Landsat Thematic Mapper (TM and ETM+), processed to a pixel resolution of 25 m, and enhanced by displaying the spectral bands: 7 (mid-infrared), 4 (near-infrared) and 2 (visible red) in the red, green and blue colours respectively. The imagery used for this study was from Landsat 5 TM and Landsat 7 ETM+.

Image processing details and validation are provided by Burrows *et al*. (2013). In brief, for each Landsat scene for each year, fire scar boundaries were interpreted using Landsat band combination 742, differenced Normalised Burn Ratio (dNBR) and differenced Near-Infrared (dNIR). The very large area and relatively long time period over which satellite imagery needed to be analysed meant that an automated processing system was warranted for efficiency and to keep costs down. The yearly extent of fire scars was determined using the differenced dNBR, which compares the reflectance of the current year with the reflectance of the previous year. Fire scars where grouped in the respective management zones. The management zone in which the centroid of a fire scar polygon was located, associated the fire scar to that management zone. The accuracy of the satellite fire scar mapping was later validated by on-ground survey (Burrows *et al*. 2013).

These data were supplemented with similar fire history data published by Bliege Bird *et al*. (2012) who used a 10-year sequence (1999-2010) of satellite imagery to reconstruct fire history in the Martu Native Title lands in the Great and Little Sandy Deserts. They examined two regimes: one where ignitions were predominantly (but not exclusively) Aboriginal hunting fires within 50 km of communities, and another where ignitions were exclusively by lightning in remote areas not visited by Aboriginal hunters. Almost all hunting fires were lit in the cooler winter months, whereas lightning fires mostly occur in the hotter spring-summer months (Bliege Bird *et al*. 2012).

2.4 Measuring fire patchiness

Combustion or burning efficiency, as defined by Russell-Smith *et al.* (2009) for tropical savanna fuels, is "*the mass of fuel that is exposed to fire that is pyrolised"*, or the proportion of the vertical fuel profile or fuel bed that burns. When spinifex grasslands burn, there is virtually complete combustion of the vertical fuel profile (fuel biomass less ash residue). Because of its discontinuous nature, burn patchiness or burn efficiency in spinifex grassland is the extent or efficiency of horizontal combustion of the fuel bed. Two levels of fire or burn patchiness were investigated in each of the management zones defined by the studies above;

i. Extent of unburnt patches within burnt patches (intra-scar patchiness). This is unburnt vegetation surrounded by burnt vegetation within an individual fire scar, or burnt patch. Intra-scar patchiness was measured using ground transects, primarily because patches in cool burns were generally smaller and more difficult to detect on satellite imagery than inter-scar patches. In areas recently burnt by hot summer wildfires and cool hunting fires intra-scar patchiness (areal per cent of unburnt vegetation) was determined on-ground by measuring the distance of burnt and unburnt patches intercepted along a series of 100 m transects. In all ~1,000 m of transect was sampled in each zone.
ii. Extent of unburnt patches between burnt patches (inter-scar patchiness). This is unburnt vegetation surrounded by or remaining between individual burnt patches or fire scars. This was sampled from 2011 SPOT satellite imagery only so is not representative of the spatio-temporal variation. Further work is needed to capture the extent of variability, but this sample is likely typical.

2.5 Measuring mulga biomass at Lorna Glen (Matuwa)

An important component of this study is to quantify the key carbon pools likely to be impacted by fire so that reliable estimates of carbon flux under managed verses unmanaged fire regimes can be quantified. Under the appropriate fire regime, the fire sensitive but long lived mulga (*Acacia aneura* and it close relatives; see Maslin and Reid (2012)) has the potential to store significant quantities of carbon in these landscapes. As part of this study, an investigation of mulga biomass was carried out with the assistance of Wiluna Martu Aboriginal Rangers at Lorna Glen (Matuwa).

The above and below ground biomass of 32 mechanically excavated mulga trees of varying sizes was measured in the field. Following the protocol of Snowdon *et al*. (2002) tree height, crown width and stem diameter(s) at ground level was measured and stem basal area calculated. Above ground biomass, including foliage, branches, bark and stems was weighed 'green' in the field using a suspended clock-dial spring balance. The 'root plate' was cleaned, cut from the above ground part of the plant and weighed. During the excavation process, most of the root system within a 0.5-1.5m radius of the main stem(s) was recovered, but many roots beyond this distance were usually severed, with the severed ends remaining in the soil. To estimate the biomass of root material remaining in the soil, the large end and small end diameter (point at which the root was severed) of recovered roots was measured, as was the distance between these dimensions. Roots >5 mm in diameter were placed into 1.0 cm diameter classes and the number of roots in each class tallied. Finer roots left in the soil were deemed to add little to the total root biomass, so were ignored. Several larger lateral roots were excavated down to a small end diameter of about 10 mm. From these measurements, a root taper function was determined for each root diameter class, and assuming a conical root shape, an estimate of the volume of root material remaining in the soil was calculated.

The mean density of root material was determined from a sample of ten root sections, each about 8 cm long and of varying diameters. These sections were oven dried, weighed and their volumes calculated by assuming the sections were cylindrical with a diameter equal to the mid-point diameter of the sample and a height equal to the length of the sample. The density of wood in stems and main branches was calculated similarly.

To determine oven dry weight of above and below ground biomass, seven samples were taken each of roots, stems and branches (with attached foliage) and moisture content of these components determined by oven drying. Oven dry weight/biomass was calculated from green weight less moisture based on the sampled moisture contents.

2.6 Mulga in the landscape

Lorna Glen (Figure 2) was used as a case study for determining the extent and distribution of mulga in spinifex-dominated landscapes. As discussed above, species of interest for carbon biosequestration in these landscapes are *A. aneura* and its close relatives, or species that have similar taxonomy, vital attributes, life histories and fire responses to *A. aneura*. At Lorna Glen, close relatives of *A. aneura* that co-occur with spinifex include *A. ayersiana, A. incurvaneura, A. mulganeura and A. aptaneura A. pteraneura and A. ramalosa var linophylla (Bruce Maslin, pers. comm.).* This group is generically referred to as 'mulga' in the current study.

Aerial photography and satellite imagery were used with ground validation and assessment to map mulga occurring in the Bullimore landsystem (spinifex dominated sand plains and dune fields), which occupies about 35% (~86,000 ha) of Lorna Glen. The study area was covered by aerial photography from two surveys - the western half was captured in 2008 and digitised with 80 cm pixels, the eastern half was captured in 2011 and digitised with 50 cm pixels. This imagery along with SPOT satellite imagery and recent Landsat 7 imagery were used in the field as a background in mapping software.

A sample of fourteen mulga groves was identified from aerial photos and ground truthed for confirmation and measurement. 'Groves' were defined as clumps of mulga comprising a canopy cover >20%. In addition to groves, mulga occurs as scattered trees in various parts of the Bullimore landsystem, but the bulk of mulga biomass occurs in groves embedded in, or fringing the Bullimore landsystem. Structural attributes of these groves, including canopy cover and stem basal area were measured using belt transects of varying dimensions to fit the size and shape of the groves. Following ground truthing, the full extent of mulga on the

Bullimore landsystem was then able to be mapped from aerial photography and estimates made of the total mulga biomass (hence carbon store) made using the previously developed relationships between canopy cover, basal area and biomass.

Soil texture at each site was estimated in the field using the ‘feel method’ where the soil is moistened and rubbed between the thumb and fingers. The way the wet soil ‘balls up’ or ‘rolls out’ and holds together gives an approximation of relative clay content. Soil samples to a depth of 30 cm were also taken beneath groves and outside the groves to determine the extent to which edaphic factors (soil texture and moisture regime / drainage) regulated the occurrence of mulga and of spinifex, but these are yet to be analysed in the laboratory.

To better understand how mulga is able to persist in a flammable, spinifex-dominated landscape, fuel measurements, or the composition and extent of the ground layer of vegetation beneath the mulga groves, was also assessed using the belt transects. Of particular interest was the cover and continuity of spinifex, as this forms the dominant fuel.

2. Results and discussion

3.1 Post fire fuel biomass accumulation

Fuel biomass accumulation following fire in desert landscapes was modelled by Brett Murphy, University of Melbourne, and is a function of time since fire and rainfall (Figure 3).

An Olson fuel accumulation curve (Olson, 1963) of the form;
Xt = Xss (1-e-kt) was fitted to the data, where:

Xt = weight of dry fuel biomass per unit area t years after fire
T = time since fire in years
Fitted parameters: Xss = weight of fine fuel accumulated under steady state conditions and k = decomposition constant.

Fuel biomass accumulation is most rapid in the first 10-15 years post fire and by about 20-25 years, it more-or-less stabilises at about 8 and 10 t/ha (mean) for low and high rainfall regions of the Western Desert respectively (Figure 3).

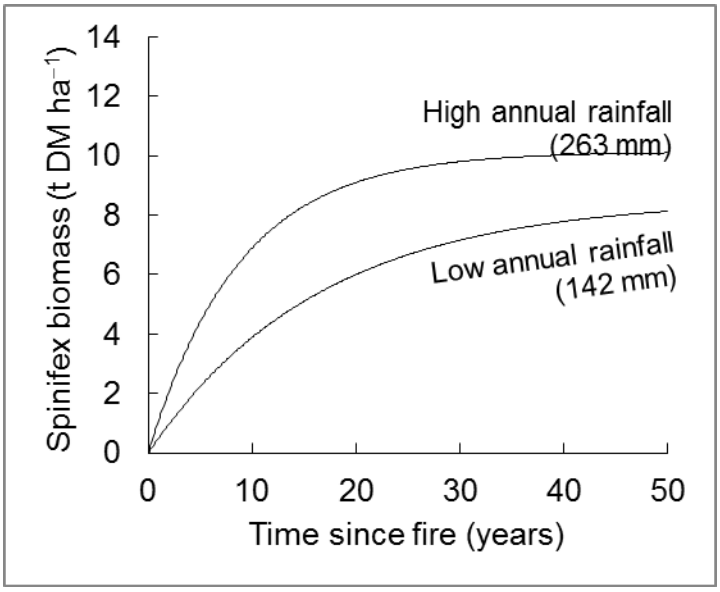

Figure 3: Post fire fuel biomass accumulation in spinifex grasslands of the Western Desert (modeling by Brett Murphy; data by N. Burrows).

The mean annual area burnt in the Martu Determination over the period 1997-2013 was 7-8% of the area, which equates to a mean fire return interval of 12-14 years. The analysis in Table 1, based on the high rainfall fuel biomass models in Figure 3 and using the savanna emissions factors (Dreyfus 2012), shows that increasing the mean fire return interval from 14 to 20 years would net a GHG abatement (i.e. methane and nitrous oxide) of 0.006 t CO_2-e ha^{-1} $year^{-1}$. This is only 13% of the abatement that WALFA generates - 0.045 t CO_2-e ha^{-1} $year^{-1}$ (Russell-Smith *et al*. 2013). Clearly, due to the rate of fuel accumulation in these desert ecosystems (Figure 3), there is little gain in abatement and sequestration benefit by extending the fire interval.

Under a 14 year mean fire return interval, mean fuel biomass would be ~5 t ha^{-1} (8.44 t CO_2-e ha^{-1}) and under a 20 year interval this increases to ~6 t ha^{-1} (10.24 t CO_2-e ha^{-1}). Therefore, increasing the fire interval to 20 years would result in an increase in sequestration (into the fuel biomass) of 1.80 t CO_2-e ha^{-1}. Annualised over 50 years, it is 0.36 t CO_2-e ha^{-1} $year^{-1}$. In most cases, it would not be feasible or ecologically desirable to repeatedly burn spinifex at intervals shorter than about 12 years under cool conditions. Extending the fire return interval to 20 years would require a supreme fire suppression effort, which is not feasible in these landscapes. Over the longer term (several decades) the mean annual area burnt in the northern part of the Western Desert is 7-8% in both areas dominated by Aboriginal burning and in areas dominated by lightning fires (Bliege Bird *et al* 2012; Burrows *et al.* 2013). The major difference being that most Aboriginal burning is done at a cooler time of year, so fires are less intense.

Table 1: Comparison of emissions and sequestration for two fire intervals in spinifex grassland using savannah burning methodology (Dreyfus 2012): C mass fraction = 0.46; Emissions factor CH_4 = 0.0031; Emission factor N_2O = 0.0075; N:C ratio = 0.0096; Elemental to molecular mass CH_4 = 1.3333; Elemental to molecular mass N_2O = 1.5714.

	14 year fire interval	20 year fire interval
Abatement		
Fuel burnt	0.58 t ha^{-1} $year^{-1}$	0.45 t ha^{-1} $year^{-1}$
CH_4 emissions	0.0011 t CH_4 ha^{-1} $year^{-1}$	0.0009 t CH_4 ha^{-1} $year^{-1}$
NO_2 emissions	0.0000 t N_2O ha^{-1} $year^{-1}$	0.0000 t N_2O ha^{-1} $year^{-1}$
TOTAL emissions	0.032 t CO_2-e ha^{-1} $year^{-1}$	0.026 t CO_2-e ha^{-1} $year^{-1}$

Baseline: 0.032 t CO_2-e ha^{-1} $year^{-1}$
With management: 0.026 t CO_2-e ha^{-1} $year^{-1}$
Abatement: = 0.006 t CO_2-e ha^{-1} $year^{-1}$

Long term sequestration
(fuel biomass) 1.80 t CO_2-e ha^{-1}
Annualised over 50 years: 0.36 t CO_2-e ha^{-1} $year^{-1}$

3.2 Area burnt

A map of the recent fire history (1998-2012) of a 93,840 km^2 sample of the Martu Native Title determination in the central-northern part of the Western Desert of WA is shown in Figure 4 (source: Burrows *et al*. 2013). Arbitrary boundaries of areas that were mostly burnt by Martu hunters in the cooler season (managed areas) are shown (the ‘cool’ season is from about April-May to August-September). Beyond these areas, fires were caused by lightning in the hotter season (September-October to March-April). In interpreting this map and other data presented here, it should be noted that while the circled areas are delineated as predominantly Martu burning, Martu did not travel to, or carry out burning in all parts of these zones, so some fires are lightning-caused and may have originated either inside or outside the Martu managed zone.

Figure 5 summarises the area burnt each year from 1994/95-2012/13 in both managed and unmanaged zones. Notable features include the ‘boom’ and ‘bust’ fire cycles associated with rainfall patterns, especially in the ‘unmanaged’ zone where the mean annual area burnt is

8.3% with a standard error of 2.01, or 24.2% of the mean, reflecting significant year-to-year variability. The mean annual area burnt in the Martu-managed zone is slightly less (7.6%) but the standard error is 1.39, or 18.3% of the mean, reflecting less year-to-year variability than in the 'unmanaged' zone. 'Area burnt' data as mapped from satellite imagery includes unburnt patches or pockets within fire scars so is higher than the actual burnt area. These data are similar to data reported by Allan and Southgate (2002) for a largely unmanaged region of the Tanami Desert (see Figure 6), which shows 'boom' and 'bust' fire cycles. Over the sixteen year period represented in Figure 6, the mean annual area burnt is ~9.6%, which is similar to data from the northern part of the Western Desert.

Using the summary fire history sample data for central Australia reported by Allan and Griffin (2002) for the period 1979/80-1984/85, the mean annual area burnt was 7.4%. These data show that in spinifex grasslands of central Australia, the annual area burnt (including unmapped unburnt patches/pockets within fire scars) is highly variable from year to year, but over the long term, is ~7-8%. Assuming a mean biomass/fuel load of 6 t ha^{-1}, and that combustion is complete (rather than patchy), this equates to a mean annual combustion of ~100.8 million tonnes of vegetation of which ~38.4 million tonnes is on Aboriginal land.

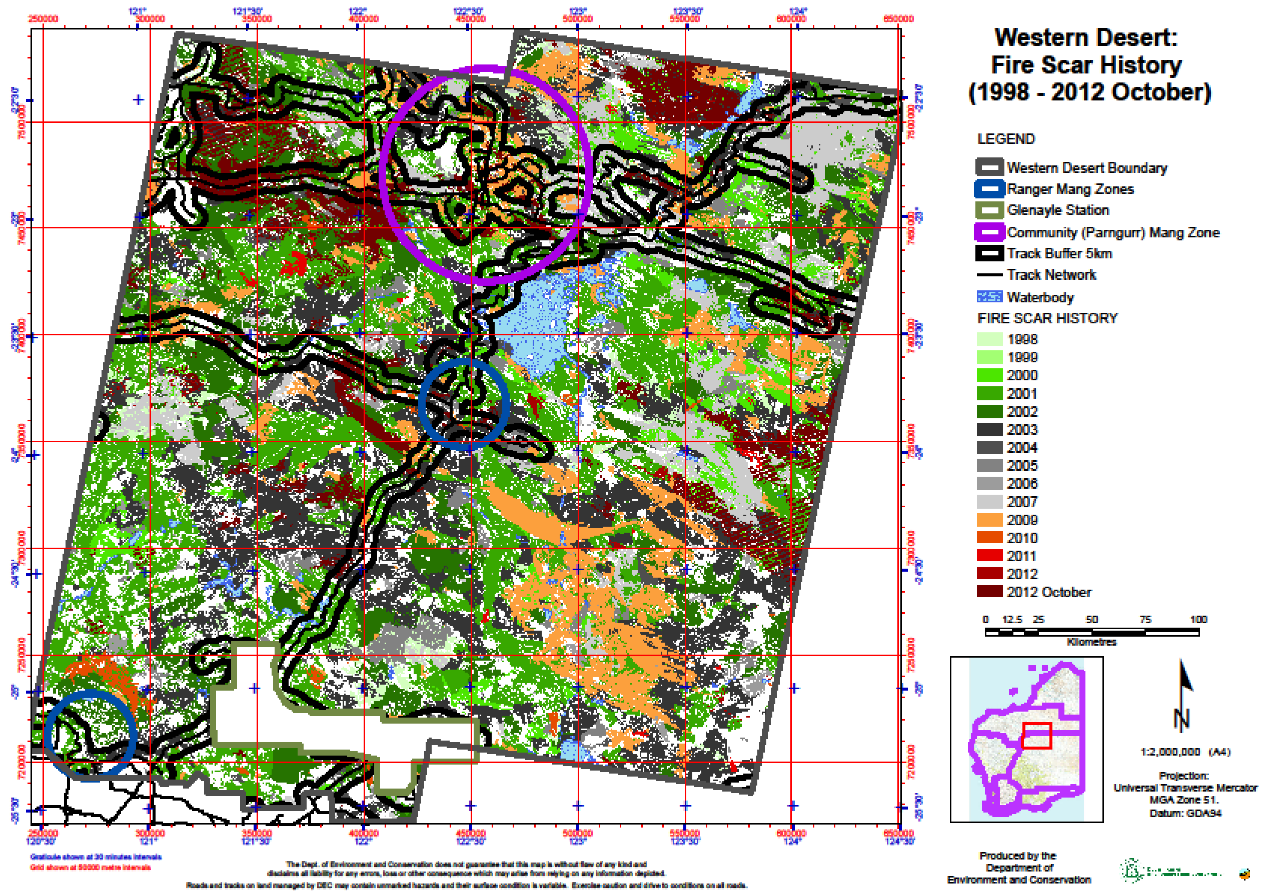

Figure 4: Fire history (1998-2012) of a ~90,000 km^2 sample of the 200,000 km^2 Martu Determination in Western Australia. Areas encircled by blue and purple lines are where Martu have been burning in recent times (Source: Burrows et al. 2013).

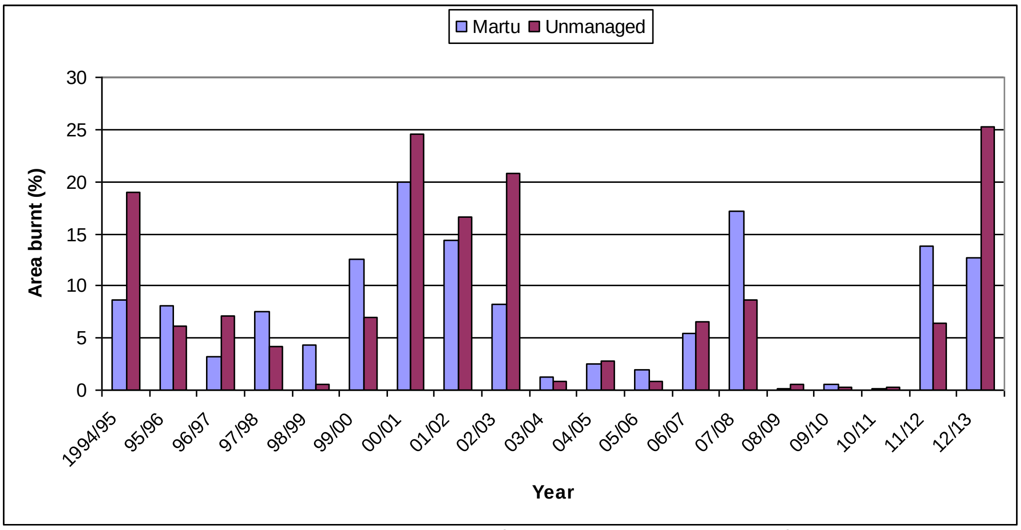

Figure 5: Proportion of a project area (~90,000 km^2) within the 200,000 km^2 Martu Native Title lands burnt each year by 'management zones'. Martu managed zone, mean = 7.6% burnt annum^{-1}; Lightning dominated zone, mean = 8.3% burnt annum^{-1} (Source: Burrows et al. 2013).

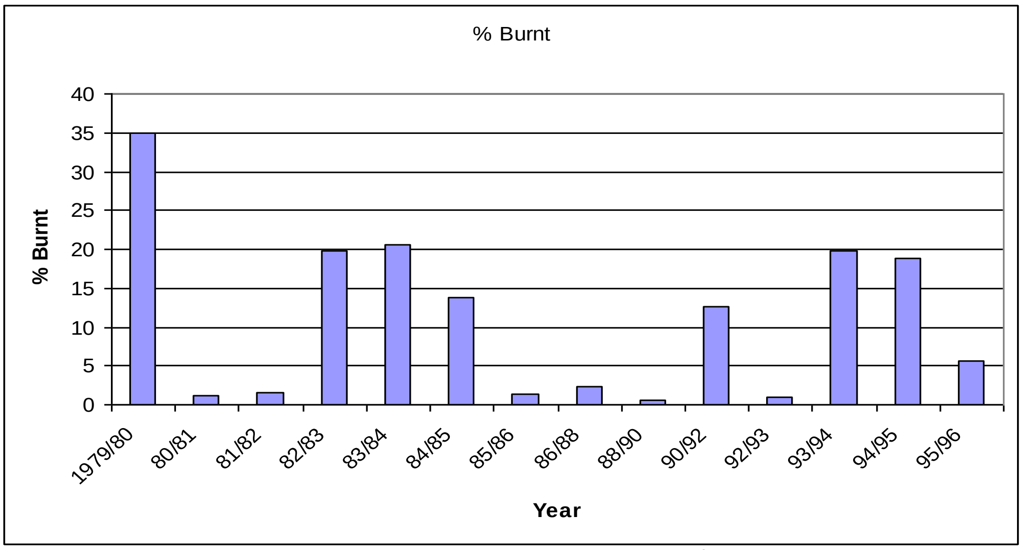

Figure 6: Proportion of the Tanami Desert region area (101,687 km^2) burnt each year; mean = 9.6% annum^{-1} (Source: Allan & Southgate 2003).

3.3 Fire patchiness

The burning efficiency (the proportion of area/fuel that is burnt within a burnt patch/landscape) based on limited data from 'cool' season hunting fires and 'hot' season wildfires is shown in Table 2. Also shown are data from 1953 aerial photography of traditional Pintupi/Martu burning. While there are limited data, as expected 'hot' season wildfires consume a significantly higher proportion of the vegetation than 'cool' season hunting fires.

Table 2: Fire scar metrics for Martu fires (1953 aerial photography, ground assessment of cool season hunting fires) and for 'hot' season wildfires (satellite imagery). Burning efficiency = patchiness, or the proportion of fuel that is burnt within a burnt patch/landscape.

Fire size (ha)	**1953 Aerial photography**	**1997- 2012**		**2011/12**	
	Martu fires	Cool season hunting fires	Hot season wildfires	Cool season hunting fires	Hot season wildfires
Mean	64	365	1,882	410 (146)	5,262 (186)
Median	10	48	809	32	92
Range	0.5-6000	10-11,957	10-346,302	10-13,746	10-105,300
Mean burning efficiency (s.e.)	0.52 (0.02)	No data		0.62 (0.02)	0.82 (0.06)

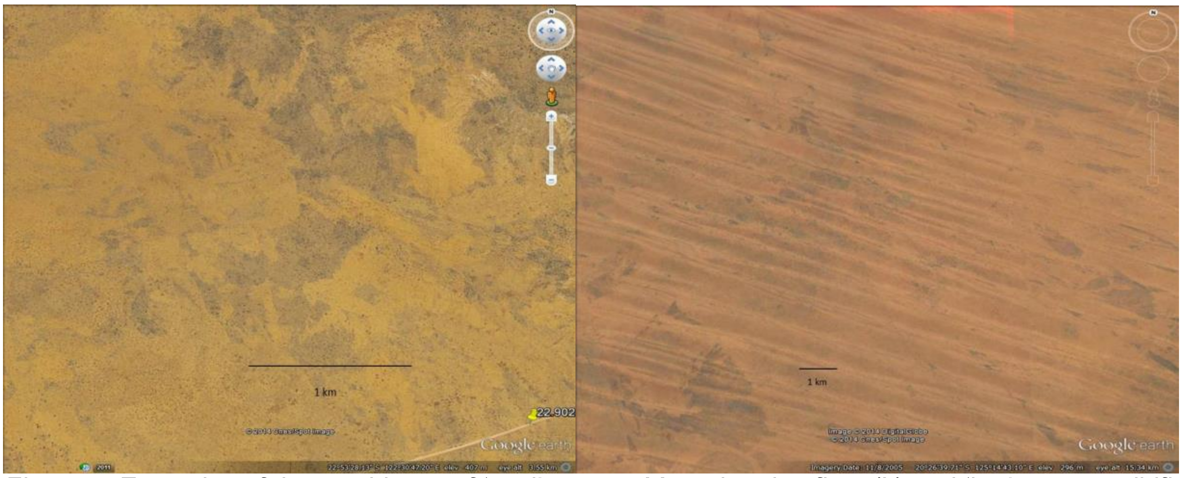

Figure 7: Examples of the patchiness of 'cool' season Martu hunting fires (L) and 'hot' season wildfires (R). Unburnt patches are darker colour. Note scale difference between images (Google images taken October 2013).

Plate 1: L – Typical patchy, low intensity cool season Martu hunting fire. R – Virtually complete combustion of vegetation following a high intensity hot season wildfire.

3.4 Mulga biomass from excavated trees

Thirty two mulga trees (*A. aneura*) of various sizes were excavated and processed to determine total dry biomass. Sampled trees ranged in height from 2.4 m – 6.0 m with stem basal areas at ground level ranging from 52.7 cm^2 – 471.1 cm^2. The root system comprised a dense network of radiating lateral and sinker roots, with no tap root. Lateral roots were mostly 10-25 cm below the soil surface. The largest roots were up to 40 mm in diameter (measured near the stem) and up to 12 m long. The oven dry density of mulga roots and above ground stem wood was calculated as 757 kg/m^3 and 1,120 kg/m^3 respectively, which is the range of other workers (e.g. Adams *et al.* 2001). The allometric equations developed by the current study (below) predict slightly higher biomass than those developed by Adams *et al*. (2001) from a smaller sample in the Pilbara region of WA. They only measured above ground dry biomass, so did not develop equations for total biomass.

Of the tree dimensions measured, stem basal area at ground level (BA) was the best predictor of total oven dry biomass (TB) (Figure 8):

$TB_{kg} = 0.663\ (BA_{cm}^{-2}) – 29.56$ $(R^2 = 0.86)$, *or:*
$TB_{tonnes} = 6.63\ (BA_{m}^{-2}) – 0.029$

Weaker relationships existed between total biomass (TB) and tree height (HT) and tree canopy area (CA). Given the potential for tree canopy area to be estimated from remote sensing (aerial photography or satellite imagery) it is likely to be a useful metric for estimating mulga biomass (Figure 9):

$TB_{tonnes} = 0.0093(CA_{m}^{2}) – 0.0187$ $(R^2 = 0.59)$

Above ground biomass (AB) was related to stem basal area (BA) and canopy cover (CA) by the following:

$AB_{kg} = 0.53(BA_{cm}^{-2}) – 22.15$ $(R^2 = 0.86)$
$AB_{kg} = 7.45(CA_{m}^{2}) -12.96$ $(R^2 = 0.61)$

The relationships between above and below ground dry biomass is shown in Figure 10. The mean shoot (above ground):root (below ground) ratio was 4.8:1, which is similar to many other tree species (5:1 – 6:1).

Plate 2: Martu Rangers cleaning the root system of an excavated mulga tree

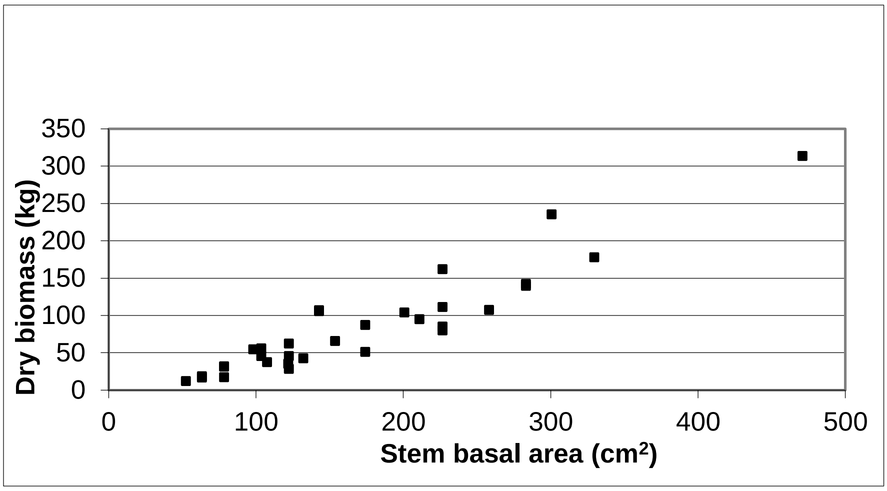

Figure 8: Relationship between total oven dry biomass of mulga stem basal area

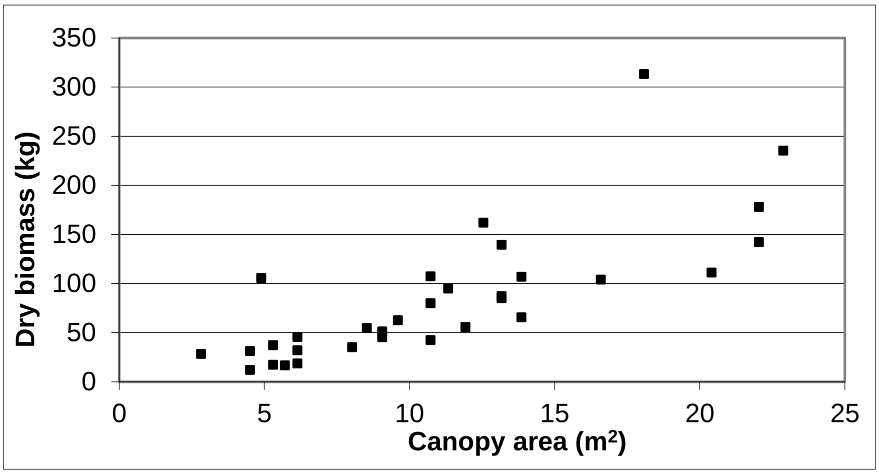

Figure 9: Relationship between total oven dry biomass of mulga and tree canopy area

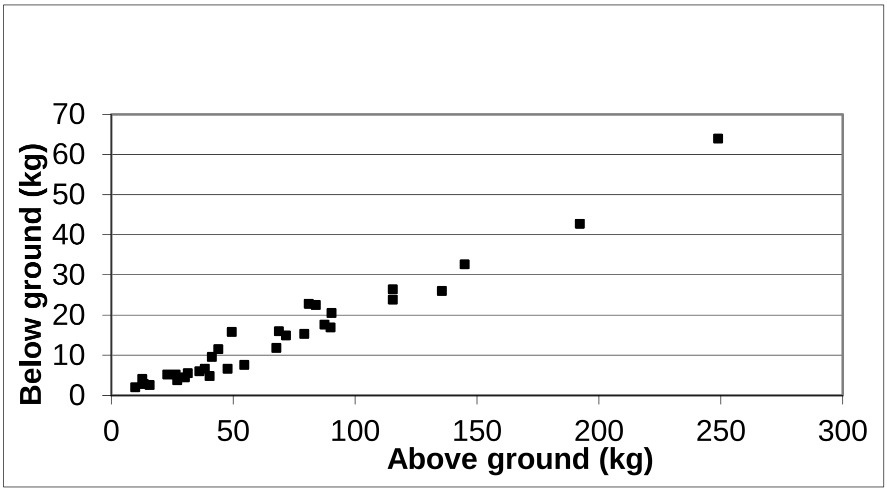

Figure 10: Relationship between above and below ground dry biomass for mulga.

3.5 Mulga in the Bullimore (spinifex) landsystem

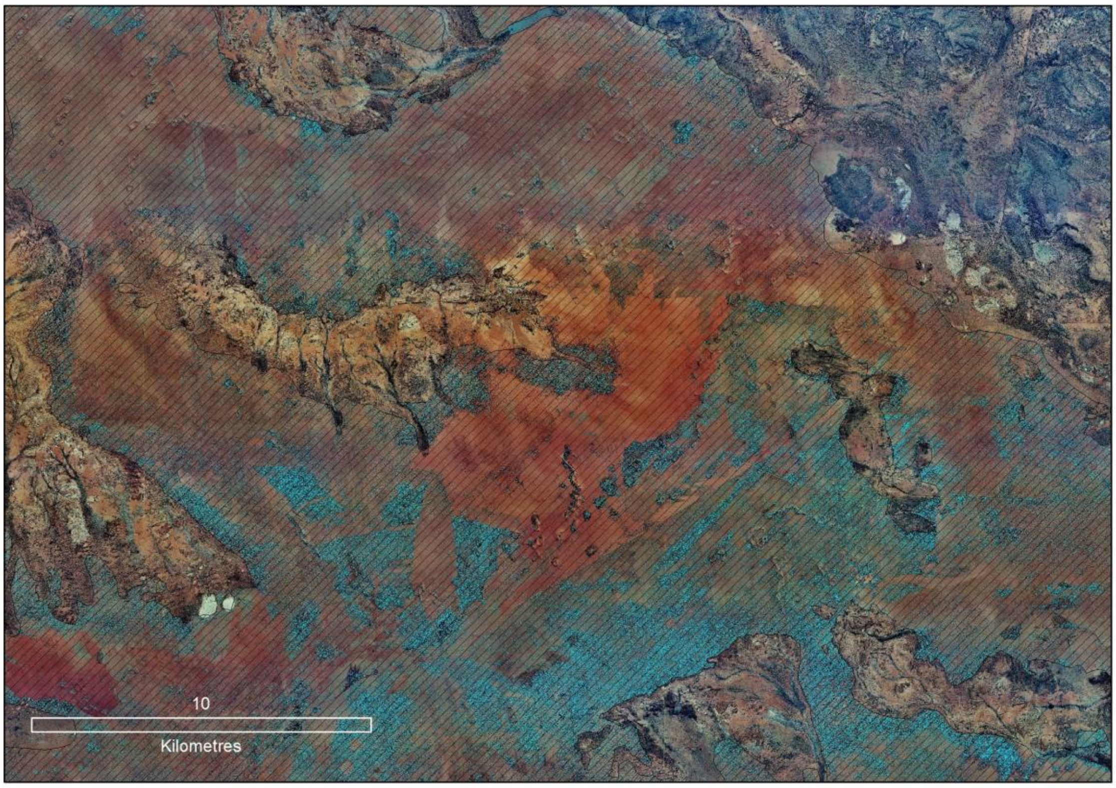

Plate 3: Enhanced aerial photograph of mulga canopies (enhanced bright blue) in the Bullimore land system (hatched) which is dominated by a ground cover of spinifex. Paler blue are other Acacia trees and shrubs.

Aeolian sand dunes and sandplains (Bullimore landsystem) comprise ~86,000 ha (38%) of Lorna Glen (Matuwa). This landsystem is dominated by a ground cover of spinifex (*Triodia spp*.) with scattered low shrubs and small trees such as mulga occurring in specific habitats usually associated with changing soil texture (Plates 3 and 4). It is an ecological enigma that a fire sensitive species such as mulga can persist in spinifex-dominated flammable habitats of the Bullimore landsystem. To better understand this, we used a combination of remote sensing (aerial photography and satellite imagery) and ground assessment.

Using aerial photography (50-80 cm pixels) (API), small groves and individual scattered mulga trees could be reliably mapped, although occasionally it was difficult to separate mulga from some other *Acacia* species. The canopy cover of mulga (%) determined by API was very similar to that determined by ground assessment (Table 3) and superior to satellite imagery. Based on automated mapping using API mulga occupies ~5.6%, or ~4,760 ha of the Bullimore landsystem. Four-band SPOT imagery (~12 m pixels) over classified some of the areas to mulga, resulting in a canopy cover estimate of 8.0%. Landsat 7 (30 m pixels) resulted in a significant over-estimation of mulga canopy (~20%).

Mulga occurs in a variety of habitats, which are summarized in Table 3. Soil texture, especially clay content, was an important determinant of the relative abundance of spinifex and mulga. Based on the field techniques for estimating soil texture, soils ranged from loamy sands (low clay content) to sandy clay loams (higher clay content). Generally, as the clay content increased, the cover of spinifex decreased and mulga increased – on sandy soils with low clay content, mulga was sparse (low cover) or absent and spinifex was abundant (high cover); on heavier, clayey soils in flow-on areas and subtle drainages, spinifex was absent (Figure 11). More detailed studies are required to better understand this relationship in these landscapes.

Plate 4(L): Mulga groves embedded in a spinifex-dominated dune swale on Lorna Glen (Matuwa). (R): Mulga grove killed by wildfire fire 11 years ago. Mulga seedlings have not reached maturity but the spinifex, although patchy, will carry fire under hot windy conditions. Another wildfire in the next 6-8 years will most likely extirpate mulga from this site.

The habitat flammability was also an important determinant of the cover of mulga on the Bullimore landsystem. This was regulated by edaphic factors described above, which influenced the cover of spinifex (fuel), hence habitat flammability. Mulga cover also influenced habitat flammability by its effect on spinifex cover. Where mulga and spinifex co-occur on similar soil textures, an inverse relationship exists between the cover of mulga and of spinifex, so in addition to the influence of soil texture, the density of mulga appears to have a suppressive effect on spinifex (fuel / flammability) cover, probably through competition for water (Figure 11).

Hence, a complex interaction exists between soil texture, fire and the composition of the mulga-spinifex mosaic. These observations are consistent with other workers. Murphy *et al*. (2010) concluded that "*in more productive parts of the landscape, mulga suppresses spinifex and fire, while in less productive parts of the landscape, fire and spinifex suppress mulga*". These findings are also in agreement with the conclusions of other workers (e.g., Nano and Clarke 2008; Bowman *et al*. 2009) who have studied mulga patch dynamics in spinifex habitats in central Australia and concluded that interactions and feedbacks existed between fire, soil and vegetation to determine the mulga mosaic.

They caution that large hot fires could lead to diminishment of mulga and expansion of spinifex. Plates 5 and 6 are examples of a small, dense mulga grove with a sparse understory of spinifex embedded in a flammable spinifex sand plain.

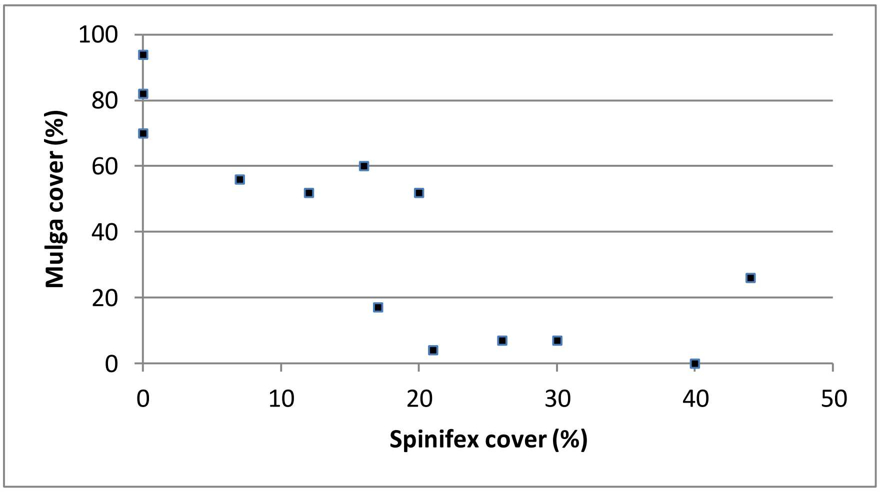

Figure 11: Relationship between mature spinifex and mulga cover on the Bullimore landsystem, Lorna Glen (Matuwa).

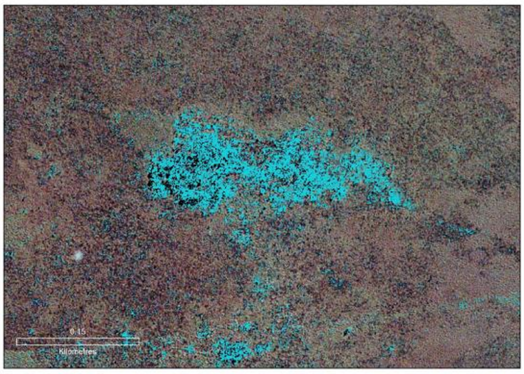

Plate 5 (L): A dense mulga grove (enhanced bright blue) embedded in a spinifex sand plain.
Plate 6 (R): Sparse spinifex understorey beneath a dense mulga grove on a spinifex plain.

In addition to the soil texture-fire-vegetation cover feedbacks described above, in some habitats, it is the continuity and patchiness of spinifex alone that is important in determining the persistence of mulga. As can be seen from Table 3, mulga also co-occurs with spinifex in some habitats where, due to local patterns of soil depth, spinifex is clumped or patchy. There are habitats depicted by site type LG9 in Table 3 comprising patches of scattered mulga over relatively dense spinifex interspersed with bare patches – this patterning is clearly visible in Plate 7. The bare patches are due to localised areas of very shallow soil (10-20 cm to hard pan), which inhibits vegetation growth.

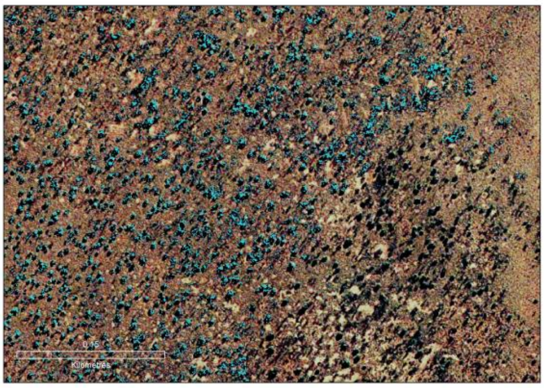

Plate 7: Mulga (enhanced bright blue) over spinifex (dark brown) in a landscape with numerous bare patches (light brown), fragmenting the continuity of spinifex. Bare patches are up to 20m across.

Table 3: Range of habitat flammability, structure and dry biomass of mulga occurring on the spinifex dominated Bullimore landsystem on Lorna Glen (Matuwa).

Site	**Spinifex cover (%)**	**Bare ground (%)**	**Mulga canopy (%)**	**Mulga basal area ($m^2 ha^{-1}$)**	**Mulga dry biomass ($t\ ha^{-1}$)**	**Landform and habitat flammability**
LG2	22	48	Gd: 30 API: 33	2.7	16	Mulga on sand plain. Low spinifex cover, low flammability 
LG3	20	34	Gd: 52 API: 55	8.91	53.7	Mulga grove in sand plain. Low spinifex cover in grove, low flammability. 
LG4	16	68	Gd: 60 API: 54	11.8	70.8	Mulga grove in sand plain. Very low spinifex cover, very low flammability 
LG4a	40	56	Gd: 0 API: 0	0	0	Sand plain adjacent to LG4 – grove in background. High spinifex cover, high flammability. Scattered trees killed by fire. 
LG5/ 6	0 (90% soft grasses/ herbs)	10	Gd: 82 API: 78	21.06	126.4	Flow-on area in sand plain. Sandy-clay soil. No spinifex, but seasonal herbs, soft grasses after rains. Flammability seasonal. 
LG7/ 8	30	45	Gd: 7 API: 6	3.76	22.6	Sand plain surrounded by stony hills. Moderate spinifex cover, moderate flammability; natural landscape barriers reduce fire risk. 

Table 3 c'td: Range of habitat flammability, structure, cover (Gd – ground assessment; API = aerial photo interpretation) and dry biomass of mulga occurring on the spinifex dominated Bullimore landsystem on Lorna Glen (Matuwa).

Site	**Spinifex cover (%)**	**Bare ground (%)**	**Mulga canopy (%)**	**Mulga basal area (m^2ha^{-1})**	**Mulga dry biomass ($t\ ha^{-1}$)**	**Landform and habitat flammability**
LG9	21	55	Gd: 4 API: 8	1.7	10.4	Sand plain with shallow soil patches. Spinifex cover low. Flammability low due to bare patches in spinifex to 20m across. 
LG10	44	28	Gd: 26 API: 26	4.7	28.6	Sand plain surrounded by rocky hills. High cover of spinifex; high flammability; natural landscape barriers reduce fire risk. 
LG11	17	60	Gd: 17 API: 16	3.9	23.5	Sand plain with bare, shallow soil patches. Spinifex cover low, flammability low. 
LG12 /13	0	30	Gd: 94 API: 94	54.9	329.5	Small dense mulga grove in slight depression in sand plain. Moderate cover of spinifex outside grove, but no spinifex in grove. Low flammability in grove. 
LG14	0 (80% herbs, soft grasses)	20	Gd: 70 API:	23.1	139.1	Flow-on area in sand plain. Sandy-clay soils. No spinifex, seasonal herbs and soft grasses, low fuel load, seasonal flammability. 

As well as edaphic factors influencing spinifex continuity and cover, hence habitat flammability, there are also landscape-scale features that enable mulga to persist in a matrix of flammable spinifex. Mulga is able to co-occur with a relatively dense, flammable understorey of spinifex in some habitats that are near to, or surrounded by natural barriers to fire spread, such as rocky hills and plains, and sand dunes. Although the spinifex cover, hence flammability, is moderate to high in these habitats, the proximity of natural barriers in the landscape reduces the risk of fire on the sand plain, so the interval between fires is increased and mulga is able to persist. Plate 8 illustrates mulga groves and scattered trees persisting on a spinifex-dominated sand plain surrounded to the north and south by sparsely vegetated stony low hills, which are barriers to fire spread. Although not entirely protected from fire, mulga persists in the penumbra of a 'fire shadow'.

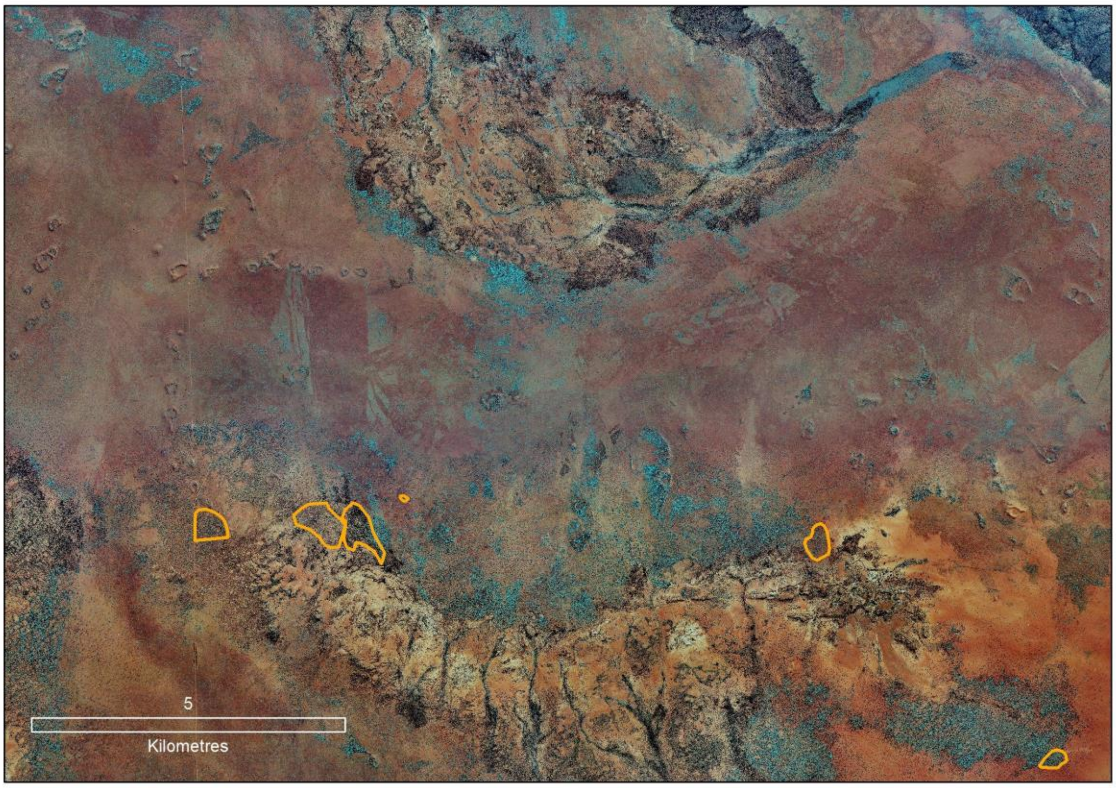

Plate 8: Mulga (enhanced bright blue) on a spinifex-dominated sand plain surrounded by stony low hills (top and bottom of plate), which are barriers to fire spread, providing some protection to mulga. Yellow circled patches are some of the sites used to ground truth aerial photography and to measure structural characteristics of mulga and underlying spinifex.

3.5 Estimate of current mulga biomass and C store

Based on aerial photography estimates of mulga cover, the basal area samples summarised in Table 3, and the allometric relationships developed by the current study, estimates of the current total dry biomass of mulga on the ~85,000 ha of Bullimore landsystem on Lorna glen (Matuwa) are as follows:

Using canopy cover to estimate total dry biomass of mulga (tonnes - $TB_{tonnes)}$:
~4,760 ha of mulga canopy = 47,600,000 m^2 of canopy:

$TB_{tonnes} = 0.0093(CA_m{}^2)$
$TB_{tonnes} = 0.0093(47{,}600{,}000m^2) = 442{,}680$ *tonnes (~203,632 tonnes of C)*

Using basal area (BAm^2):

Mean BAm^2 = 13.64 m^2ha^{-1} (Table 3)
$TB_{tonnes} = 6.63\ (BA_m{}^{-2})$
$TB_{tonnes} = 6.63(13.64m^2 \times 4{,}250ha) = 384{,}341$ tonnes (~176,796 tonnes of C)

Estimate of current spinifex above ground biomass and C store
~85,000 ha of spinifex; mean above ground dry biomass = 6.3 t ha^{-1}
85,000 ha x 6.3 t ha^{-1} x $0.46_{(C\text{-}fraction)}$ = 246,330 tonnes of C.

3. Implications for fire management

This feasibility study aimed to answer the questions:

- What is the abatement and sequestration potential (t. CO2-e p.a.) from both mulga and spinifex components under a typical range of rainfall and landscape conditions?
- Can 'natural' (pre-European settlement), or traditional Indigenous fire regimes deliver effective biomass accumulation (biosequestration) and GHG abatement at landscapes scales?

Fire management has the potential to significantly reduce emissions and increase biosequestration in spinifex grasslands by shifting the fire regime and by carrying out strategic protection burning. Emissions abatement and sequestration estimates developed in this study are based on regions of the Western Desert with a long term annual average rainfall of ~260 mm. Biomass / fuel productivity data are not available for higher rainfall regions of central Australia, but clearly, in more productive regions, higher levels of emissions abatement and sequestration will be achieved per unit area of land managed than reported here.

4.1 Shifting the fire regime from the current regime of predominantly 'hot season' wildfires to one of 'cool season' hunting / prescribed fires, similar to 'natural' or traditional Aboriginal fire management.

Emissions abatement and sequestration
Over the longer term, the mean annual area burnt in the spinifex grasslands of much of central Australia, regardless of the 'management zone', is about 7-8%. Currently, about 98% of the area burnt is burnt by large, intense hot season fires. Available data show that in landscapes burnt predominantly by Aboriginal people in the cool season, the fires are smaller, less intense and patchier than hot season wildfires, consistent with fire behaviour expected under the different seasonal conditions. Based on limited sampling, fire scar patchiness ratio (area unburnt-to-area burnt) in landscapes burnt by hot season fires is 0.18 (burn efficiency = 0.82), compared with 0.38 (burn efficiency = 0.62) for landscapes burnt by cool season fires. That is, hot season fires consume ~20% more of the plant biomass than cool season fires. By way of example, Table 4 below compares annualized emissions and sequestration (spinifex/fuel biomass) for two scenarios (managed and unmanaged fire) assuming on average 7% of the 20 million ha Martu Determination was burnt by cool season fires only each year.

Based on the calculations in Table 4 (below), burning 7% per annum (~6,000 ha) of the spinifex grasslands on Lorna Glen under cool conditions would result in an emissions abatement of just 546 t CO_2-e $year^{-1}$. Burning 7% per annum (1.4 million ha) of the 20 million ha area of the Martu Native Title Determination in the cool season would result in emissions abatement of ~127,400 t CO_2-e $year^{-1}$.

Table 4: Emissions abatement potential with managed fire regimes in the spinifex grasslands of central Australia (mean annual rainfall ~260 mm). This assumes a mean fire interval of 14 years and an available fuel load of 8.1 t ha^{-1}. Burning efficiency: Cool season fires=0.62; Hot season fires=0.82. Comparison of emissions and sequestration for managed verses unmanaged fire regimes uses savannah burning methodology (see Table 1).

	Managed cool season fires	**Unmanaged hot season fires**
Abatement		
Fuel burnt	5.02 t ha^{-1} year^{-1}	6.64 t ha^{-1} year^{-1}
CH_4 emissions	0.0095 t CH_4 ha^{-1} year^{-1}	0.0126 t CH_4 ha^{-1} year^{-1}
NO_2 emissions	0.0003 t N_2O ha^{-1} year^{-1}	0.0003 t N_2O ha^{-1} year^{-1}
TOTAL emissions	0.281 t CO_2-e ha^{-1} year^{-1}	0.372 t CO_2-e ha^{-1} year^{-1}

Baseline (unmanaged fire) = 0.372 t CO_2-e ha^{-1} year^{-1}
With fire management = 0.281 t CO_2-e ha^{-1} year^{-1}
Abatement = 0.091 t CO_2-e ha^{-1} year^{-1} (24% reduction)

Mulga biosequestration

Under the appropriate fire management, there is potential to store carbon in the long-lived but fire sensitive stands of mulga that occur in the spinifex landsystem. Conversely, inappropriate fire regimes risk destroying this carbon stock.

For example, currently there is an estimated ~180,000-200,000 tonnes of carbon stored in mulga on the 85,000 ha of Bullimore landsystem on Lorna Glen (~2.35 t ha^{-1}).

As described above, in the Bullimore landsystem, mulga generally occupies habitats that are:

i) lower flammability than the surrounding spinifex-dominated landscape due to edaphic factors that reduce the cover and quantity of spinifex (the fuel);
ii) Lower flammability due to the suppressive effect of mulga on spinifex (fuel) cover and quantity.
iii) It occurs in 'penumbral fire shadows', where natural landscape-scale fire spread barriers reduce the risk of frequent fires, leading to a longer fire interval and the persistence of mulga. The minimum tolerable fire interval for mulga in these landscapes is ~26 years (Ward *et al.* 2014).

Flammability and fire risk differentials that exist between mulga-spinifex associations and surrounding spinifex-dominated sand plains and dune fields can be utilized by fire managers to protect mulga from lethal fire. Using a spinifex fire spread model developed by Burrows *et al*. (2009), Figure 12 is an example of potential rate of spread of fire in low spinifex cover (20-25%) beneath mulga stands under hot dry conditions and cool moist conditions. Because of the fuel structure and biomass in and around mulga, stands are at greatest risk from hot season fires and less likely to be damaged by cool season fires. Furthermore, implementing cool season fires that burn the more flammable spinifex fuels surrounding mulga, but don't burn the less flammable spinifex around mulga, further reduces the risk of hot season fires burning the mulga. There is some evidence that in the past, Aboriginal people burnt the more flammable spinifex around mulga groves under cool conditions to protect the groves from hot season fires (Start 1989).

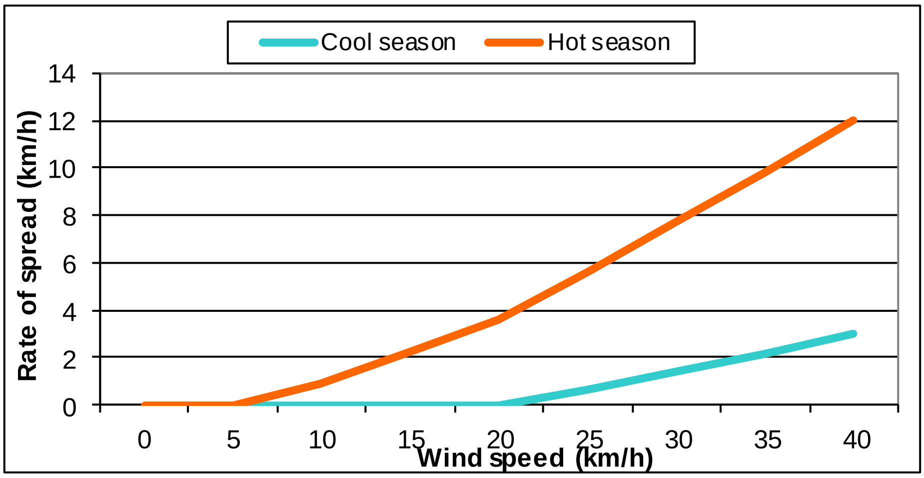

Figure 12: Risk of fire burning mulga stands (as represented by fire rate of spread), in different seasons

Mulga occurring in penumbral fire shadows could be further protected by strategically burning in the cool season to link natural landscape-scale fire barriers such as stony plains, hills, lakes and clay pans. Cool season burning to protect mulga would have the added benefit of restricting the size of hot season wildfires.

While there is evidence that large hot season wildfires increase the risk of mulga being replaced by spinifex (Start 1986; Latz 1995; Allan and Southgate 2002; Bowman *et al*. 2008; Nano and Clarke 2008; Ward *et al*. 2014), there are insufficient data to reliably quantify the carbon sequestration benefits of protecting and enhancing mulga in these landscapes through good fire management. Studying mulga stands in the Gibson Desert, Ward *et al.* (2014) reported that 23% of their study sites re-burnt under hot season conditions within 3-10 years of the original fire. Mulga was either extirpated or significantly reduced on these sites and they concluded that successive, relatively frequent (<26 years) hot season fires would likely extirpate mulga. The extent to which this has occurred under a wildfire regime since a departure from widespread traditional Aboriginal burning, and the extent to which mulga could be protected under a managed fire regime, remains to be quantified. Allan and Southgate (2002) reported that within the Tanami subregion in 1984, there were six patches of mature mulga covering 8.2 km^2 but after successive wildfires through the 1980s and 1990s, this was reduced to 2.2 km^2, a 73% reduction, by 1995.

There are no mensurational data to enable calculation of biomass/carbon loss associated with these declines. However, if these mature stands were similar in structure and biomass to those measured at Lorna Glen, then a 73% reduction in mature mulga due to wildfires over 11 years would equate to a carbon loss of 131,400-146,000 tonnes. This somewhat crude analysis does not account for a) the potential sequestration associated with any mulga regeneration, but assumes the stands were extirpated by frequent fire, and b) carbon stored in dead mulga (stags), although these are usually burnt in the next fire.

In addition to the lack of quantification of the long term effect of wildfire regimes on mulga biomass, there are few reliable maps of the distribution of mulga and associated mensurational metrics to enable calculation of carbon stocks in mulga stands more widely.

Mulga and its close relatives are not the only long lived woody species that are vulnerable to a regime of large intense wildfires. Examples of other species vulnerable to a hot wildfire regime include cypress pine (C*allitris* spp.), *Acacia shirleyi* and A. *undoolyana*.

4.2 Strategic prescribed burning to reduce the size of summer wildfires

This includes buffer burning or edging from roads and tracks under cool conditions to create fuel reduced buffers. In most circumstances, a 100 m buffer is adequate to stop the spread of wildfire for 7-10 years (depending on site type and rainfall). Where there are species such as eucalypts that are conducive to spotting, then the buffers may need to be deeper (several hundred meters). Buffer burning from roads can be carried out from the ground.

The size of wildfires can also be restricted by strategically linking natural fire breaks such as stony hills and plains, lakes, etc., or recent wildfires using buffer burning, or wind driven strips ignited either from the ground, or in remote areas, using aircraft.

4. Fire management capacity of remote desert Aboriginal communities

Aboriginal communities have reclaimed some 800,000 km^2 of spinifex-dominated lands spinifex (*Triodia* spp.) of central Australia, of which ~700,000 km^2 is flammable and has the potential to burn every 7-10 years. Aboriginal people have used fire skilfully and purposefully for thousands of years for a variety of reasons including to regenerate and rejuvenate country, hunting, promoting the regeneration of food and medicine plants, signaling, protecting cultural values and for spiritual reasons.

Today, while maintaining traditional values and customs, most desert Aboriginal people live in European-style communities and use vehicles to travel to visit family and friends, to attend ceremonies, sporting events, funerals and other functions, and to hunt. Thus, access to country for hunting and burning is largely limited by vehicular access. Also, the necessity to move through the landscape and hunt using fire on a daily basis is not as critical to survival today as it was pre-contact. Nevertheless, fire remains highly significant to desert communities and is integral to caring for country responsibilities. In addition to hunting and other cultural fire activities, most desert communities have formal fire and land management plans. In Western Australia for example, Martu have supported and enabled the development of a fire management strategy for the Martu and Birriliburru Native Title Determination areas, an area of some 200,000 km^2 of the central and northern portion of the Western Desert (Catt 2013). Similarly, fire management and patch-burning is a critical component of land management over the 250,000 km^2 of Ngaanyatjarra Lands and the 54,000 km^2 of the Spinifex Native Title Determination (Great Victoria Desert).

The broad objectives of fire management on these and other Aboriginal lands in central Australia are to; improve the health and biodiversity of country, reduce the extent and impacts of hot season wildfires, increase bush tucker resources, facilitate inter-generational transfer of cultural knowledge, protect and maintain sites and other assets, protect infrastructure and people and to provide employment and economic opportunities for communities (see Catt 2013). The strategies for achieving these aims include extension and expansion of traditional fire management techniques into areas that have been infrequently visited and using modern technologies to replicate aspects of traditional fire use across the landscape. Over the last 10 years or so, desert Aboriginal communities have developed considerable experience with carrying out cool season burns using both on ground, 'traditional' methods, and modern technology such as aerially-mounted incendiary machines. Communities have also developed a familiarity with using satellite imagery to plan, implement and monitor burns and wildfires (Burrows *et al.* 2013).

While there has been some significant progress towards these aims, the extent to which the strategies can be implemented is largely limited by capacity within the communities, which is in turn, linked to funding. Historically, the bulk of funding to support land and fire management on Aboriginal lands has been delivered through various state and federal government programs, which are normally short term (2-4 years). These funding packages provided by various government programs have enabled people to get back on to country to carry out burning (and other activities), either from the ground or from aircraft. While there have been some good outcomes from these programs, and communities have built some capacity in fire management, there is a need for a sustainable, continuous commercial driver for fire and land management in order to generate long-term, sustainable benefits to communities and country.

However, the amount of burning done is a very small proportion of the total area of spinifex country that burns each year. For example, on the Martu and Birriliburu Native Title Determination areas alone (~200,000 km^2), averaged over several decades, ~14,000 km^2 (~7%) is burnt each year. Of this about 400 km^2 (2.8% of total area burnt) is burnt by Aboriginal people in the cool season, the remainder being burnt by wildfires in the hot season.

As evidenced by the current study, there is a complete alignment with the traditional Aboriginal fire regime, with the fire management aims and aspirations of contemporary Aboriginal communities and with fire management necessary to deliver significant emissions reduction and carbon sequestration. Conversely, unmanaged (lightning-driven) fire regimes in the hot season, which today impact most of the spinifex grasslands, threaten the health and biodiversity of country, threaten Aboriginal communities and cultural values and result in significantly higher levels of emissions and a reduction in carbon biosequestration potential. For these reasons, there is a high level of interest in central Australian Aboriginal communities in the potential of sustainable 'self-funded' fire and land management through emissions abatement and carbon sequestration arising from good fire management.

The commercial viability of such a program, as with other business ventures, will be a function of a carbon market (trading carbon credits), the cost of delivering abatement and biosequestration through good fire management and the quantum of the credits from abatement. This feasibility study has demonstrated that there is significant potential for multiple benefits to Aboriginal communities, for the environment and for biodiversity in central Australia by reinstating traditional Aboriginal fire regimes in these vast landscapes. However, because of the relatively low productivity of these landscapes compared with northern Australian savannas, very large areas will need to be treated to generate significant abatement benefits. For example, about 1 million ha per annum will need to be burnt in the cool season (burning efficiency 0.62) to generate an emissions abatement of ~100,000 t CO_2-e (using savanna burning emissions methodology) (Figure 13).

Figure 14 shows a comparison of CO_2-equivalent emissions (using savannah burning emissions methodology) from hot season and cool season fires in a 500,000 km^2 (project) area of Aboriginal-owned lands in the Western Desert comprising Martu, Ngaanyatjarra and Pila Nguru Native Title Determinations. Currently, about 98% of this 'project' area burnt each year is burnt by wildfires in the 'hot' season (late spring, summer). As discussed above, the area burnt each year is highly variable, but over the long term (several decades or more), the mean annual area burnt is ~7% (35,000 km^2). Optimally, if all or most of this area was burnt in the cool season by patchy, managed fires, rather than the hot season, then the mean annual abatement would be ~318,500 t CO_2-e (Figure 14).

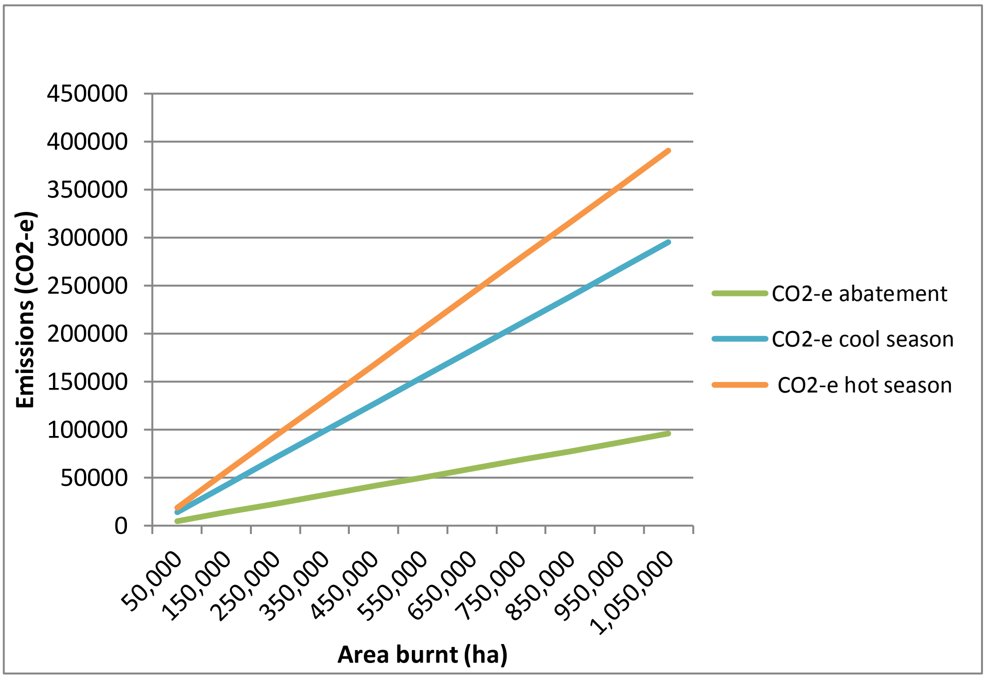

Figure 13: Estimates of CO_2-equivalent emissions and abatement from burning various areas of 14 year old spinifex fuels under different seasonal conditions.

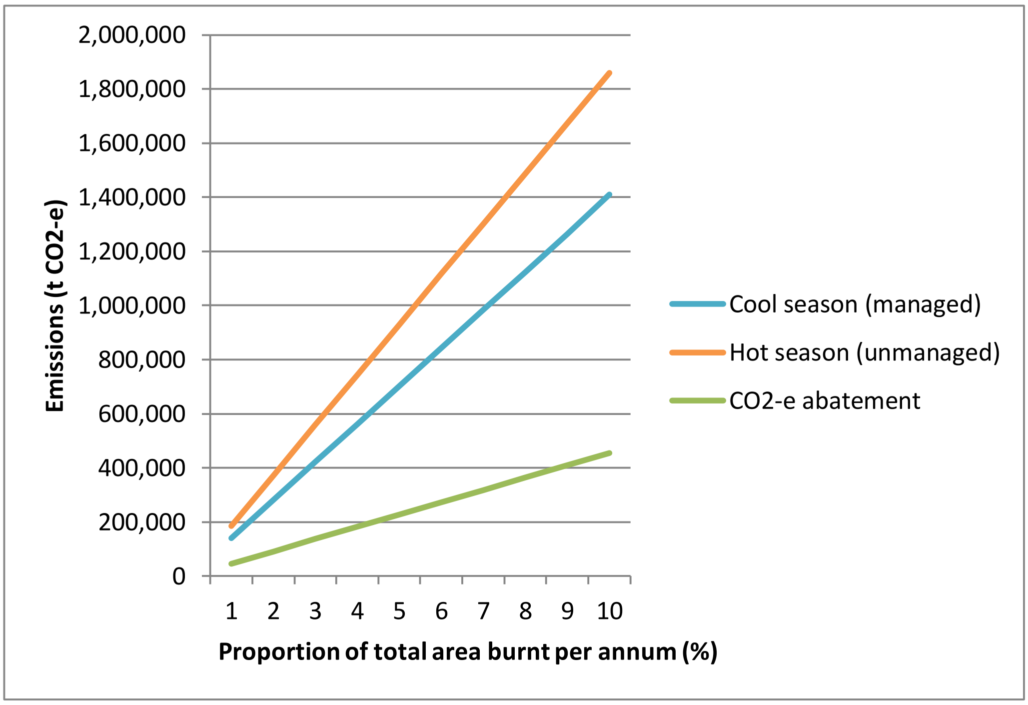

Figure 14: Estimates of CO_2-equivalent emissions and abatement from burning various proportions of 14 year old spinifex in a 500,000 km^2 'project area' of the Western Desert.

Using savannah burning emissions methodology, to generate 100,000 tonnes of CO_2-e abatement per annum from the 500,000 km^2 'project area' would require about 30% of the total area burnt each year, to be burnt in the cool season (assumes a burning efficiency of 0.62). This equates to a mean annual burning program for the project area of ~1,000,000 ha (or ~2% of the project area per annum). For a smaller project area, such as the northern Martu Determination (200,000 km^2), to generate 100,000 tonnes of CO_2-e abatement per annum would require about 5% of the area to be burnt each year under cool conditions, or about 70% of the total area burnt per annum.

To achieve this amount of cool season burning would require a significant increase in fire management capacity in Aboriginal communities in central Australia, a capacity that would need to be built progressively over a period of time. It would also require strengthening of partnerships with other fire and land management agencies. To eventually achieve this amount of burning on an annual basis is daunting, but it could be achieved over a ten year period. This will require good planning, training, capacity building, collaboration, co-operation between desert Aboriginal communities, aircraft to carry out the burning in less accessible areas and remote sensing to plan, monitor and evaluate burn programs. In general terms, the capacity to ultimately carry out a 1 million ha annual burning program in the cool season (May to end of August) in a 500,000 km^2 'project area' of the Western Desert, to be built up over time, is estimated to be as follows:

- Fire management planning expertise – including an ability to acquire and interpret fire scars from satellite imagery and aerial photographs, expertise in GIS and fire planning (full time). At least two people with these skills would be needed to service the 'project area'. Estimated cost: $250,000 per annum.
- Coordinator: At least one person to service the 'project area'. Estimated cost: $125,000 per annum (full time).
- 10-12 trained Incendiary Machine Operators (IMOs) and aircraft burn navigators (seasonal). Estimated cost: $250,000 per annum.
- Training, equipment, vehicle running, wages for on-ground fire crews (seasonal). Estimated cost: $500,000 per annum.
- Aircraft hire: $100,000 per annum.

Total estimated cost to patch-burn ~2% of the 'project area' per annum to realise ~100,000 tonnes of CO_2-e abatement (in addition to cultural, social, environmental and biodiversity benefits) is ~$1.225 million per annum.

Carbon biosequestration
In addition to GHG abatement, this program has potential to significantly increase biosequestration of carbon in these landscapes through the protection of mulga and (and other fire sensitive, long-lived woody vegetation) from death and extirpation by hot season wildfires. The biosequestration benefits can only be speculative because there are insufficient data on the distribution, biomass, stand structure, extent of extirpation due to fire regime, etc. of these taxa. Crude, ball park estimates can be made using data from Lorna Glen (see above), and making some assumptions about mulga and its persistence across the broader project area.

Assumptions:
- Mulga (and its close relatives) occurs over 5.6% (by canopy cover), or 2.8 million ha of the 500,000 km^2 'project area'.
- 4.5% of this is protected each year by cool season burns = 126,000 ha $annum^{-1}$ protected. This is mulga that would / could be extirpated by hot season fires.
- Mulga is extirpated by frequent hot season fires (<26 year intervals).
- Dead mulga (stags) are burnt in the next fire, so are not a long term carbon store, nor a long term source of emissions.
- Using canopy cover to estimate total dry biomass of mulga (tonnes - $TB_{tonnes)}$ protected per annum (Figure 9):

  ~126,000 ha of mulga canopy = 1,260,000,000 m^2 of mulga canopy:
  TB_{tonnes} = 0.0093(1,260,000,000) = 11,718,000 tonnes dry biomass in mulga.

Carbon = 0.46(11,718,000) = 5,390,280 tonnes sequestration benefit.

5. Further research and future directions

Estimates of emissions abatement and biosequestration developed as part of this feasibility study are based on limited data, so need to be interpreted cautiously. Further research and information is needed to develop better estimates of spinifex grasslands burning emissions and biosequestration. This includes:

- Accurate quantification of GHG emissions from the combustion of spinifex-dominated vegetation types in central Australia.
- Further assessment of other vegetation / fuel classes and associated properties (biomass dynamics, emissions) within the broader range of spinifex grasslands of central Australia, beyond the bioregional approach reported here for the Western Desert region of Western Australia.
- Further investigation of combustion efficiency and patchiness (proportion of unburnt vegetation) of fires burning under different seasonal conditions in different spinifex vegetation / fuel classes, including cool season Aboriginal hunting fires and hot season wildfires.
- Further validation of remote sensing techniques (satellite imagery, aerial photography) to accurately map and quantify at a fine scale, fire scars and unburnt patches within and between fire scares.
- Fuel biomass dynamics models for higher rainfall regions and that account for annual / seasonal variability in rainfall rather than longer term rainfall as provided by the current study.
- Refinements to existing fire behaviour models for spinifex grasslands to enable better predictions of low intensity, cool season patchy fires in various vegetation /fuel classes that comprise spinifex grasslands.
- Further investigation of remote sensing methods for mapping the distribution and cover of mulga (and its close relatives) growing in association with spinifex. Fine scale mapping is necessary to estimate the biomass of mulga and to estimate how this biomass changes under managed and unmanaged fire regimes.
- Further investigations into other woody, long-lived species that have the potential to be reduced or extirpated by unmanaged fire regimes and that could be significant for carbon storage.

There is a need for a more detailed analysis of a) the business case for investing in such a program in central Australia and b) capacity building needed in Aboriginal communities to carry out a large scale prescribed burning program to reduce emissions and increase sequestration. To address these critical knowledge gaps and operational issues, I suggest the next step is to implement a small scale trail, perhaps over an area of ~10,000 km^2. Preferably this trail should be carried out on lands for which a) there is strong interest from Aboriginal communities, b) there exists good fire history and fuel biomass accumulation data, and, c) Aboriginal communities, in partnership with others, have experience with, and capacity to, carry out a small scale (pilot) ground and aerial burning program for emissions abatement.

6. Conclusion

Changing the current unmanaged fire regime across some 2.1 million km^2 of spinifex grasslands in arid and semi-arid Australia from predominantly hot season wildfires to predominantly cool season fires, akin to traditional Aboriginal fire management, has potential to deliver multiple cultural, social and environmental benefits. However, it is clear from this feasibility study that large areas of central Australia will need to be appropriately managed with fire if significant greenhouse gas emissions, sequestration and other benefits are to be realized. This will require a major coordinated, planned program to significantly build capacity of desert communities over an appropriate time scale; it will require cooperation between communities and it will require strong engagement by other fire and land management agencies across various jurisdictions, perhaps under the umbrella of the 'Central Australian Fire Management Program'. If realized, this program would be the largest fire management program in the world, the scale of the program being commensurate with the scale of the bushfire problem in central Australia – big problems need big solutions. A more detailed investigation and analysis of the willingness and the capacity of Aboriginal communities, government agencies and other landholders to undertake the extent and scale of burning that is required in spinifex dominated landscapes to realise significant emissions abatement is needed, as is a proper cost-benefit analysis of such a program. This analysis needs to include all social, cultural, economic and environmental benefits likely to accrue from such a program.

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