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Estimating the financial risks of *Andropogon gayanus* to greenhouse gas abatement projects in northern Australia

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Abstract
Financial mechanisms such as offsets are one strategy to abate greenhouse gas emissions, and the carbon market is expanding with a growing demand for offset products. However, in the case of carbon offsets, if the carbon is released due to intentional or unintentional reversal through environmental events such as fire, the financial liability to replace lost offsets will likely fall on the provider. This liability may have implications for future participation in programmes, but common strategies such as buffer pool and insurance products can be used to minimize this liability. In order for these strategies to be effective, an understanding of the spatial and temporal distributions of expected reversals is needed. We use the case study of savanna burning, an approved greenhouse gas abatement methodology under the Carbon Farming Initiative in Australia, to examine potential risks to carbon markets in northern Australia and quantify the financial risks. We focus our analysis on the threat of *Andropogon gayanus* (gamba grass) to savanna burning due to its documented impacts of increased fuel loads and altered fire regimes. We assess the spatial and financial extent to which gamba grass poses a risk to savanna burning programmes in northern Australia. We find that 75% of the eligible area for savanna burning is spatially coincident with the high suitability range for gamba grass. Our analysis demonstrates that the presence of gamba grass seriously impacts the financial viability of savanna burning projects. For example, in order to recuperate the annual costs of controlling 1 ha of gamba grass infestation, 290 ha of land must be enrolled in annual carbon abatement credits. Our results show an immediate need to contain gamba grass to its current extent to avoid future spread into large expanses of land, which are currently profitable for savanna burning.

Keywords: carbon market, climate change, fire management, risk, exotic grass invasion, *Andropogon gayanus* (gamba grass)

S Online supplementary data available from stacks.iop.org/ERL/8/025018/mmedia

1. Introduction

Climate change and other human driven changes are a major influence on the natural world and immediate action is needed to address these (Rockstrom *et al* 2009, Steffen *et al* 2007). Global agreements such as the Kyoto Protocol and the recent announcements from the UN Durban climate conference aim to reduce greenhouse gas (GHG) emissions (Rajamani 2012) while the Convention on Biological Diversity has set targets to protect global biodiversity (CBD 2010). These global agreements have supported the growth of financial products to leverage expanding investments in carbon offsets to conserve biodiversity. While the increased interest in offset programmes is promising for environmental outcomes, the long-term viability of these programmes will be directly linked to offset providers managing financial risks associated with carbon offset products. For example, in the case of carbon offsets the intentional or unintentional release of carbon back to the atmosphere due to storms, fire, pests, land use decisions, and many other factors may result in a financial liability to replace lost offsets (Galik and Jackson 2009, Mignone *et al* 2009, Palmer 2011). If the risks associated with carbon products are too great, risk-averse landholders may choose to not participate in future programmes due to the associated financial liabilities.

The global carbon market is valued at US$176 billion (Kossoy and Guigon 2012) and is growing in countries such as Australia. The Australian Carbon Farming Initiative (CFI, a voluntary carbon offset scheme approved in 2011, The Hon Greg Combet AM MP 16 June 2011) presents an important opportunity to develop a carbon market that supports alternative economies with associated job creation, particularly in northern Australia. In addition, the dual objective of conserving biodiversity and reducing the GHG emissions offers important opportunities for cost-effective land management investments (Douglass *et al* 2011). However, the success of the CFI and the uptake of offset opportunities by landholders will be strongly influenced by the profitability and long-term financial sustainability of offset products. The CFI has additionality and permanence obligations for sequestration projects including a required 5% risk buffer (DCCEE 2012b). The buffer pool is strictly to cover the temporary loss of carbon and does not insure project proponents against potential loss of income or costs of re-establishing carbon stores. In addition, the individual risk profile of a project may have a much higher risk of threats, such as fires and storms, than the required 5% buffer pool. The spatial and temporal distribution of potential risks to both sequestration and abatement activities as well as the financial impacts on project proponents have not been directly addressed in the context of the CFI. Understanding the potential risks to offset products is a critical next step in the development of the CFI so that offset providers can avoid, reduce and mitigate threats. We contribute to this step by examining one approved methodology, savanna burning, for carbon offsets under the CFI and elucidating the potential financial risks.

The savanna burning methodology involves the use of controlled fire management across Australia's tropical savanna to achieve annual abatement of GHG emissions by reducing emissions relative to an established baseline. The Australian savanna region is vast, covering 25% of the Australian landmass (~2 million km^2) (Woinarski *et al* 2007). It is frequently burnt including extensive areas of late dry season wildfires and the associated GHG emissions generate 3% of Australia's total emissions (Russell-Smith *et al* 2009a). The savanna burning methodology is aimed at reducing the total area of savanna burnt each year and/or the proportion of late dry season fires that burn large areas with high combustion efficiencies (DCCEE 2011, Russell-Smith *et al* 2009a).

Given the extent of Australia's savanna, controlled fire management has the potential to significantly reduce Australia's total emissions and improve savanna ecosystem health. Heckbert *et al* (2012) applied a simulation model that calculated GHG emissions and abatement based on the savanna burning methodology and cost assumptions based on financial data from existing burning projects in the region. They demonstrated that under the current price of $23 per metric tonne of carbon dioxide equivalents (CO_2-e), savanna burning would be economically viable across 51 million ha and abate 1.6 million t of CO_2-e per year (Heckbert *et al* 2012). The first major savanna burning project, Western Arnhem Land Fire Abatement (WALFA) project in the Northern Territory, has demonstrated the potential for a GHG abatement programme to produce co-benefits including biodiversity benefits and economic opportunities for regional Aboriginal communities that are concurrent with their own objectives for managing and living on their country (Fitzsimons *et al* 2012, Heckbert *et al* 2011, Greiner and Stanley 2012).

While Australia's savanna is largely intact, invasive grasses pose a major threat to its ecological function and biodiversity, particularly through increased fuel loads and changed fire regimes (Setterfield *et al* 2010, Brooks *et al* 2010, Foxcroft *et al* 2010). This threat is recognized in the CFI savanna burning methodology which lists invasive grasses with high biomass as a 'specific exception' (DCCEE 2011) to the vegetation types that can be included and therefore invaded land must be excluded from enrolment. The African grass *Andropogon gayanus* Kunth. (gamba grass) is the invasive grass species that poses the greatest threat to Australian savannas (Brooks *et al* 2010). Fine fuel loads in gamba grass invaded sites are three times higher than native grass sites and fire intensity increases significantly, from typically 1 to 3 MW m^{-1} in native grass fires to 16 MW m^{-1} in gamba grass fuelled fires in the early dry season (Setterfield *et al* 2010). Setterfield *et al* (2013) estimate that fuel loads in the heavily invaded region of the Northern Territory have increased from 6 to 10 t ha^{-1} due to gamba grass. The flame height is greater in the invaded sites resulting in more fire damage to the tree and shrub layers and reduction in the carbon stored in the woody component of the vegetation (Brooks *et al* 2010, Setterfield *et al* 2010). If invaded sites are not burnt in one fire season, the fire fuel load increases resulting in more intense, high combustion fires in the following year (Setterfield *et al* 2010).

Gamba grass has spread rapidly from the initial paddocks in which it was sown in the 1980s and modelling predicts that most of Australia's mesic savanna is suitable for invasion (Northern Territory Government 2009). This area is spatially concurrent with the region approved for savanna burning. The extent of the risk of gamba grass invasion on savanna burning initiatives has not been quantified or accounted for in current assessments of savanna burning programmes across northern Australian (NAILSMA 2009, Heckbert *et al* 2012) or other programmes considering GHG abatement through savanna burning.

Therefore, the aim of this paper is to provide an assessment of the spatial extent to which gamba grass poses a risk to Australia's savanna burning programmes including a consideration of the spatial correlation of the current distribution of gamba grass with GHG abatement values. We also examine the costs of managing gamba grass relative to the financial benefits of carbon offsets from savanna burning to determine the financial threat that gamba grass poses to the long-term viability of these programmes. Our analysis is directly relevant to emerging carbon products in Australia and provides guidance on the financial risks to savanna burning from gamba grass and the financial sustainability of savanna burning offsets where gamba grass is present. While our analysis is based on gamba grass, it provides a framework for assessing the risks from other invasive high biomass grasses threatening Australia's savanna. Our analysis also demonstrates the importance of identifying potential risks so that appropriate measures can be taken to avoid, reduce and mitigate these threats.

2. Methods

2.1. Study area and distribution of gamba grass

In order to assess the risk to GHG abatement values from savanna burning by gamba grass we assembled data sets on current and potential distribution of gamba grass and expected abatement values and associated profits from savanna burning. We defined our study region as the savanna regions with rainfall greater than 800 mm a year as the current methodology applies to regions greater than 1000 mm but work is underway to extend to lower rainfall regions (BOM 2012) (figure 1). Data on the modelled potential distribution of gamba grass was provided by the Northern Territory Government (sourced from Weeds Branch Northern Territory Government, NRETAS 2008) and mapped current gamba grass infestations for the Northern Territory were primarily our own data (250 m grid, see mapping methods in Petty *et al* 2012) with additional locations provided by the Northern Territory Government (NRETAS 2008, figure 1). The current distribution of gamba grass for Western Australia and Queensland was provided by the Australian Weeds Committee (figure 1, Australian Weeds Committee 2012).

2.2. Mapped expected GHG abatement values and profits associated with savanna burning

We mapped the expected CO_2-e abatement values from savanna burning using the approved Carbon Farming Initiative (CFI) methodology. All costs and benefits associated with savanna burning were calculated as of 2012 in Australian dollars. The baseline emissions were calculated as the average annual emissions over a period of 10 years prior to the project. Annual emissions (of CH_4 and N_2O) were calculated on a per hectare basis (100 m grid) across the region based on calibrated values for burning efficiency, fuel load, emission factor, carbon content and nitrogen content (values specified in the methodology as a function of vegetation type and burning history, DCCEE 2011). These calculations required the use of vegetation cover and fire scar data. The only available vegetation data for the full region was the national vegetation information system data (NVIS 2010). Although this vegetation is mapped at coarser resolution than that required for properties qualifying under the approved methodology, we believe this is appropriate for mapping variability of values at a regional scale. As fire scar data is not yet available for the full baseline period, we used fire frequency and late fire frequency from North Australian Fire Information (NAFI 2012) over the baseline period to calculate average years since last burn and proportion of early and late season burning per hectare for the region. We used these to calculate average annual CO_2-e emissions over the baseline period. We calculated project emissions as 66% of baseline emissions as was estimated for the WALFA region by Russell-Smith *et al* (2009b). Lastly, the net expected annual abatement (t CO_2-e) was calculated as the difference in baseline emissions and project emissions. Expected annual revenue from savanna burning was calculated by multiplying expected annual abatement (t CO_2-e) by the initial price of $23 AUD per metric tonne of carbon dioxide equivalents (t CO_2-e) (figure 2). Expected net annual profit from savanna burning was calculated as the difference in revenue and input costs per ha (input costs include items such as staff expenses, regular operational costs, and recurrent capital and have been estimated based on financial costs of savanna burning projects in the region at $0.4685 per ha, Heckbert *et al* 2012) (figure 2).

2.3. Modelled control and eradication costs for gamba grass infestations

We modelled the costs of gamba grass control and eradication using cost estimates for 95 hypothetical gamba grass infestations provided by professional weed managers from the Centrogen Weed Specialist Company. Control of gamba grass was defined as management to prevent spread from the invasion site and to prevent further increase in density within the site. Control efforts include chemical treatment of the boundaries of infestations and the burning of gamba grass to increase accessibility for treatment of plants along edges of infestations. Control efforts must occur in perpetuity in order to effectively stop increases in size of gamba grass infestations. Eradication of gamba grass was defined as the local eradication of a gamba grass infestation through intense chemical treatment over a timeframe of 6–8 years depending on the size and density. At the time of data collection, Centrogen was the main weed management contractor in the Northern Territory undertaking gamba grass management projects on public and private land with extensive experience in costing control and eradication projects. Several weed managers at Centrogen worked together to collectively provide total weed management costs from each infestation, including labour, equipment, chemical, travel, monitoring and planning costs. In addition to cost estimates for all management inputs, the Centrogen team provided comments on the management approach used for control and eradication of different infestation types (classified by size and density).

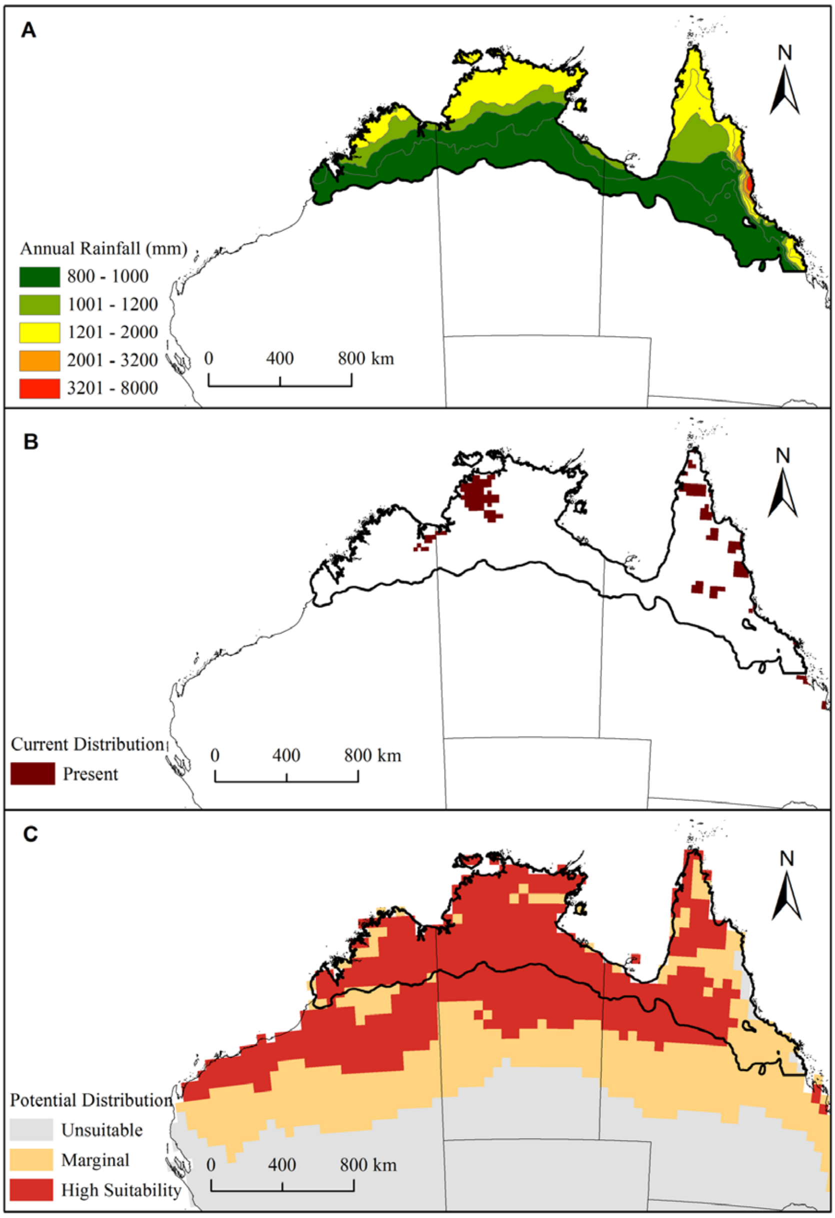

Figure 1. Northern Australia study region (defined by northern savanna region with >800 mm rainfall, outlined in black). (A) Annual rainfall isophytes from Bureau of Meteorology (BOM). Project areas must be savanna vegetation with more than 1000 mm annual rainfall. For our study we include all northern savanna regions with greater than 800 mm annual rainfall to account for potential expansion of the methodology to lower rainfall regions. (B) Current distribution of *Andropogon gayanus*. Data was assembled for the Northern Territory from mapped infestations (250 m grid). While other records of presence of *Andropogon gayanus* exist we have included only mapped infestations for which we have data to model costs of control and eradication. Data for Western Australia and Queensland interpreted from the National Strategic Plan (based on 20 km × 20 km grid cells derived data supplied by the jurisdictions Australian Weeds Committee 2012). (C) Potential distribution of *Andropogon gayanus* interpreted from CLIMATCH modelling and classified as unsuitably, marginal suitability or high suitability (NRETAS 2008).

These cost estimates were used to parameterize control and eradication cost models as a function of density and size of infestation (see supplementary materials 1 for full model details, available at stacks.iop.org/ERL/8/025018/mmedia). The cost models were then tested against expert estimates of eradication costs (see supplementary materials 2 for full details, available at stacks.iop.org/ERL/8/025018/mmedia). We applied the cost models to a range of infestation sizes for each density class. For each density class and size we calculated the net present value over the management timeframe (in perpetuity for control and 6–8 years for eradication depending on size and density class using a 3% interest rate based on the current Reserve Bank of Australia cash rates, RBA 2012). We plotted net present value against size of infestation to explore under what conditions eradication and control were more cost efficient. We then used the control and eradication models to estimate annual control costs and annual eradication costs across the eradication time frame for all mapped infestations in the Northern Territory (figure 1(B)).

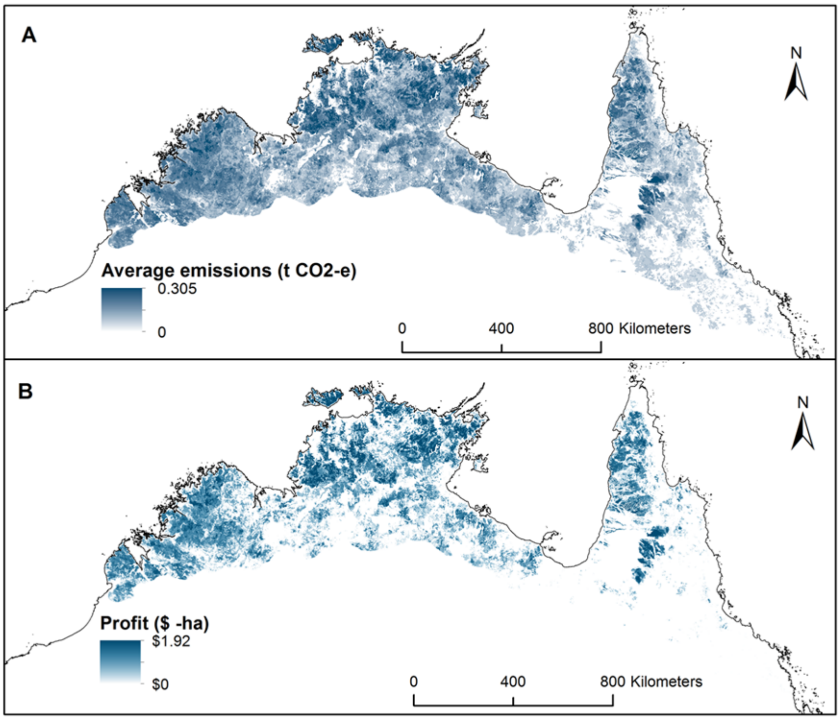

Figure 2. (A) Expected annual greenhouse gas (GHG) abatement in tons of carbon dioxide equivalents (t CO_2-e). (B) Expected annual per hectare profit from savanna burning.

Table 1. Summary statistics of all eligible properties in the Northern Territory that are profitable for (A) carbon abatement credits ($n = 884$) and (B) the subset of those properties with gamba grass infestations ($n = 199$). The minimum, maximum, mean and mode are given for property size (ha), annual abatement per ha (t CO_2-e ha^{-1}), gamba infestation size (ha) and gamba density class of properties. Gamba density classes adhere to the cover classes record in surveys and are: 1 = 0%, 2 = <1%, 3 = 1–10%, 4 = 10–50%, 5 = >50%.

	Minimum	Maximum	Mean	Mode
A				
Property size (ha)	101	7 845 070	42 630	128
Average abatement per ha (calculated per property as total abatement per ha (t CO_2-e ha^{-1}))	0.00	0.08	0.03	0.05
B				
Property size (ha)	103	320 104	13 320	128
Average abatement per ha (calculated per property as total abatement per ha (t CO_2-e ha^{-1}))	0.00	0.08	0.04	0.047
Gamba density class	2	5	3	2
Gamba infestation size (ha)	6.25	11 156.25	357	6.25

2.4. Analysis of risks

For the study region we calculated the percentage of total area eligible for savanna burning that is in each of three categories of suitability for gamba grass: not suitable for gamba grass, marginally suitable region and highly suitable region (based on Climatch analysis). For property scale economic analyses we restricted our analysis to properties of at least 100 ha (enrolled projects must be at least 1 km^2 (100 ha)) in the Northern Territory, as this is the only state or territory where detailed gamba grass data was available, and we assumed that 100% of the eligible vegetation within a property would be used for abatement. For each property in the Northern Territory we summarized the expected annual GHG abatement from savanna burning, the total area infested by gamba grass, the average density of gamba grass infestations and the annual control and eradication costs as well as net present value of gamba control (calculated in perpetuity) and eradication costs (calculated over the eradication time frame, between 6 and 8 years dependent on size and density of infestation). We summarized these details for all properties that have a profit from savanna burning and for the subset of properties that also have gamba infestations (table 1).

In order to understand the financial risk posed by gamba grass to properties enrolled in savanna burning abatement projects we considered two motivations for managing gamba grass in order to mitigate the risk to their abatement credits. First, we considered the situation in which a

Table 2. Control and eradication costs of gamba grass ($AUD) and metrics for economic viability of managing gamba grass as part of a savanna burning carbon abatement programme (calculated at the property level and then averaged, $n = 199$).

	NPV per ha ($AUD per ha)	Average annual cost of management per ha ($AUD per ha)	Annual ha enrolled in carbon abatement to pay for 1 ha gamba management (ha)	Years abatement to equal NPV gamba management (years)
Average control	$1377	$43	290	70
Average eradication	$877	$120	780	73

Table 3. Summary statistics for three example properties.

Property area (ha)	9392	13 118	6011
Annual carbon abatement per ha (t CO_2-e ha^{-1})	0.0318	0.0470	0.0313
Annual carbon abatement profit per ha ($AUD ha^{-1})	$0.26	$0.61	$0.25
Gamba density class	3	2	2
Gamba infestation size (ha)	325	12.5	37.5
NPV control ($AUD)	$112 020	$29 940	$30 040
NPV eradication ($AUD)	$349 000	$9410	$23 060
NPV control per ha ($AUD ha^{-1})	$344.68	$2395.20	$801.17
NPV eradication per ha ($AUD ha^{-1})	$1073.85	$752.80	$615.04
Time for carbon profit to equal NPV gamba grass control (years)	28	9	15
Time for carbon profit to equal NPV gamba grass eradication (years)	54	3	12

landholder controls gamba grass in order to (1) protect against gamba grass spread within their property and associated loss of eligible hectares for enrolment in carbon offsets and (2) protect against the loss of abatement credits on enrolled land due to potential movement of intense fires from gamba infested land onto land enrolled in carbon offsets. Second, we considered the situation in which a landholder eradicates gamba grass in order to make the land eligible for subsequent enrolment in carbon offsets. We considered these two situations separately rather than considering only the most cost efficient of the two management options as they reflect different landholder motivations and therefore cost efficiency may not be the sole factor in a landholder's decision to control or eradicate. We investigated the economic viability of these two situations by first calculating the average per ha cost of management for each property and the net present value of control and eradication costs associated with gamba grass on each property (using a 3% interest rate based on the current Reserve Bank of Australia cash rates, RBA 2012). We then calculated two metrics to assess economic viability of the above situations: (1) the number of hectares that a property would need to enrol in carbon credits to break even with 1 ha of gamba management costs (i.e. the ratio of per ha annual gamba grass management costs to per ha annual carbon credit profits) and (2) the amount of time that the property would need to sell annual carbon credits at the current price of $23 per tonne in order to break even with gamba management costs (i.e. solve for the number of annual periods such that the net present value of carbon credit profits are equal to gamba grass management costs). All summary statistics were calculated for each property and then averaged across properties and reported in table 2. In addition, we provide three example properties that are profitable for GHG abatement but have gamba infestations that will need to be controlled or eradicated (table 3).

3. Results

The potential spatial extent of savanna burning projects across northern Australia is coincident with the potential spatial extent of gamba grass (figure 1). Across our study region, only 5% of the area which qualifies for savanna burning is out of range for gamba grass while 75% of the region is part of the highly suitable range for gamba grass (figure 1(C)).

The average annual GHG emissions (t CO_2-e) per ha over the baseline period are given in figure 2(A) and range from 0 to 0.305 t CO_2-e per hectare. The expected profit per hectare ($AUD) from GHG abatement at a price of $23 AUD per tonne CO_2-e is given in figure 2(B) and values range from $0 to $1.92.

Control costs are relatively uniform across size and density classes (figure 3), reflecting that control efforts are typically herbicide spray efforts along the perimeter of infestations and therefore not sensitive to density. However, eradication costs diverge for density classes, with dense infestations becoming increasingly costly for large infestations. The cost curves are linearly increasing with small jumps in the eradication cost curves at 100 and 500 ha reflecting changes in equipment costs at those sizes. Where eradication and control cost curves cross indicates a change in cost-efficient strategies. In general, eradication is more cost efficient than control for smaller infestations (figure 3). For example, scattered infestations (density class $<1\%$) are more cost efficient to eradicate up to 56 ha after which it is more cost efficient to control (figure 3(B)). For the smallest infestations (6.25 ha), the net present value of eradication costs ranges from ~$6000 to $16 000 and the net present value of control costs ranges from ~$32 000 to $33 500 (figure 3). Summary statistics of all properties with a positive carbon offset profit and the subset of those properties with gamba grass are provided in table 1. There were 884 eligible profitable properties in the Northern Territory. Approximately

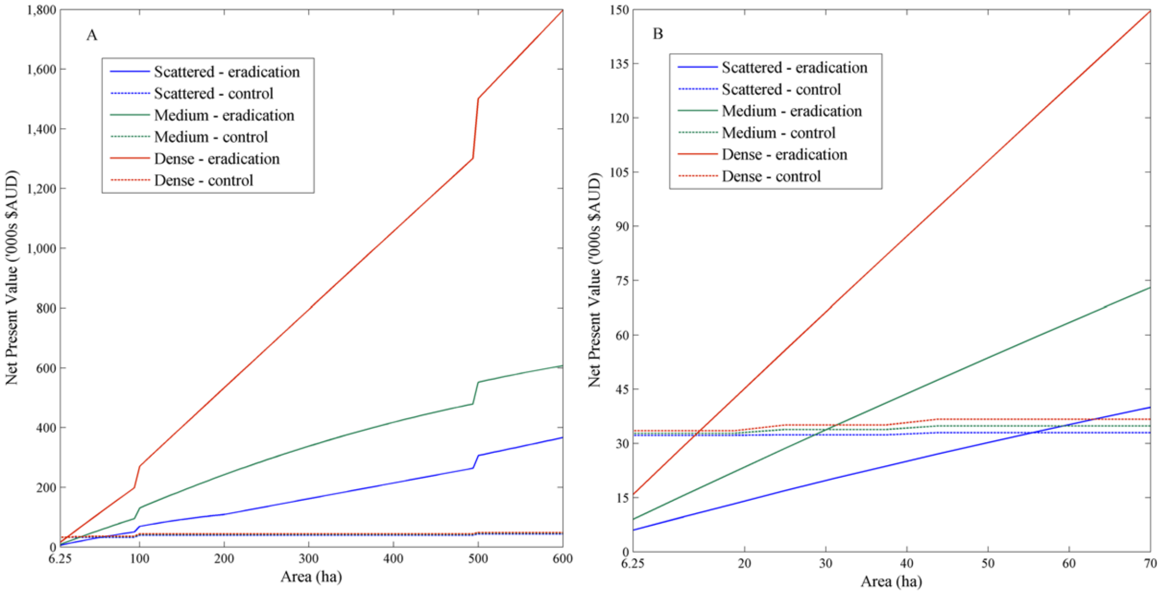

Figure 3. Net present value of eradication and control costs for gamba grass. (A) Net present value (in thousands, $AUD) for a range of gamba grass infestation sizes for the three density classes (scattered <1%, medium 1–50%, dense >50%). Jumps in the curves at 100 ha and 500 ha reflect changes in equipment costs at those sizes. (B) Net present value (in thousands, $AUD) for gamba grass infestations up to 70 ha to show the changes in cost-efficient approaches (where the eradication and control curves cross) for the three density classes. For example, eradication is more cost efficient for scattered infestations up to ~56 ha after which it is more cost efficient to control scattered infestations.

22% of the properties that can run profitable GHG abatement programmes (defined as profit > 0) have gamba grass infestations (199 of 884 properties). Those properties that have gamba grass are smaller than the average profitable property. The average density class of gamba infestations is relatively low (1–10% cover) and the average size of infestation is 357 ha.

The average annual per ha cost of gamba grass eradication is nearly three times that of control. However, when considering the per hectare net present value, the cost of eradication is approximately two thirds that of control. This is due to control being in perpetuity whereas eradication occurs over 6–8 years depending on the size and density of infestation. On an annual basis, in order to recuperate the costs of controlling 1 ha of gamba grass infestation, 290 ha of land must be enrolled in GHG abatement credits. Nearly three times that amount of land, 780 ha, is needed to recuperate the costs of eradicating 1 ha of gamba grass infestation. If a landholder sequestered all profits from GHG abatement credits and placed them in an endowment fund at 3% per annum interest to recover the net present value of costs of gamba grass control or eradication, the average time required for profits to be placed in an endowment fund is 70 years for control or 73 years for eradication.

We provide a summary of three example properties in table 3 to elucidate under what conditions control of gamba grass would be more economically viable than eradication of gamba grass. The amount of time that a landholder would need to invest all carbon offset profits into an endowment fund at 3% interest in order to pay for gamba grass control efforts is larger for larger gamba infestations; however for properties that have higher abatement potential the profit is greater and therefore reduces the amount of time.

4. Discussion

The Western Arnhem Land Fire Abatement (WALFA) has demonstrated the potential for savanna burning to produce economic benefits and Aboriginal communities across northern Australia are now working to extend the WALFA project model with the goal of supporting jobs on country for land management. However, we calculated that 75% of land across northern Australia that is eligible for enrolment in savanna burning is highly suitable for gamba grass. Our analysis demonstrates that the economic viability of savanna burning enterprises is compromised by the presence of gamba grass, with an average ratio of 290 ha of uninfested land needed to be enrolled in carbon credits to fund control of 1 ha of gamba grass infestation.

Based on our calculations, the expected profit per hectare ($AUD) from GHG abatement at a price of $23 AUD per tonne CO_2-e ranges from $0 to $1.92. The magnitude and spatial heterogeneity of emissions and expected profits are similar to previously published figures using alternate estimation techniques (average estimated annual GHG emissions range from 0 to 0.313 t CO_2e- per ha and expected profits have a maximum of $1.98, Heckbert *et al* 2012). In the Northern Territory, our analysis suggests that GHG abatement credits are profitable on nearly 900 eligible properties at the current price of $23 per tonne CO_2-e. However, 22% of those properties have existing gamba grass infestations which pose a major economic threat to their profitability. Controlling gamba grass is a minimum land management action in order to maintain savanna burning enterprises; however the average time frame required to break even on profits invested in an endowment to fund control costs is 70 years suggesting that gamba grass makes savanna burning un-economical on properties.

On larger and therefore more profitable properties in our study region (examples given in table 3), the number of years required for GHG abatement profits to be invested in an endowment fund to cover control or eradication of gamba grass still ranges from 3 to 54 years. The requirement of long-term investment of profits to address the threat posed by gamba grass may deter landholders from entering into savanna burning enterprises. For example, a previous study in the Daly catchment, Northern Territory (in which several savanna burning programmes are now underway) had a reported average period of ownership of 12 years and maximum reported ownership of 70 years (Adams *et al* 2012). This suggests that the average landholder would need to sequester 100% of their profits for the entire duration of their ownership in order to fund the long-term management of gamba grass.

Our analysis assumes an interest rate of 3%, a price of $23 per tonne CO_2-e, an assumed 34% reduction from baseline emissions and regional scale analysis of abatement values which rely on coarse scale mapping products. Therefore, there are a number of uncertainties associated with our regional analysis. There will be local scale variations in abatement values depending on actual fire severity, whereas our calculations capture only that fire events have occurred. In addition, abatement values will vary at a property level depending on fire management effectiveness. Lastly, if the price per tonne CO_2-e decreases, the number of properties that are profitable for savanna burning will decrease and the number of hectares enrolled in savanna burning required to fund one hectare of gamba grass will increase. The recent announcement to fully link the Australian emissions trading scheme with the European Union Emissions Trading System (EU ETS) by 2018 (DCCEE 2012a) suggests that prices will fluctuate. At a price of $15 per tonne Heckbert *et al* (2012) find that the number of profitable hectares for savanna burning drops from 51 million (at current price of $23 per tonne) to 23 million ha. Lower per tonne CO_2-e prices will result in lower abatement profits and therefore increased programme costs associated with gamba grass control and eradication may pose a greater financial risk to savanna burning opportunities than estimated here.

While gamba grass clearly presents a threat to the expansion of savanna burning programmes in northern Australia and their long-term economic viability, many of the existing infestations are still small. For example, of the 199 with infestations, 31 (16%) have the smallest size infestation mapped (6.25 ha) and the average net present value for eradication per infestation is $6500 (figure 3). This means that gamba grass can be eradicated from 16% of the properties currently infested for a total one-time investment of just $200 000. In addition, approximately half of the infested properties (95 of 199) have infestations less than 50 ha and eradication is more cost efficient than long-term control for these properties. For these properties, the presence of gamba grass may be less of a deterrent to entering the carbon market given that it is more cost efficient to eradicate gamba grass and then enrol those lands in savanna burning as compared to being committed to controlling gamba grass in perpetuity.

Our discussion thus far has focused on the direct threat that gamba grass poses within a property to GHG abatement opportunities. However, quantification of the spread rate of gamba grass from the initial source paddocks in northern Australia suggested explosive rates of spread analogous to highly invasive plants elsewhere (Petty *et al* 2012). Given this, gamba grass on neighbouring properties may also pose a significant threat to properties enrolled in GHG abatement programmes if gamba grass spreads into the property and establishes infestations. The threat posed by infestations on nearby properties may be addressed through enforcement of the existing legal declaration of gamba grass as a weed under the Northern Territory Weeds Management Act 2001. However, this does require a robust governance system which enforces the existing legislation through issuance of fines and land management or directions notices. While this is theoretically possible, a recent study showed that only recently, and only in Victoria, has there been a concerted effort to enforce weeds law in command and control manner (Martin *et al* 2012, McLennan 2012).

For properties engaged in GHG abatement enterprises, it will be critical to prevent new infestations through spread from neighbouring properties and reduce the likelihood of hot fires fuelled by gamba grass from moving onto their property. In the event that neighbouring properties do not control gamba grass and therefore become sources of both gamba grass and fire spread, what are the legal obligations for the lost revenue to neighbouring GHG abatement enterprises? Martin *et al* (2012) summarize court cases relating to nuisance or negligence and weeds and elucidate the difficulties of demonstrating liability which may hinge upon the ability to show that the landholder brought the weeds onto the property and the weeds contributed to a ‘non-natural’ use of the land. Given that many properties are likely to have changed ownership a number of times since gamba grass was either planted or first invaded the property through natural spread, it may be difficult to demonstrate liability given landholders have inherited gamba grass infestations rather than brought it onto the property themselves. However, relating to the spread of gamba grass fuelled fires, the *Goldman v Hargrave* (1967) court confirmed the liability of the occupier in that he failed to uphold his duty of care when he allowed a fire started by lighting striking a tree to spread and cause damage to his neighbours.

Gamba grass presents a long-term threat to GHG abatement programmes. However, many of the infestations on properties are currently small and not financially onerous to eradicate. In addition, current gamba infestations total ~1.5 million ha, only 2% of the current potential range (Australian Weeds Committee 2012) compared to a potential 51 million ha of profitable savanna burning land (Heckbert *et al* 2012). Therefore, immediate containment of the existing gamba infestations would be a significant step in mitigating the risk posed by gamba grass to savanna burning at a regional scale. Containment of gamba grass can be achieved and supported through existing legislation which allows for the Northern Territory government to issue fines and land management or directions notices to those landholders not actively controlling gamba grass. Our analysis elucidates the potential for large gamba grass infestations to be a financial barrier to landholders entering into GHG abatement programmes. However, our analysis also lays the foundations for understanding the extent of the risk posed by gamba grass and ensuring that appropriate management of infestations occurs to mitigate these risks. Lastly, given the appropriate governance structures, the threat posed by gamba grass on neighbouring properties can be addressed so that this is not a deterrent to landholders wanting to enter into the carbon market.

Offset programmes provide potential economic opportunities for development which result in environmental outcomes, such as carbon sequestration as well as biodiversity benefits. However, the potential for reversal and the subsequent impact on actual offsets may pose financial risks to participants in the offset market and therefore act as a barrier to new future landholders entering the market. We have demonstrated that gamba grass poses a real threat to the financial viability of GHG abatement enterprises in northern Australia. This is only one case study of a known environmental driver that may directly impact on offset activities. Storms, fire, pests, and many other factors may result in reversal and therefore have financial implications associated with lost offsets (Galik and Jackson 2009, Mignone *et al* 2009, Palmer 2011). Environmental offset markets are relatively new and therefore there is an opportunity to elucidate and account for these risks when designing offset programmes. In addition, if there is an appropriate analysis of the risk to each project then appropriate mechanisms can be used to mitigate these risks including market mechanisms such as insurance products (Diaz 2010, van Oosterzee *et al* 2012). A robust estimation of the financial liabilities and likelihood of reversals due to environmental drivers such as gamba grass allows for offset programmes to mitigate these threats or buffer against financial losses so that the long-term viability of the enterprise is not at risk.

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