CSIRO PUBLISHING
www.publish.csiro.au/journals/fpb *Functional Plant Biology*, 2004, **31**, 415–422

Viewpoint:

Assessing the carbon sequestration potential of mesic savannas in the Northern Territory, Australia: approaches, uncertainties and potential impacts of fire

Richard J. Williams[A,B,F], *Lindsay B. Hutley*[A,C], *Garry D. Cook*[A,B], *Jeremy Russell-Smith*[A,D], *Andrew Edwards*[A,D] *and Xiayong Chen*[C,E]

[A]Cooperative Research Centre for Tropical Savanna Management.
[B]CSIRO Sustainable Ecosystems, PMB 44 Winnellie, NT 0821, Australia.
[C]School of Science and Primary Industries, Charles Darwin University, Darwin, NT 0909, Australia.
[D]Bushfires Council of the Northern Territory, PO Box 37346, Winnellie, NT 0821, Australia.
[E]Current address: Department of Geography, University of Toronto, Canada.
[F]Corresponding author; email: Dick.Williams@csiro.au

Abstract. Tropical savannas cover a quarter of the Australian landmass and the biome represents a significant potential carbon sink. However, these savannas are subject to frequent and extensive fire. Fire regimes are likely to affect the productivity and carbon sequestration potential of savannas, through effects on both biomass and carbon emissions. The carbon sequestration potential has been estimated for some savanna sites by quantifying carbon storage in biomass and soil pools, and the fluxes to these pools. Using different techniques, previous work in these savannas has indicated that net ecosystem productivity [NEP, net primary productivity (NPP) less heterotrophic respiration] was about –3 t C ha^{-1} y^{-1} (i.e. a carbon sink). However, the impacts of fire were not accounted for in these calculations. Estimates of NEP have been combined with remotely-sensed estimates of area burnt and associated emissions for a an extensive area of mesic savanna in Arnhem Land, NT, Australia. Combining NEP estimates with precise fire data provides an estimate of net biome productivity (NBP), a production index that includes carbon loss through disturbance (fire), and is thus a more realistic indicator of sequestration rate from this biome. This preliminary analysis suggests that NBP is approximately –1 t C ha^{-1} y^{-1} (i.e. a carbon sink). A reduction in the annual area burnt is likely to increase the sink size. Uncertainties surrounding these estimates of NBP and the implications of these uncertainties for land management in these extensive landscapes are discussed.

Keywords: Aboriginal land, Arnhem Land, carbon accounting, global change, land use, net biome productivity, net ecosystem productivity, remote sensing, tropical savanna.

Introduction

Australia's tropical savannas occupy approximately two million square kilometres — or about a quarter of the continent — north of about 20° S in northern Western Australia (WA), the northern half of the Northern Territory (NT) and inland of the Great Dividing Range in north Queensland (Mott *et al.* 1985). These vast landscapes are generally structurally intact, with relatively little tree clearing for agriculture and forestry compared with southern Australia (Ridpath 1985; Braithwaite and Werner 1987). The savannas have a strongly seasonal climate with respect to moisture availability. Growth is prolific in the 4–5-month wet season, and the vast majority of carbon is fixed during this time (Eamus *et al.* 2001; Eamus and Prior 2001). However, this is followed by a predictable dry season, during which the annual grass-dominated understorey cures, and the annual fire season begins (Williams *et al.* 1997, 2002). Fire is frequent, particularly in the mesic savannas, and the fire regimes are dominated by surface or grass fires (rather than crown fires). Intervals between fires are typically measured in years, rather than decades or centuries (Williams *et al.* 2002).

The extent of the Australian savannas, their degree of intactness and their fire-prone nature raises questions about the role of the savannas in the nation's carbon budget. What are the stocks and fluxes? Are the savannas a carbon source

Abbreviations used: ALFA, Arnhem Land fire abatement; AVHRR, advanced very high resolution radiometer; NBP, net biome productivity; NEP, net ecosystem productivity; NPP, net primary productivity.

 10.1071/FP03215 1445-4408/04/050415

or sink — do any gains just go up in smoke? And how might we address these questions?

Critical to this thinking have been efforts designed to estimate two important measures of the strength of landscape sequestration (or otherwise) of carbon in various forests across the world: net ecosystem productivity (NEP) and net biome productivity (NBP; Schulze *et al.* 2000; Kirschbaum *et al.* 2001). Net ecosystem productivity is defined as the carbon fixed by ecosystems due to NPP less carbon emissions back to the atmosphere due to heterotrophic respiration. Net biome productivity is NEP minus the carbon losses due to disturbance (e.g. timber harvesting, fire, insect plagues) and is a long-term measure as it represents sequestration at a temporal scale equivalent to the return time for disturbance events.

There have been relatively few attempts to measure or estimate NBP in the ecosystems of the world (Chen *et al.* 2000). This is due to difficulties in estimating NEP, and accurately capturing short-lived disturbance events that result in losses of carbon sequestered over some considerable period of time. For forest ecosystems, sequestration may occur over 50–300-year time-frames, whereas disturbance events may occur over a number of hours, days or several years (Körner 2003). Körner (2003) suggests that some current estimates of terrestrial ecosystem sink strength may be overestimated by an order of magnitude due to a failure to provided estimates over time frames that equate to actual disturbance cycles rather than short-term annual estimates of NEP. The savannas of northern Australia are reasonably well placed to contribute to this important research issue. Due to recent ecophysiological research that has resulted in estimates of NEP (Eamus *et al.* 2001; Chen *et al.* 2003) and because the ecology of the main disturbance agent in this landscape, fire, is becoming better understood (Andersen *et al.* 2003; Cook 2003; Russell-Smith *et al.* 2003*b*; Williams *et al.* 2002, 2003*a*, *b*) estimating the long-term sequestration rate, NBP, is feasible.

In this paper, we apply the NEP/NBP framework to the issue of fire and carbon sequestration potential in Australia's savannas. We take previous estimates of NEP for mesic savanna sites in the Darwin/Katherine region, and combine these with estimates of emissions (based on area burnt) for a large study area in Arnhem Land, Northern Territory, to estimate NBP. Our aim is not necessarily to produce a definitive estimate, but to highlight an approach to measuring NBP at scales relevant to land management, in particular fire abatement in the savannas. We canvass the idea of NBP as a potential land management metric, highlight uncertainties involved in its measurement, and indicate where further research should be directed to refine such estimates of NBP.

Study region and sites

The study region is the mesic tropical savanna biome of the Northern Territory, Australia, north of approximately 15° S. There is a strong rainfall gradient, from coastal to inland regions (Fig. 1; Williams *et al.*1996; Cook *et al.* 2002). The vegetation is overwhelmingly savanna open-forest and woodland. The vast majority of savannas are dominated by eucalypts, with a grass understorey. There are dozens of different types mapped at 1:1000000 and 1:2000000 (Wilson *et al.* 1990; Fox *et al.* 2001) but one of the most widespread is the group of communities within the mesic savanna region, variously dominated by *Eucalyptus miniata* Cunn. ex Schauer and *E. tetrodonta* F. Muell. Across this region there is approximately 132000 km^2 of this broad vegetation type (Fig. 1; Wilson *et al.* 1990). The distribution, phenology, ecophysiology, fire regimes, fuels, and biomass allometry of this vegetation type have been well studied (Williams *et al.* 1998, 2003*b*; Eamus and Prior 2001; O'Grady *et al.* 2000).

For this vegetation type we have NEP estimates and detailed fire history and emissions estimates from a number of sites and regions, which form the foundation for estimating NBP. There are estimates of NEP from several *E. miniata*/*E. tetrodonta* sites in the Darwin/Katherine region (Chen *et al.* 2003). There are also good estimates of area burnt, and the associated emissions, for a large area (32000 km^2) of this vegetation type in Western Arnhem Land (Russell-Smith *et al.* 2003*a*). Within Arnhem Land, we focus on a region known as the Arnhemland Fire Abatement region (ALFA region; Fig. 1), which is the focus of a developing, multi-disciplinary project on landscape fire management on Aboriginal land.

The ALFA region is Aboriginal land, 500 km east of Darwin, and covers an area of 60000 km^2. Average annual rainfall ranges from 900 to 1400 mm. Approximately 32000 km^2 of the study area consists of *E. miniata*/*E. tetrodonta* open-forest or woodland with tall-grass (annual sorghum; perennial tall-grass) understorey. The formation is represented by a number of different vegetation units, as mapped by Wilson *et al.* (1990), and we have included the following in our *E. miniata*/*E. tetrodonta* vegetation type: Units 4, 7–10, and 12–14. These mapping units are all dominated by *E. miniata* and/or *E. tetrodonta*, with a monsoon tall-grass understorey of annual sorghum and/or perennial grasses; they vary in the composition of the associated tree species. They are all floristically and structurally similar to sites used by Eamus and Chen to derive their NEP estimates. Although livestock grazing is a major land use in the savannas (Dyer *et al.* 2001), the ALFA region is not used for extensive pastoralism. This was another reason for the selection of the ALFA region for this study, as the effects of fire — the major agent of — disturbance are not confounded with extensive livestock grazing. Grazing by native marsupials has not been quantified, but is assumed to be small in comparison with fire.

The fire history, vegetation and fuels of the region are all well documented, because the region is a focus study area for major multi-disciplinary program of land management on Aboriginal Land. The region, like most of the northern half of the Northern Territory (known as the 'Top End'), is subject to frequent fire, with 40–60% of the area burnt each year. One explicit aim of the ALFA project is to reduce the average area burnt each year from current levels to around 25%. This will reduce anthropogenic emissions substantially (most of the fires are anthropogenically lit), but reduction of annual area burnt is also a desirable policy on both biodiversity grounds (Andersen *et al.* 2003; Williams *et al.* 2003*b*), and socio-economic grounds (Altman 2001). The ALFA region is thus an excellent 'natural laboratory' within which to estimate NBP and hence assess the potential impacts of fire abatement on carbon sequestration potential.

Estimating carbon sequestration strength

Estimating NEP

Two approaches have been used to estimate NEP for *E. miniata*/*E. tetrodonta* savannas in the NT. The first approach used eddy covariance methods. This micrometeorological method is the most direct measure available of mass (CO_2 and water vapour) and energy exchange between plant canopies and the lower atmosphere and has been widely used in global change biology (Baldocchi 2003). Eamus *et al.* (2001) used this method over a 2-y period (1997–98) over *E. miniata* and *E. tetrodonta* dominated open-forest savanna near Howard Springs, NT, 40 km SE of Darwin. Annual rainfall at Howard Springs is about 1750 mm, the soil a massive red sandy loam, approximately 1–2m deep. The site is currently vacant Crown land, but was formerly part of Koolpinyah Station. The general area was disturbed during cyclone Tracey in 1974, (Bowman 1986; Wilson and Bowman 1987) but the impact of that cyclone at the study site is not known. The area had been burnt annually or biennially (as is the norm for the region; Williams *et al.* 2003*a*) prior to the flux campaign. Importantly, the area within 1 km of the tower supporting the eddy covariance equipment was not burnt over the course of the Eamus *et al.* (2001) study.

Measurement campaigns were conducted over a 2-y period and were designed to capture the range of fluxes of CO_2 and water over several wet-dry seasonal cycles. Over this period, NEP for was estimated to be –2.8 t C ha^{-1} y^{-1} (Eamus *et al.* 2001; note, both NEP and NBP are expressed in units of t C ha^{-1} y^{-1}; negative values for flux imply a carbon sink, and positive measurements imply a carbon source). The flux tower at Howard Springs is still operational, so we can provide, based on unpublished data, estimates of the inter-annual variation in the NEP. For the years 2001–03, NEP ranged from –0.7 to –2.6 t C ha^{-1} y^{-1}

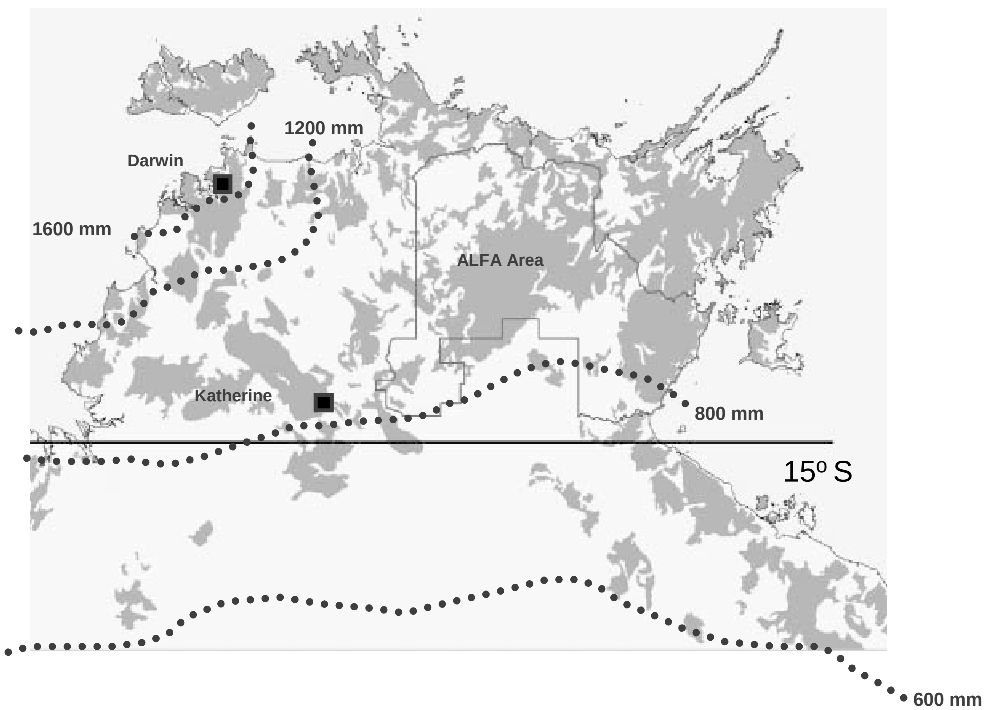

Fig. 1. Map of the northern section (the 'Top End') of the Northern Territory, Australia, showing sampling sites (Darwin, Katherine) where carbon and water fluxes have been measured using eddy covariance techniques. Annual rainfall isohyets (mm) and the location of the Arnhem Land Fire Abatement study region (ALFA region) are also indicated. The shaded areas represent the distribution of *Eucalyptus miniata*/ *E. tetrodonta* forest and woodland in the NT. Location of 15° S indicated.

(Beringer *et al.* 2003*b*). These estimates are similar to the non-fire affected estimate of NEP provided by Eamus *et al.* (2001) at the same site for 1997–98.

Hutley *et al.* (unpublished data) undertook short-term flux measurement campaigns using the eddy covariance technique along the rainfall gradient between Darwin (annual rainfall 1600 mm) and Newcastle Waters (annual rainfall 520 mm). Simple extrapolation of wet and dry season point measurements gave an NEP estimate for the *E. miniata*/*E. tetrodonta* savannas for a site near Katherine (average annual rainfall 950 mm) of –2.4 t C ha^{-1} y^{-1}, although this estimate is based on a limited data set.

The second approach to estimating NEP (Chen *et al.* 2003) used inventory methods to construct a complete carbon balance by measuring both carbon stocks and productivity (above and below ground), at the Howard Springs site. Measurements were also made at other savanna sites, over a 3-y period (1999–2001). From the estimates of productivity, and estimates of soil CO_2 efflux (Chen *et al.* 2002) and total canopy respiration (leaf and stem), NEP for *E. miniata*/*E. tetrodonta* savanna was estimated to be –3.8 t C ha^{-1} y^{-1} (Chen *et al.* 2003).

These estimates of NEP all indicate that *E. miniata*/*E. tetrodonta* savannas act as a carbon sink. Moreover, the magnitude and direction of the estimates of the size of the sink are broadly consistent with each other, and with various estimates of sink strength for other forest or woodland vegetation types across the world (Eamus *et al.* 2001; Baldocchi 2003).

Estimating NBP

Fire is the major agent of disturbance in the mesic savannas of the top end of the NT, particularly the *E. miniata*/*E. tetrodonta* savannas (Williams *et al.* 2002), and thus must be taken into account when estimating carbon sequestration strength in the savannas. Fire is relevant to all land use issues in northern Australia: pastoral production, biodiversity conservation, greenhouse emissions, human health (Dyer *et al.* 2001; Williams *et al.* 2002), and is a potential driver of socio-economics of land use change (Dyer and Stafford Smith 2003). However, there is limited knowledge of the size of stocks, magnitude and direction of carbon fluxes, the medium–long term potential for carbon sequestration, and the influence of land use, in this case variation in fire regime, on sequestration strength.

We have estimated NBP from the above point estimates of NEP in the Darwin/Katherine region combined with estimates of area burnt and associated carbon emissions (Russell-Smith *et al.* 2003*a*) for the extensive *E. miniata*/*E. tetrodonta* savannas in the ALFA region.

Estimating NEP at regional scales

We have no direct estimates of NEP from the ALFA region (the Howard Springs and Katherine sites are not within the ALFA region). However, we can provide a range of estimates of NEP from a variety of published and unpublished data sources from the NT. To do this, we have used a range of estimates of NEP, from –1 to –3 t C ha^{-1} y^{-1}, as argued below.

We assume an upper value for NEP for mesic tall grass savanna of –3 t C ha^{-1} y^{-1}, based on Eamus *et al.* (2001) and Chen *et al.* (2003). We have assumed a lower value of –1.0 t C ha^{-1} y^{-1}, given that Hannan *et al.* (1998) reported an NEP value of –0.3 t C ha^{-1} y^{-1} for an arid, Sahelian savanna in Africa where average annual rainfall was < 300 mm. A potential representative value for the region is also provided by Hutley *et al.* (unpublished data), who estimated NEP (in the absence of fire) for Katherine (near the SW region of the ALFA study area) to be –2.4 t C ha^{-1} y^{-1}.

Another approach to estimating NEP for the ALFA region is to scale the Eamus/Chen estimate presented above, based on variation in leaf area index. Tree basal area and leaf area index are strongly related to average annual rainfall in *E. miniata* communities (Cook *et al.* 2002; Hoogerwerf and van Wierengen 1999; Williams and Hutley unpublished data). Tree basal area in the Katherine region is approximately 70% of that of Darwin (Cook *et al.* 2002). In a study of tree water use (Hutley *et al.* 2001), tree LAI for the Katherine sites was about 60% of that of the Darwin sites. If we assume that NEP is broadly correlated with tree LAI, then a regional estimate of NEP is in the range of –2 to –2.5 t C ha^{-1} y^{-1}.

Both the Darwin and Katherine estimates of NEP may be overestimates, as these estimates were based on measurements made in high rainfall years (Eamus *et al.* 2001) and the Darwin measurements were made at a medium-age savanna site still regenerating after a severe cyclone in 1974 (Wilson and Bowman 1987). There is also emerging evidence from recent and on-going eddy covariance measurements at the Darwin site (Beringer *et al.* 2003*a*, *b*) that NEP may vary by 50% from year to year. Recently modelled estimates of NEP for various sites and regions in Australia, both temperate and tropical, have also highlighted substantial inter-annual variability (Kirschbaum *et al.* 2003; Wang and Barrett 2003). To account for such potential variation, we have estimated NBP in –0.5 t C ha^{-1} y^{-1} increments of NEP within our specified range of –1 to –3 t C ha^{-1} y^{-1}, for the various fire scenarios (57% area burnt; 25% area burnt).

Carbon emissions estimates

We have based our initial estimates of carbon emissions on 1999, a year for which the estimates of NEP were made at Howard Springs. It was also an extreme fire year for the region, during which 57% of the *E. miniata*/*E. tetrodonta* woodlands in the ALFA region burnt. (The normal range for the Arnhem Land region is between 40 and 60% of country burnt in any one year; Russell-Smith *et al.* 2003*a*; Bushfires Council of the Northern Territory unpublished data).

Table 1. Area burnt, fuels burning efficiencies and mass of carbon emitted for two fire regimes in *Eucalyptus miniata*/*E. tetrodonta* woodland, with tall grass understorey in the Arnhem Land Fire Abatement Region of the Northern Territory, Australia

Regimes: the 1999 dry season (April–November), when 57% of the *E. miniata*/*E. tetrodonta* woodland burnt; planned target (reducing % area burnt per annum to approximately 25%). Total study area, approximately 60000 km^2, of which 32482 km^2 is *E. miniata*/*E. tetrodonta* woodland. Columns are: % EDS; Area EDS, % and area (km^2) of study region burnt by early dry season fire; % LDS; Area LDS, % and area (km^2) of study region burnt by late dry season fire; % TOT; Area TOT, % and area (km^2) of study region burnt in total; Fuel (t ha^{-1}), fuel load (t ha^{-1}); ComEff, combustion efficiency; C-Mass, carbon mass fraction; Mass fuel (Mt), mass of fuel; Mass C emit (Mt), mass of carbon emitted. See text for further explanation of derivation of variables

Fire regime	% EDS	Area EDS (km^2)	% LDS	Area LDS (km^2)	% TOT	Area TOT (km^2)	Fuel (t ha^{-1})	ComEff	C-Mass	Mass fuel (Mt)	Mass C emit (Mt)
1999	9.5	3077	47.6	15466	57.1	1854300	4.64	0.72	0.46	6.19	2.84
Planned target	15.0	4872	10.0	3248	25.0	812100	4.64	0.72	0.46	2.30	1.06

Our methods follow Russell-Smith *et al.* (2003*a*), who estimated emissions for 1999 from the area of the NT north of 15°S latitude, which included the ALFA study area. We have assumed an average fuel load of 4.6 t (dry weight of biomass) ha^{-1} across these landscapes, based on detailed measurements of fine fuel accumulation and fire behaviour studies in *E. miniata* stands at Kapalga, in Kakadu National Park (Cook 1994; Williams *et al.* 1998). Burning efficiency was assumed to be 72%, as per the Australian National Greenhouse Gas Inventory (2000). The C mass-fraction used for the mix of woody and grassy fine fuels typical of savannas was 46%. This was based on values of approximately 41–46% for grasses, and 48% for woody litter (Gifford 2000). The total area burnt, the mass of fuel consumed, and the total masses of carbon emissions for two fire scenarios (the 57% of area burnt in 1999; and the abatement target value of 25%) are presented in Table 1.

Calculating NBP

Given the regional estimates of NEP and carbon emissions estimates above, we can calculate NBP. The calculations underlying the estimates of NBP, for the various estimates of NEP, were are based on the five components listed below (where symbols in parentheses represent standard Australian Greenhouse office National Greenhouse Gas Inventory symbols):

(1) area burnt (A_{jkl}) = total area × % area burnt,
(2) mass of fuel consumed (M_{jkl}) = area burnt (A_{jkl}) × burning efficiency (Zi_k) × fuel load (Fl_{jkl}),
(3) mass of carbon emitted = mass fuel consumed (M_{jkl}) × carbon mass fraction (CC_i),
(4) carbon sink mass = NEP value × area,
(5) NBP = (carbon sink mass – carbon emission mass)/total area.

The results for the ranges of NEP specified above (–1 to –3 t C ha^{-1} y^{-1}), assuming 57% of the ALFA study region burnt, and for 25% of the ALFA study region burnt, are given in Table 2. Under the 57% burnt scenario, NBP values range from –0.1 to –2.1 t C ha^{-1} y^{-1}, or, on average –1.1 t C ha^{-1} y^{-1}. The comparative values of NBP, assuming a reduction to 25% of the country burnt under successful fire abatement, are –0.7 to –2.7 t C ha^{-1} y^{-1}, an increase (for each estimate of NEP) of about 0.5 t C ha^{-1} y^{-1} (Table 2). Thus, under both fire scenarios, the *E. miniata*/*E. tetrodonta* savannas are acting as a carbon sink, and fire abatement increases the size of the sink.

Discussion

Estimates of NEP and NBP

The analyses presented in this paper show that the mesic savannas of the NT act as a weak carbon sink. Net sequestration of carbon was possible even under a scenario of some 60% of the savanna being burnt in 1999, and for all assumed values of NEP between –1 and –3 t C ha^{-1} y^{-1}. In our opinion, the NEP of the ALFA region is most likely to be of the order of –2 t C ha^{-1} y^{-1}, which results in NBP values of –1 to –1.5 t C ha^{-1} y^{-1}, depending on area burnt. Further research is clearly needed to reduce these uncertainties.

Table 2. Estimates of net biome productivity (NBP, t C ha^{-1} y^{-1}; note negative value, signifying carbon sink) for 32484 km^2 of the *Eucalyptus miniata*/*E. tetrodonta* vegetation type in the Arnhem Land Fire Abatement (ALFA) Region of the Northern Territory, Australia

(See Fig. 1 for location)

The NBP values are calculated for five levels of net ecosystem productivity (NEP; t C ha^{-1} y^{-1}), assuming two values of the annual extent of fire in the region, 57% of the area burnt (Burn 57; the actual figures for 1999) and 25% of the area burnt (Burn 25; a desirable target for various land management purposes). Sink refers to the potential carbon sink strength (in Mt) for given levels of NEP. See text for further explanation of the derivation of the variables

NEP (t C ha^{-1} y^{-1})	Sink (Mt)	NBP (t C ha^{-1} y^{-1}) Burn57	NBP (t C ha^{-1} y^{-1}) Burn25
–3	9745200	2.12	–2.67
–2.5	8121000	1.62	–2.17
–2	6496800	1.12	–1.67
–1.5	4872600	0.62	–1.17
–1	3248400	0.12	–0.67

The estimate of NBP presented in this paper is broadly consistent with other estimates of NBP for this vegetation type. Using eddy covariance during fires at the Howard Springs site, over the 2002 dry season, Beringer *et al.* (2003*b*) demonstrated a sink of –0.6 t C ha^{-1} y^{-1}. Chen (2002) estimated a sink strength of –1.3 t C ha^{-1} y^{-1}, based on broad-scale estimates of fire history for the northern half of the NT (Beringer *et al.* 1995) but which was not specific to his study site (estimates of burning efficiency and fuel loads were the same as those used in this analysis).

Our analyses (Table 2) show that fire regime, in particular the area burnt each year, and hence fire frequency, affects the size of the sink. For a given NEP, reducing annual area burnt from near current maximal levels (60% of area burnt per annum) to what is a likely achievable minim level (25% burnt per annum) increases the sink size by approximately –0.5 t C ha^{-1} y^{-1}.

There are a number of uncertainties associated with our estimate of NBP. We have extrapolated a value of NEP from a point source near Darwin to a substantial area of similar vegetation on similar landscapes, but hundreds of km from the point-source estimate. In contrast, the data describing fire history are site specific for the ALFA region and estimates of area burnt and emissions are probably correct to within 10–20% for the Arnhem Land region (Russell-Smith *et al.* 2003*a*). These values would be more robust than the estimates of NEP for this region.

The burning efficiency value (72%) is based on Australian Greenhouse Office (AGO) protocols (Australian National Greenhouse Gas Inventory 2000). Consumption of fuel is less than this for early dry season fires that are less than 2000 kW m^{-1} for *E. miniata*/*Sorghum* landscapes at Kapalga in nearby Kakadu National Park (Williams *et al.* 1998). It was close to 100% for the more intense late dry season fires at Kapalga, but that was for line ignitions several kilometers long. Average intensity, and hence fuel consumption at the landscape scale is likely to be lower for point-based ignitions and elliptical fires (Cheney and Sullivan 1997), even under late dry season fire weather conditions that generate more intense fires. However, 72% is a reasonable estimate of burning efficiency. More work is required on detection and estimation of fuel consumption at landscape scale, using emerging fine resolution sensors such as ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer; 15 m resolution), as opposed to coarse resolution sensors as used in the past such as Advanced Very High Resolution Radiometer (AVHRR, 1 km resolution; Russell-Smith *et al.* 2003*b*).

We have taken no account of consumption of coarse fuels, but these fuels may contribute significantly to emissions. These include ground fuels (dead branches, trunks etc) and standing live fuels (trunks and branches of small saplings). Chen (2002) provided estimates of 0.2–2 t C ha^{-1}, but did not attempt to estimate consumption. There are no data at present on the consumption of such fuels in Australian savanna fires, although it is likely some coarse fuels will be consumed during more intense late dry season fires (Williams *et al.* 1999). There was no detectable change in the basal area of tree stands of in *E. miniata*/*E. tetrodonta* open forest over 5 y of annual early dry season fires at Kapalga (Williams *et al. 2003a)*, but a 20% decline in live tree basal area occurred over a 5-y period of annual late dry season fires. This represents a reduction in photosynthetic capacity due to a reduction in leaf area, plus some additional (but presently unquantified) combustion of both fine and coarse fuels. Both a reduction of photosynthetic capacity, and combustion of coarse fuel, in response to annual late dry season fires, would have the effect of reducing NBP, or may indeed make savannas subject to annual late dry season fires a source of carbon rather than a weak sink (Chen 2002, Chen *et al.* 2003). Clearly further research is needed on the contribution of coarse fuels to the carbon budget of this extensive biome.

Future research

Current international debate regarding mitigation of greenhouse emissions is considering both emissions and carbon sequestration, including storing carbon on land, and the sources of the fluxes (anthropogenic and 'natural'). However, there are considerable uncertainties in estimates of flux strength (Scholes and Noble 2001). Reducing such uncertainties in north Australian savannas will require further research that combines fundamental ecophysiology and fire ecology. Although various greenhouse gas accounting protocols account for savanna burning through its effects on emissions, the Australian National Carbon Accounting System currently has no component in the accounting protocols for carbon sink strength in native forests or woodlands. Only those sinks that result from direct human action are credited under the Kyoto Protocol (Scholes and Noble 2001). Any trading in carbon emissions is likely to require robust estimates of spatial and temporal size and persistence of any sink. Investment in the basic ecophysiology of fire and carbon sequestration in Australia's savannas would therefore seem warranted, and enable a more robust case for fire abatement to be developed. Such abatement would not only potentially reduce emissions and increase sequestration, but would also lead to complementary benefits for biodiversity (Russell-Smith *et al.* 1998; Andersen *et al.* 2003; Williams *et al.* 2003*a*, *b*). Implementing fire abatement will require close cooperation between researchers, land managers and local Aboriginal landowners, through employment and improved participation in land management, and is an explicit component of the ALFA project. We believe investment in such multi-disciplinary research aimed at quantifying NBP in the savannas is clearly in the national interest, given their extent, and because NBP provides the most robust measure of the longer-term carbon sequestration capacity of ecosystems. More accurate estimates of NBP will also allow costs and benefits of various land use options to be more clearly identified than at present.

Acknowledgments

We thank our colleagues at the Cooperative Research Centre for Tropical Savanna Management and the Cooperative Research Centre for Greenhouse Accounting for stimulating discussions. Oliver Woldring (Northern Territory Greenhouse Unit), Damian Barrett (CSIRO Plant industry) and Rod Fensham (Queensland Herbarium) commented on various drafts of the manuscript. Tommy Murphy, Ronny Wearmouth and Barry Round provided help in the field.

References

Altman J (2001) Sustainable development options on Aboriginal land: the hybrid economy in the twenty-first century. Discussion paper 226/201. (Centre for Aboriginal Economic Policy Research: Australian National University, Canberra)

Andersen AN, Cook GD, Williams RJ (Eds) (2003) ‘Fire in tropical savannas: the Kapalga fire experiment.’ (Springer-Verlag: New York, NY)

Australian National Greenhouse Gas Inventory (2000). ‘Australian Greenhouse Office — Australian National Greenhouse Gas Inventory Committee. National Greenhouse gas inventory 1998’. (Australian Greenhouse Office: Canberra).

Beringer J, Packham D, Tapper N (1995) Biomass burning and resulting emissions in the Northern Territory, Australia. *International Journal of Wildland Fire* **5**, 229–235.

Beringer J, Hutley LB, Tapper NJ, Coutts A, Kerley A, O’Grady AP (2003*a*) Fire impacts on surface heat, moisture and carbon fluxes from a tropical savanna in north Australia. *International Journal of Wildland Fire* **12**, 333–340. doi:10.1071/WF03023

Beringer J, Hutley LB, Tapper NJ (2003*b*) Impact of savanna fires on the atmospheric fluxes of carbon, water and energy, and feedbacks to climate. In ‘Proceedings of the tropical savannas and seasonally dry forests’. pp. 19. (Royal Botanic Gardens: Edinburgh, September 2003)

Bowman DMJS (1986) Stand characteristics, understorey associates and environmental correlates of *Eucalyptus tetrodonta* F. Muell. forests on Gunn Point, northern Australia. *Vegetatio* **65**, 105–113.

Braithwaite RW, Werner PA (1987) The biological value of Kakadu National Park. *Search* **18**, 296–301.

Baldocchi DD (2003) Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. *Global Change Biology* **9**, 479–492.

Chen WJ, Chen J, Cihlar J (2000) An integrated terrestrial ecosystem carbon-budget model based on changes in disturbance, climate, and atmospheric chemistry. *Ecological Modelling* **135**, 55–79. doi:10.1016/S0304-3800(00)00371-9

Chen X, Hutley LB, Eamus D (2003) Carbon balance of a tropical savanna in northern Australia. *Oecologia* **137**, 405–416. doi:10.1007/S00442-003-1358-5

Chen X (2002) ‘Carbon balance of a eucalypt open forest savanna of northern Australia. PhD Thesis.’ (Northern Territory University: Darwin, NT)

Chen X, Eamus D, Hutley LB (2002) Seasonal patterns of soil carbon dioxide efflux from a wet–dry tropical savanna of northern Australia. *Australian Journal of Botany* **50**, 43–51. doi:10.1071/BT01049

Cheney NP, Sullivan A (1997) ‘Grassfires fuel weather and fire behaviour.’ (CSIRO Publishing: Melbourne)

Cook GD (1994) The fate of nutrients during fires in a tropical savanna. *Australian Journal of Ecology* **19**, 359–365.

Cook GD (2003) Fuel dynamics, nutrients and atmospheric chemistry. In ‘Fire in tropical savannas: the Kapalga fire experiment.’ pp. 47–58. (Eds AN Andersen, GD Cook and RJ Williams) (Springer-Verlag: New York, NY)

Cook GD, Williams RJ, Hutley LB, O’Grady AP, Liedloff AC (2002) Variation in vegetative water use in the savannas of the North Australian tropical transect. *Journal of Vegetation Science* **13**, 413–418.

Dyer R, Jacklyn P, Partridge I, Russell-Smith J, Williams RJ (2001) ‘Savanna burning: understanding and using fire in Northern Australia.’ (Tropical Savannas Cooperative Research Centre: Darwin, NT)

Dyer R, Stafford Smith M (2003) Ecological and economic assessment of prescribed burning options in semi-arid pastoral lands. *International Journal of Wildland Fire* **12**, 403–413.

Eamus D, Prior L (2001) Ecophysiology of trees of seasonally dry tropics: Comparisons among phenologies. *Advances in Ecological Research* **32**, 113–197.

Eamus D, Hutley LB, O’Grady AP (2001) Daily and seasonal patterns of carbon and water fluxes above a north Australian savanna. *Tree Physiology* **21**, 977–988.

Fox ID, Neldner VJ, Wilson GW, Bannink PJ, Wilson BA *et al*. (2001) ‘The vegetation of the Australian tropical savannas.’ 1:2000000 scale map in three sheets. (Queensland Herbarium, Environmental Protection Agency: Brisbane)

Gifford RM (2000) ‘Carbon contents of above-ground tissues of forest and woodland trees. National Carbon Accounting System.’ Technical report No. 22. (Australian Greenhouse Office: Canberra)

Hoogerwerf CG, van Wierengen SM (1999). ‘Leaf area index in the savannas of northern Australia.’ BSc Honours thesis. (Waginengin University: Waginengin, The Netherlands)

Hannan NP, Kabat P, Dolman AJ, Elbers JA (1998) Photosynthesis and carbon balance of a Sahelian fallow savanna. *Global Change Biology* **4**, 523–538.

Hutley LB, O’Grady AP, Eamus D (2001) Monsoonal influences on evapotranspiration of savanna vegetation of northern Australia. *Oecologia* **126**, 434–443. doi:10.1007/S004420000539

Kirschbaum MUF, Eamus D, Gifford RM, Roxburgh SH, Sands PJ (2001) Definitions of some ecological terms commonly used in carbon accounting. In ‘Net ecosystem exchange’. (Eds MUF Kirschbaum and R Mueller) pp. 1–5. (CRC for Carbon Accounting: Canberra)

Kirschbaum MUF, Simioni G, Medlyn BE, McMurtrie RE (2003) On the importance of including soil nutrient feedback effects for predicting ecosystem carbon exchange. *Functional Plant Biology* **30**, 223–237.

Körner Ch (2003) Slow in, rapid out — carbon flux studies and Kyoto targets. *Science* **300**, 1242–1243. doi:10.1126/SCIENCE.1084460

Mott JJ, Williams J, Andrew MA, Gillison AN (1985) Australian savanna ecosystems. In ‘Ecology and management of the world’s savannas’. (Eds JC Tothill and JJ Mott) pp. 56-82. (Australian Academy of Science: Canberra)

O’Grady AP, Chen X, Eamus D, Hutley LB (2000) Composition, leaf area index and standing biomass of eucalypt open forests near Darwin in the Northern Territory Australia. *Australian Journal of Botany* **48**, 629–638.

Ridpath MG (1985) Ecology of the wet–dry tropics: how different? *Proceedings of the Ecological Society of Australia* **13**, 3–20.

Russell-Smith J, Ryan PG, Klessa D, Waight G, Harwood R (1998) Fire regimes fire-sensitive vegetation and fire management of the sandstone Arnhem Plateau monsoonal northern Australia. *Journal of Applied Ecology* **35**, 829–846.

Russell-Smith J, Edwards A, Cook GD (2003*a*) Reliability of biomass burning estimates from savanna fires: Biomass burning in northern Australia during the 1999 Biomass Burning and Lightning Experiment B field campaign. *Journal of Geophysical Research* **108 (D3)**: Art. No. 8405.

Russell-Smith J, Whitehead P, Williams R (2003*b*) Fire and savanna landscapes in northern Australia — regional lessons and global challenges. *International Journal of Wildland Fire* **12**, i–iv. doi:10.1071/WFV12N4TOC

Scholes R, Noble I (2001) Storing carbon on land. *Science* **294**, 1012–1013. doi:10.1126/SCIENCE.1065307

Schulze E-D, Wirth C, Heimann M (2000) Managing forests after Kyoto. *Science* **289**, 2058–2059. doi:10.1126/SCIENCE.289.5487.2058

Wang YP, Barrett DJ (2003) Estimating regional terrestrial carbon fluxes for the Australian continent using a multiple scale approach. I. Using remotely sensed data and ecological observations of net primary productivity. *Tellus* **55B**, 270–289.

Williams RJ, Duff GA, Bowman DMJS, Cook GD (1996) Variation in the composition and structure of tropical savannas as a function of rainfall and soil texture along a large-scale climatic gradient in the Northern Territory, Australia. *Journal of Biogeography* **23**, 747–756.

Williams RJ, Cook GD, Ludwig JL, Tongway D (1997) Torch, trees, teeth and tussocks: disturbance in the tropical savannas of the Northern Territory, Australia. In 'Frontiers in ecology. Building the links'. (Eds N Klomp and I Lunt) pp. 55-66. (Elsevier: Oxford, UK)

Williams RJ, Gill AM, Moore PHR (1998) Seasonal changes in fire behaviour in a tropical savanna in northern Australia. *International Journal of Wildland Fire* **8**, 227–239.

Williams RJ, Cook GD, Gill AM, Moore PHR (1999) Fire regime fire intensity and tree survival in a tropical savanna in northern Australia. *Australian Journal of Ecology* **24**, 50–59. doi:10.1046/J.1442-9993.1999.00946.X

Williams RJ, Griffiths AD, Allan G (2002) Fire regimes and biodiversity in the wet-dry tropical savanna landscapes of northern Australia. In 'Flammable Australia: the fire regimes and biodiversity of a continent'. (Eds RA Bradstock, JA Williams and AM Gill) pp. 281–304. (Cambridge University Press: Cambridge, UK)

Williams RJ, Muller WJ, Wahren C-H, Setterfield SA, Cusack J (2003*a*) Vegetation. In 'Fire in tropical savannas: the Kapalga fire experiment'. (Eds AN Andersen, GD Cook and RJ Williams) pp. 79–106. (Springer-Verlag: New York, NY)

Williams RJ, Woinarski JCZ, Andersen AN (2003*b*) Fire experiments in northern Australia: contributions to ecological understanding and biodiversity conservation in tropical savannas. *International Journal of Wildland Fire* **12**, 391–402. doi:10.1071/WF03025

Wilson BA, Bowman DMJS (1987) Fire, storm, flood and drought: the vegetation ecology of the Howard Peninsula, Northern Territory, Australia. *Australian Journal of Ecology* **12**, 165–174.

Wilson BA, Brocklehurst PS, Clark MJ, Dickinson KJM (1990) 'Vegetation survey of the Northern Territory, Australia.' Technical report No. 49. (Conservation Commission of the Northern Territory: Darwin, NT)

Manuscript received 5 November 2004, accepted 15 April 2004