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Assessing the value of ecosystem services delivered by prescribed fire management in Australian tropical savannas

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ABSTRACT

The savannas of tropical northern Australia, covering 1.9M km^2, are relatively unmodified and support a very sparse human population (0.5 person/km^2). Largely marginalised and impoverished Indigenous communities are key stakeholders in the region with legal rights to >60% of the land. Colonisation in the late 19th century significantly impacted long-standing Indigenous land management practices, resulting, until recently, in fire regimes dominated by extensive wildfires emitting, on average, >16Mt of greenhouse gases (GHG) per annum. To manage these emissions, the Australian Government in 2013 enacted an incentivised scheme—the Savanna Burning Methodology (SBM) under the Carbon Farming Initiative Act (2011)—to reduce wildfires through strategically applied prescribed burning. This paper assesses the value of ecosystem services (ES) delivered by fine-scale fire management under the SBM that is now applied to 25% of the 1.2 M km^2 regulatory eligible savanna area, abating >7 Mt of GHG emissions per annum. While this scheme delivers and maintains a diverse range of ES supporting (i) the well-being of local Indigenous people, estimated at $189 million/yr (using a substitute value of government expenditure on Indigenous welfare), and (ii) many off-site ES for regional and global populations, the realised market value for GHG emissions abatement represents < 1% (i.e. USD 74.6 million since 2013) of the total value of ES. This assessment emphasizes the: (i) need to recognise the many benefits derived from SB; (ii) challenges associated with valuing ES for regional savanna stakeholders; (iii) further development of incentivised mechanisms for maintaining the flow of ES across sparsely settled northern Australian savannas. This assessment has broader implications globally where Indigenous and local communities aspire to sustainably manage their lands

1. Introduction

Tropical savannas occupy 1.9 M km^2 of northern Australia, covering a quarter of the Australian landmass, incorporating a diverse range of vegetation types including open grasslands, shrublands, savanna woodlands, and monsoon/tropical forests (Woinarski et al. 2007; Fig. 1). The savanna landscape, traditionally managed by Indigenous peoples over millennia through implementation of fine-scale mosaic burning, supports diverse flora and fauna, has well-preserved soil and water resources, and is relatively little modified by contemporary land use practices (Garnaut 2008; Woinarski et al. 2007). As a result, Australia's northern savanna ecoystems support an array of services delivered to local, regional and global populations (Russell-Smith et al., 2019a; Sangha et al. 2017a).

Australian savannas represent relics of ancient ecological and social landscape interactions. The eucalypts which now dominate the savannas are well adapted to fire, radiating from ~15 million years BP as the climate dried (Woinarski et al. 2007). Development of contemporary savanna formations accelerated with cyclic Pleistocene aridity, from ~3 million years BP. Anthropogenic burning is likely to span >60,000 years associated with the current known prehistory of human occupation (Clarkson et al. 2017), but especially in the later Holocene period (from ~3000 years BP) with rapidly increasing population sizes (Williams et al. 2015), which together have contributed to Indigenous land (and

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fire) management that shape present day savannas.

In the recent past, the vast savanna landscape has become prone to frequent and extensive wildfires, emitting, on average, >16Mt of accountable greenhouse gases (GHG), annually, contributing 2–4% of Australia's total GHG emissions (Cook and Meyer 2009; Murphy et al. 2014; Edwards et al. 2015; Fig. 2). To manage these fire emissions, consistent, ongoing fine-scale management of fire across the entire savanna landscape is imperative (Russell-Smith et al. 2013; Russell-Smith and Whitehead 2015; Russell-Smith and Sangha 2018). Such management further affords a wide range of ecosystem services (ES—the benefits that humans obtain from natural systems) including climate regulation through GHG emissions abatement, biodiversity maintenance, water regulation, as well as a range of cultural, ceremonial, and spiritual services for ~125,000 Indigenous peoples resident in ~200 Indigenous communities widely dispersed across the entire northern landscape (Fig. 3) (Russell-Smith et al., 2009; Russell-Smith et al., 2015; Social Ventures Australia, 2016; Sangha et al. 2017a; Sangha et al. 2019a; Fig. 3). Those ES play a vital, if largely unrecognised, role enhancing the well-being of regional Indigenous and non-Indigenous communities, with broader benefits to society generally. Globally, the role of managing fire to obtain ES has been recognised by many, including Gillson et al. (2019), Pais et al. (2020), Pausas and Keeley (2019), and Russell-Smith (2016).

In Australia, current policy settings largely fail to integrate ES that flow from managing the savanna landscape with the well-being of Indigenous and non-Indigenous people (Hatfield-Dodds et al. 2016; Sangha et al. 2019a). Such integration is particularly compelling in remote savanna settings where Indigenous peoples have ongoing imbued relationships with their traditional lands and derive well-being benefits from such connections (Dodson 1997; Muir 1998; Grieves 2007). Land relates to all aspects of people's life (e.g. identity, culture, spirituality, learning, knowledge and skills to use and manage land and other resources), and family/clan relationships that are defined by connections to their ancestral clan estates. Managing land in a culturally appropriate way is vital to ensure the continuity of benefits (i.e. ES) that people obtain from, and connections with, their lands (Russell-Smith et al. 2009).

This paper aims to assess the total value of benefits (i.e. ES for Indigenous well-being as well as for the wider public), delivered in the eligible 1.2 M km^2 northern savanna region covered under Australia's regulatory Savanna Burning Methodology (Commonwealth of Australia [CoA] 2015; Commonwealth of Australia, 2018) (Fig.1,2). Our purpose for assessing the monetary value of ES is to emphasise the importance (not necessarily the quantum itself) of a wide range of non-market benefits that flow from managing fire in Australia's tropical savannas to inform policy decision makers, land managers, and the wider public. This study also highlights the mutli-dimensional nature of ES and demonstrates that associated non-marketable benefits need to be considered for developing appropriate policies addressing well-being, education, health and other related sectors, particularly for dispersed Indigenous communities.

This assessment is the first of its kind in Australia for estimating the value of ES derived from maintaining and managing the vast savanna landscape. We provide local as well as regional assessments of ES to encourage policy makers to appropriately invest in fire and land management programs, and build Indigenous and local capabilities and knowledges not just in Australia but across the globe. This assessment is also very timely for informing the Australian Government's 'Developing the North' agenda (2015), which focuses solely on developing conventional economies such as mining and agriculture, without considering opportunities for carbon and related ES economies (see Russell-Smith and Sangha 2018). However, we recognise that this paper represents an initial assessment of the total value of ES delivered by SBM, noting that the sum total of nuanced regional evaluations of the many non-market values is likely to be much greater given contributions towards empowerment of local people and the associated reduced societal costs for the governments for implementing SBM.

1.1. Fire management context

In Australia, ongoing Indigenous connections with the savanna landscape offer special insights into the management of this vast region over millennia. In the past, traditional burning practices—characterised by small (multi hectare-scale) patchy fires—were undertaken as people traversed their estates for a variety of hunting, gathering, cultural, and spiritual purposes (Garde et al., 2008; Ritchie, 2009). As a result, over time the savanna landscape has co-evolved with fire, including the influence of Indigenous management practised over millennia (Lewis et al., 1994; Bowman, 1998; Bird et al., 2005).

Traditional fire management across northern Australia was markedly disrupted by European colonisation from the mid-1800s. Such disruption also affected traditional governance systems and relationships among and between different clan groups (Ritchie, 2009; Fache and Moizo, 2015). From the 1970s Aboriginal people were able to start

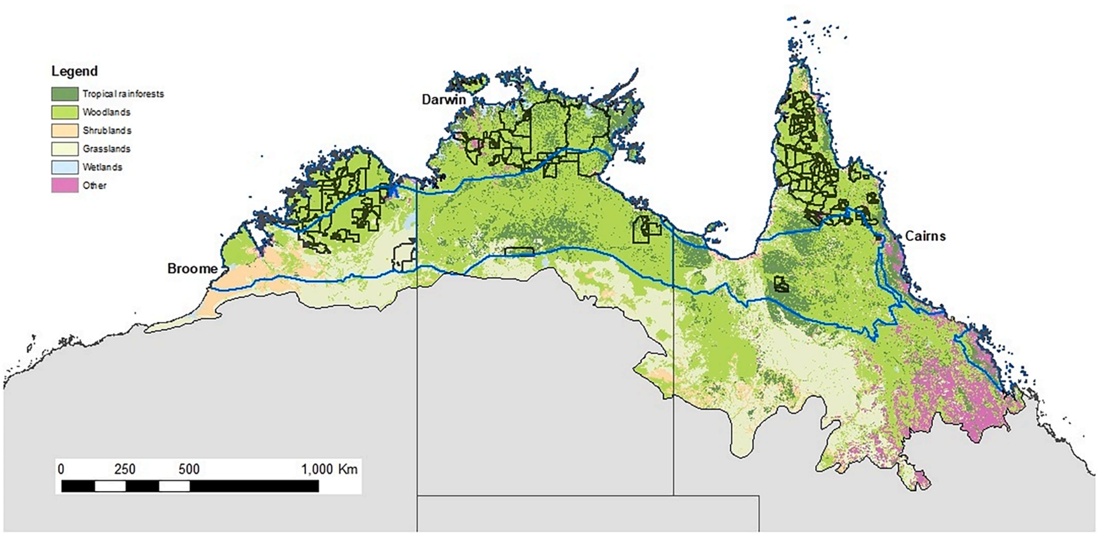

Fig. 1. Dominant vegetation types (following the Australian National Vegetation Information System dataset) across tropical savannas in northern Australia with greenhouse gas emissions abatement 'carbon'/Savanna Burning projects (outlined in black) above the 600 mm rainfall isohyet (blue line) using data from the carbon project register by the Emissions Reduction Fund, Australian Government.

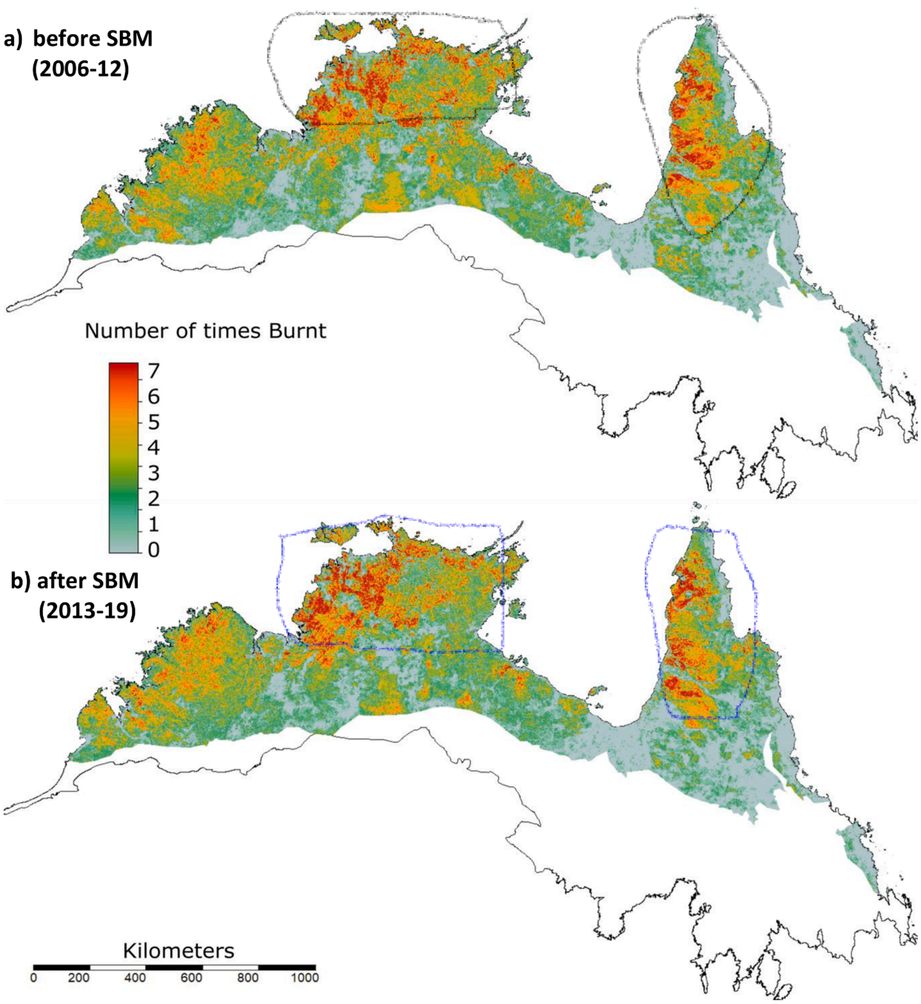

Fig. 2. Fire frequency across the focal study area (above 600 mm rainfall isohyet) within the savannas for periods: a) before i.e. 2006–2012 and, b) after i.e. 2013–2019 the implementation of the Savanna Burning Methodology (SBM; Emissions Reduction scheme) (data obtained from NAFI- North Australia and Rangelands Fire Information website: https://firenorth.org.au/nafi3/). Changes are more evident in marked areas with less red areas after SBM (b) in Cape York Peninsula, Qld (on the right) and Arnhem Land (the Top End of the NT).

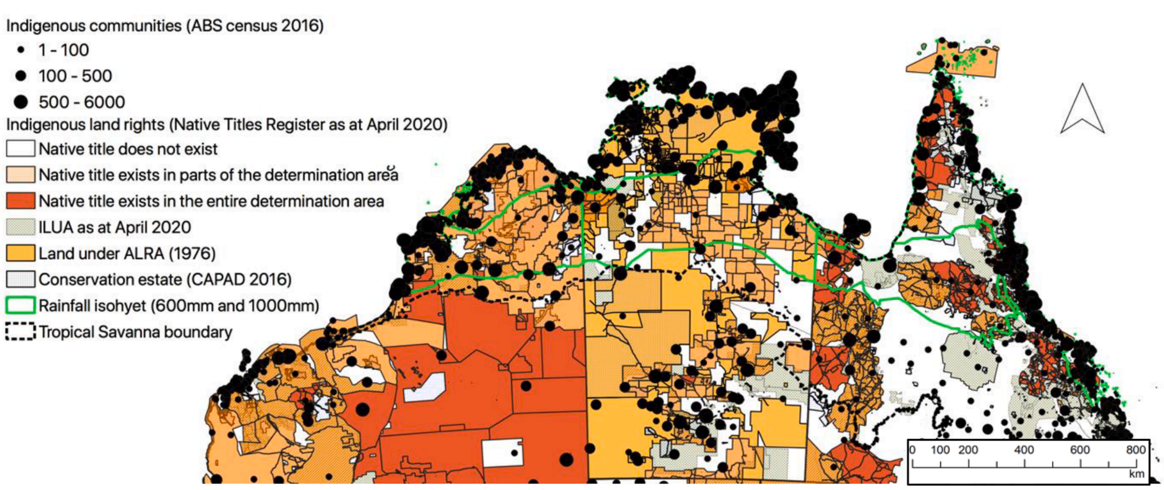

Fig. 3. Distribution of discrete Indigenous communities (ABS census 2016), Indigenous land rights under Native title, Indigenous Land Use Agreement (ILUA), Aboriginal Land Rights Act (1976; ALRA), and conservation estate above the 600 mm rainfall isohyet (using a combination of datasets: National Native Title Tribunal dataset [April 2020], NT land tenure data for ALRA; and CAPAD [Collaborative Australian Protective Areas] Dataset 2016).

reclaiming their traditional lands under the Commonwelath of Australia's Aboriginal Land Rights Act 1976 (ALRA) in the Northern Territory, and later in other north Australian jurisdictions under the Commonwealth of Australia's 1992 Native Title legislation—enabling Indigenous peoples to begin reconstruction and revival of traditional knowledges and skills (Altman 2014; Altman and Francis 2014; Dodson 1997). Recognition of traditional land management knowledges, especially the 'right to burn', came much later in the 1990s, enabling people to fulfil spiritual and cultural responsibilities towards their estates. This customary management has now evolved into a well-recognised fire management practice with wider scientific and political support, commonly referred to as 'prescribed burning' or 'savanna burning' (Russell-Smith et al., 2009; Russell-Smith et al., 2013). Prescribed burning may differ from traditional management approaches by focusing on strategic management of fuel loads, whereas traditional management approaches focus more generally on sustainable resource management on clan estates throughout the seasonal cycle (Jones et al., 2018; Yibarbuk et al. 2001; Garde et al., 2008).

This revival of Indigenous fire management practices has contributed significantly to the protection and management of savanna landscapes (Appendix 1; Edwards et al. 2021), especially reducing the impacts of extensive, severe late dry season (LDS) wildfires ignited both by people and lightning. Strategic application of small, patchy burns as firebreaks, and more generally to reduce fuel loads, in the early dry season (EDS, March-July) mitigates the risk of extensive LDS (August-December) wildfires which causes huge losses to various natural and man-made assets, including climate change. In the Indigenous vernacular, prescribed burning is often described as 'cleaning-up *country*', by which people mean to clear the rank (senescent) grass and protect land and water resources. However, effective fire management of fire-prone savannas at vast landscape-scales, and under sparse human occupancy (<0.1 persons km-^{2}), presents a singular challenge.

Following inclusion of savanna burning as an accountable activity for Annex 1 (Advanced Economy) countries under the Kyoto Protocol (UNFCCC Secretariate, 2007), a singular collaboration between scientists and Indigenous Elders was undertaken through the 2000s to develop a first-of-its-kind, market-based Savanna Burning (SB) GHG emissions accounting methodology (Russell-Smith et al. 2009a; Russell-Smith et al. 2009b; Russell-Smith et al., 2013). The SB approach accounts for and incentivises the undertaking of prescribed burning in the EDS period, before August, under relatively mild fire-weather conditions, to reduce the risk of extensive LDS wildfires and resultant GHG emissions (Murphy et al. 2015). In 2011, SB was formalised under Australian Commonwealth Law through the Carbon Farming Initiative Act (2011), involving the establishment of an accredited accounting methodology for the calculation of GHG emissions reductions from registered projects (CoA 2013). Implementation of the SB Methodology (SBM) is restricted to savanna regions receiving >600mm annual rainfall (CoA 2013; COA, 2015; Commonwealth of Australia, 2018). In 2014, the Australian Government established the Emissions Reduction Fund (ERF) and invested AUD 2.55 billion for the next five years as a means for purchasing carbon credits (Australian Carbon Credit Unit—ACCUs) from GHG emissions abatement. This fund has recently been renewed with another AUD 2 billion investment, under the rebadged Climate Solutions Fund (Australian Government 2020).

SBM demonstrates the merger of traditional knowledge with contemporary scientific tools and techniques including: daily and seasonal satellite-derived fire monitoring—the North Australia Fire Information website (NAFI; https://www.firenorth.org.au/nafi3/); application of aerial burning with incendiaries from helicopters to cover large, otherwise inaccessible, areas; and growing development of LDS fire suppression activities.

Since 2013, there has been significant progress in the uptake of SBM. As at May 2020, 76 projects were operating—each land parcel applying SBM is registered as a carbon/Savanna Burning (SB) project—covering an area of ~29 M ha (i.e. 25% of the eligible project region) (Fig. 4). Apart from abating GHG emissions, SB has contributed to the maintenance of ES including: conservation of biodiversity, land and water resources (Appendix 1; Russell-Smith et al. 2015; Russell-Smith et al., 2019b; Ansell et al., 2020; Evans and Russell-Smith 2020; Edwards et al. 2021); socio-economic outcomes for improved health, employment, rebuilding relationships among clan groups, peoples' connection to *country*, re-learning traditional ceremonies and practices *in situ* (Burgess et al. 2009; Sangha et al. 2017a; Sangha et al., 2017b; Social Ventures Australia, 2016). As one Indigenous Elder recently commented:

> ***"This fire management program has been successful on so many levels: culturally, economically and environmentally. Through reinstating traditional burning practices, new generations of landowners have been trained in traditional and western fire management, hundreds of thousands of tonnes of greenhouse gas have been abated, and the landscape is being managed in the right way."***

Dean Yibarbuk (Fire ecologist and Senior Traditional Owner, West Arnhem Land), Savanna Fire Forum, 9-11 Feb 2020, Charles Darwin University.

2. Methods

Our focal area covers 1.2 M km^2 (63%) of the Australian tropical savannas, above the 600mm rainfall isohyet, where regulated SB emissions reduction is recognised and practised by the land managers (Fig. 4). Here we describe the socio-economic and ecological context of fire management, followed by the evaluation of ES. The methods used to assess the ES values are based on standard techniques applied by Costanza et al. (2014), de Groot et al. (2012), Sangha et al. (2017a; Sangha

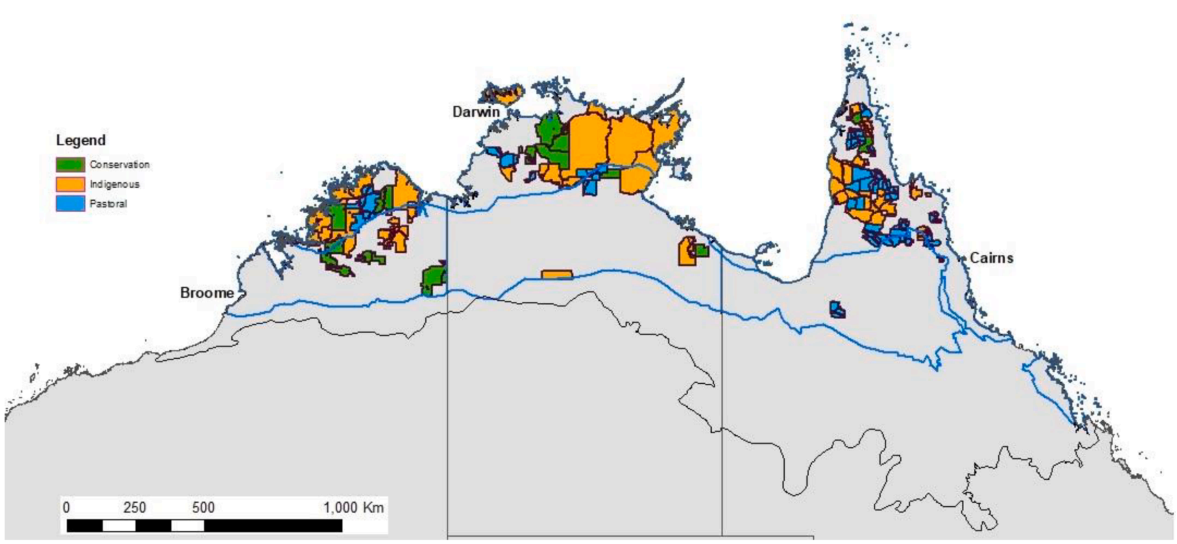

Fig. 4. Greenhouse gas emission abatement 'carbon' projects under main land uses, as registered in May 2020 on the Emissions Reduction Fund register (http://www.cleanenergyregulator.gov.au/ERF/project-and-contracts-registers/project-register).

et al., 2019a; 2019d) and others.

2.1. Socio-economic data

Australian Bureau of Statistics (ABS) 2016 census data were used to estimate the total number of Indigenous peoples and the number of discrete communities residing in our focal study area.

We defined the 'eligible workforce' (individuals who could be engaged in prescribed burning), as persons between the age of 20-59 across each State and Territory jurisdiction to estimate well-being benefits (details in Appendix 2).

2.2. Ecological data: Land use and GHG emissions

The Emissions Reduction Fund (ERF) project register (http://www.cleanenergyregulator.gov.au/ERF/project-and-contracts-registers/project-register), accessed in May 2020, provided the spatial extents of carbon projects required for SB valuation analyses. In that register, a land parcel where fire management is applied for abating GHG emissions is registered as a 'carbon'/SB project. We estimated the area for all carbon/SB projects under three major land use categories: Indigenous (mainly, use and management for Indigenous purposes by Indigenous peoples); pastoral (mostly rangeland beef cattle production); conservation (for protection of biodiversity). Spatial extent data were derived as follows: land tenure data for each state and territory (from respective State and Territory Government websites); native title and other Indigenous land rights data (from the National Native Title Tribunal dataset [NNTL; April 2020]; Aboriginal freehold land in the Northern Territory under the Aboriginal Land Rights [ALRA] Act 1976); and protected area data from CAPAD 2016 (Collaborative Australian Protective Areas Dataset).

Indigenous lands comprise Native Title (exclusive and inclusive), and, for the Northern Territory, Aboriginal Land (Scheduled under the Aboriginal Land Rights Act) and Aboriginal Land (Northern Territory [NT] enhanced Freehold). This category also includes Indigenous-owned Protected Areas (IPA; 2019) which otherwise comprise part of Australia's National Reserve System (2020). Pastoral lands were defined as all other lands outside of Conservation and Indigenous areas.

Data on the quantity of accredited GHG emissions abatement, measured in Australian Carbon Credit Units (ACCUs, where 1 tonne

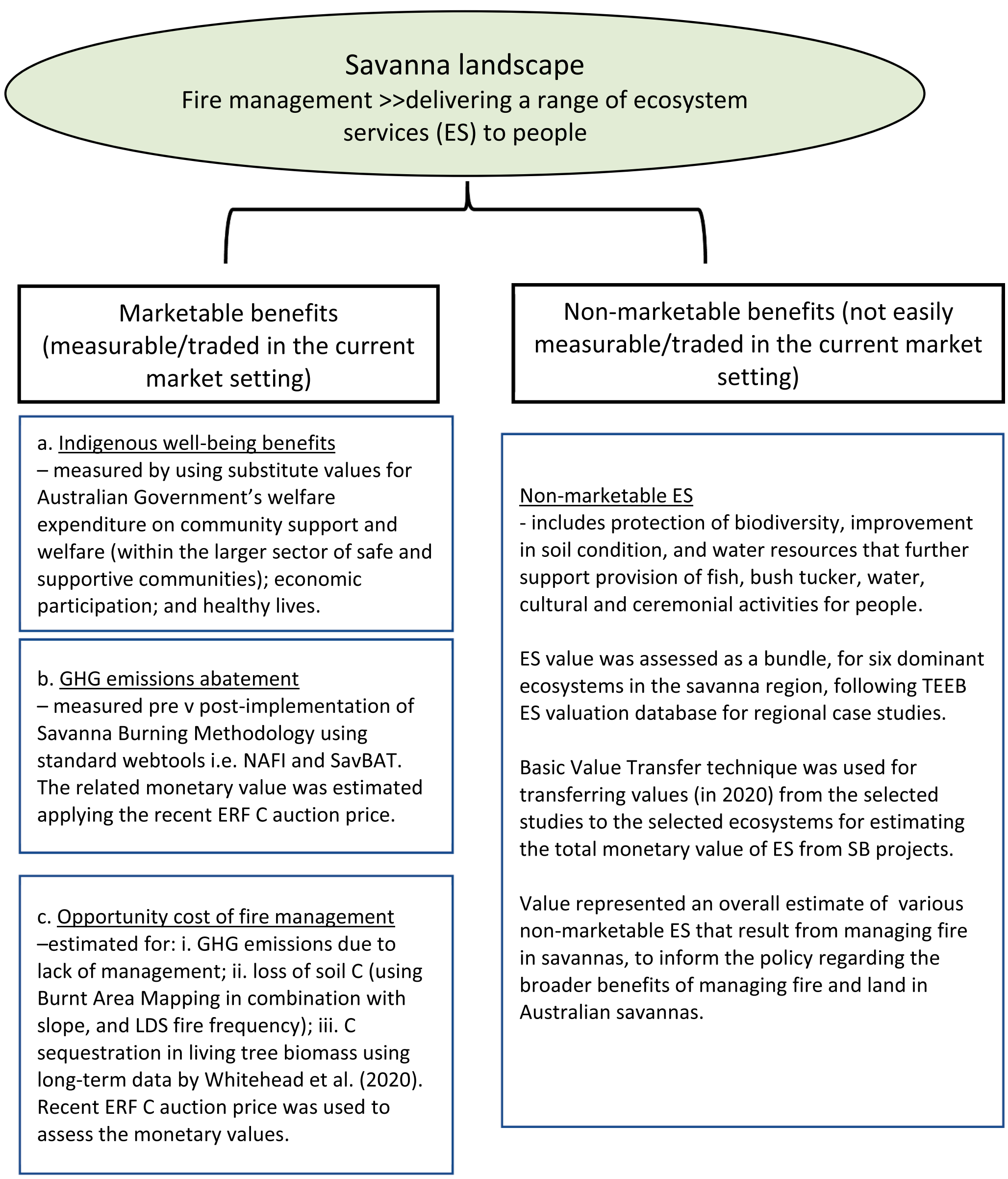

Fig. 5. An outline of assessed ES and related methods used in this study.

CO_2-e of GHG emissions abatement = 1 ACCU), were obtained from the ERF project register (2020).

2.3. Value estimations for marketable and non-marketable benefits

An outline of assessed marketable and non-marketable services, and related methods is presented in Fig. 5, and detailed below.

2.3.1. Marketable benefits

2.3.1.1. Indigenous well-being benefits. To estimate well-being benefits that Indigenous peoples obtain from managing fire across the northern landscape, we used a substitute value of welfare expenditure afforded by the Australian Government for enhancing their welfare (following Sangha et al., 2017a; Sangha et al., 2019b). On average, the Australian Government spends USD 28,727/person/yr on Indigenous welfare (Steering Committee for the Review of Government Service Provision [SCRGSP] 2017) including six different sectors each with several sub-sectors, such as safe and supportive communities, early childhood development, and economic participation. We considered only two of those six sectors, i.e. *economic participation*, and *healthy lives*, and a sub-sector *community support and welfare* within the safe and supportive communities sector, assuming that people derive equivalent benefits from being on *country* (for details see Sangha et al., 2017a; Sangha et al., 2019a). The total cost savings for the selected welfare sectors were estimated for part of the eligible Indigenous workforce, where 25% of the total workforce in the NT and WA, and 16% in Qld, was considered for estimating well-being cost-savings, in proportion with Indigenous participation in SB projects and assuming that the Indigenous workforce benefits from "Working-on Country" opportunities (Russell-Smith and Sangha, 2018; Social Ventures Australia, 2016; Australian Government's Indigenous Ranger Program—https://www.niaa.gov.au/indigenous-affairs/environment/indigenous-ranger-program). These welfare savings offer a conservative estimate of the local benefits, which extend beyond the selected three welfare sectors described above for emotional, spiritual and cultural benefits, childhood development and learning—many of which are not readily measured monetarily.

2.3.1.2. GHG emissions abatement benefits under SB methodology. We estimated the monetary value of GHG emissions abatement for the registered 76 SB projects (as at May 2020) using the ERF register (2020). The average annual GHG emissions for each land use (Indigenous, pastoral, conservation), for the period 2013-2019, were calculated using fire histories derived from NAFI (https://firenorth.org.au/nafi3/)—a web-based tool developed for and used by land managers to monitor fire. The related emissions from burnt areas were calculated applying SavBat v3 (https://v3.savbat.environment.gov.au/) — a standard tool used by the Australian Government to assess GHG emissions from wildfires, which automates the GIS processes and mathematical equations required to estimate the net abatement for SB projects. Both these tools enable assessment of the amount of GHG emissions abatement for each registered SB project (details in Murphy et al. 2015). The ERF register reports GHG emissions abatement online for each registered SB project (Emissions Reduction Fund Register, 2020; http://www.cleanenergyregulator.gov.au/ERF/project-and-contracts-registers). All the SB projects were mapped using ArcGIS 10.5 for spatial analysis. Further details for estimating GHG emissions are mentioned in Appendix 3.

The monetary value of ACCUs was calculated applying the current carbon price from the latest ERF auction (held by the Clean Energy Regulator, Australian Government) in March 2020 as AUD 16.14 per ACCU (USD 10.4 using a conversion rate of 0.64 as on 19 May 2020).

2.3.1.3. Opportunity cost of fire management. Significant opportunity costs have been incurred for GHG emissions, loss of soil carbon (C) and reduced C sequestration in the living tree biomass, in the absence of SBM on fire management. Applying available data from various north Australian studies (e.g. Ansell et al. 2020; Evans and Russell-Smith 2020; Edwards et al. 2015; Murphy et al. 2014; Loughran et al. 2004), we assume that, since 2013, SB has contributed to GHG emissions abatement, increased soil carbon and tree biomass, and overall resulted in better management of lands across the savanna landscape due to less wildfires (Edwards et al. 2021).

To assess these opportunity costs (i.e. the forgone benefits that would have been derived from fire management if SBM were implemented earlier), we estimated the average annual carbon values, over a period of 2006-2012 pre-SBM, equating to the same number of years in the post-SB period, 2013-2019, for: 1. GHG emissions; 2. loss of organic carbon (C) in soils; and 3. reduced C storage in the living tree biomass (details given in Appendix 3). For each of these pools we used the current C auction price of USD 10.4/tonne relating to GHG emissions abatement.

For GHG emissions, we estimated the average GHG emissions for each SB project under Indigenous, pastoral and conservation land uses applying NAFI and SavBat v3 (details in Murphy et al. 2015). The loss of surface Soil Organic Carbon (SOC—a measure of organic carbon in soil that changes rapidly with land management practices) due to fire regime was estimated using Burnt Area Mapping in combination with slope and LDS fire frequency for each SB project areas as both the fire frequency and topography impact on soil loss (following Edwards et al. 2015).

To estimate the opportunity cost of C stored in living tree biomass, an average figure of 0.6 tonnes/ha/yr was used following assessment of a long-term, tree monitoring dataset (236 plots, monitored for 3–24 years; following Murphy et al. 2021) specific to the Australian savannas.

2.3.2. Non-marketable Ecosystem Services

We measured the non-market values of ES that flow from managing fires on land parcels registered as SB projects within our focal 1.2M km^2 study area, using standard approaches (following Costanza et al. 2014; de Groot et al. 2012; Sangha et al. 2017a; Sangha et al., 2019d), as described below. We conservatively assume that fire management contributes 25% (see below) of the total value of ES that flow from 29M ha area under SB projects (as at May 2020), based on positive biodiversity, soil condition, and water condition outcomes (as reported by Russell-Smith et al. 2009; Edwards et al. 2015; Edwards et al., 2021; Murphy et al. 2019; Russell-Smith et al., 2019a; Russell-Smith et al., 2019b; Russell-Smith et al., 2019c; Warddeken Land Management Ltd., 2018-19; Ansell et al. 2020; Evans and Russell-Smith 2020; Radford et al. 2020). Fire is recognised as a key driver in tropical savannas, influencing biophysical processes and functions, and a range of social interactions that Indigenous peoples have with the landscape (Russell-Smith et al., 2009; Russell-Smith et al., 2019a). Wildfires typically are intense, severe and extensive (Yates et al. 2008), and prescribed SBM management has demonstrated a 50% reduction in wildfires and associated ecological impacts across the regulated SB region since 2012 (Fig. 2; Edwards et al. 2021).

To map different ecosystem types, the Australian National Vegetation Information System (NVIS) dataset was reclassified to six dominant ecosystem types, i.e. monsoon/tropical rainforests, woodlands, shrublands, grasslands, wetlands, and others including scrubland, chenopods, cleared or non-native vegetation. All spatial layers were converted to 1×1 ha resolution raster format and intersected using ArcMap 10.5 Geographic Information Systems software.

2.3.2.1. Value of ES in monetary units. ES, from all the carbon projects under three land uses, were assessed as a bundle in monetary units, applying various indirect methods, namely Basic Value Transfer (BVT), using The Economics of Ecosystems and Biodiversity (TEEB) database of 1310 studies, developed by van der Ploeg and de Groot (2010). ES include regulating services such as climate and water regulation, provisioning services such as provision of bushtucker (ie. bush foods), bush medicine, materials for cultural ceremonies, water resources etc., and cultural services such as communal fire camps, cultural learning on *country*, and ceremonial activities.

Six dominant ecosystems i.e. woodlands, grasslands, tropical rainforests, shrublands, wetlands, and others were mapped to value ES. Regional studies (Blackwell 2006; Curtis 2004), and the the TEEB database (de Groot et al. 2012), were used to calculate the median values for each of the six dominant regional ecosystems described above (following Sangha et al. 2017a). For example, for woodlands, the median values were derived from 46 ES values (Appendix 3, Sangha et al. 2017a). TEEB ES values were adjusted using the World Bank GDP deflation (inflation) rates and Purchasing Power Parity (PPP) where currencies were not mentioned in USD. Average inflation rates were used as of 19 May 2020. Derived and adjusted ES values per ha/yr were applied as follows: USD 4,158 for tropical rainforests; USD 896 for woodlands; USD 448 for shrublands; USD 445 for grasslands; USD 2,078 for wetlands; and USD 223 for other ecosystem. As described above, we accounted for 25% of total ES benefits derived from SB (refer Appendix 3). All ES values are presented in USD, unless stated otherwise.

We acknowledge the limitations of BVT, since the purchasing power of people varies within a region depending upon biophysical and cultural characteristics, and the financial capacities of people (Boyle et al. 2009; Plummer 2009; Rosenberger and Loomis 2017; Sangha et al. 2017a; Rogers et al. 2019). We applied only pertinent ES values from Australian and other contextually appropriate savanna case studies, as provided in the TEEB database. Additionally, we note that regional savanna fire management offers vital off-site ES, such as climate and water regulation, with benefits to broader national and global populations.

3. Results

3.1. Socio-economic account

Our focal study area supports a total population of 900,900 people (ABS 2016 census), i.e. $<$ 1 person/km^2, of which 14% are Indigenous. The majority of the population, mainly non-Indigenous, reside in towns such as Cairns, Ingham, Townsville, Mt Isa, Ayr and Home Hill in Queensland (Qld); Darwin, Palmerston, and Katherine in the NT; and Broome, Derby and Kununurra in Western Australia (WA). Outside of these towns, the Indigenous population comprises a much greater proportion (~90%).

There are 315 remote Indigenous communities: 129 in the NT, 156 in Qld, and 30 in WA.They are widely dispersed across the study area, with 188 communities supporting $>$ 100 people each (Fig. 3) (Appendix 2). Out of the total 125,000 Indigenous population, almost half (60,502), between the ages of 20-59, are identified here as the 'eligible workforce'.

Geographically, 90% of the Indigenous population lives in remote communities (Fig. 3), and those who live in towns frequently visit their homelands (ABS, 2016). Remote communities are often hundreds of kilometres from urban centres, with minimal employment opportunities (e.g. arts and crafts; Australian Government-supported ranger programs; SB projects). Indigenous peoples have significant legal land rights and perpetual cultural relationships with their lands. As of April 2020, 60% of the region comprised legally recognised Indigenous interests in land; half of which is under freehold title, and the other half under Native Title/Indigenous Land Use Agreements (ILUAs) that recognise ongoing affiliation with traditional estates, but without granting economic property rights (Fig. 3).

3.2. Ecological account: Land use and GHG emissions

There were 76 active carbon projects (as at May 2020), covering an area of ~29 M ha, i.e. 25% of the area available to Savanna Burning projects (Table 1). Approximately 62% of the managed area is under Indigenous land use, comprising 18 M ha in total, and the rest, ~19% each, under pastoral and conservation land uses.

Table 1
Total area (ha) under Savanna Burning/carbon projects (number of active carbon projects as of May 2020 in parenthesis) and related Australian Carbon Credit Units under Indigenous, pastoral, and conservation land uses.

	Northern Territory	Queensland	Western Australia	Total for three jurisdictions
Area (ha) under fire management	13,783,619	7,214,533	7,789,532	28,787,684
Indigenous	10,326,370 (11)	3,304,735 (11)	4,300,534 (5)	17,931,639 (27)
Pastoral	1,041,614 (6)	3,606,864 (26)	843,741 (1)	5,492,219 (33)
Conservation	2,415,635 (6)	302,934 (2)	2,645,257 (7)	5,363,826 (15)
Area under LDS fires (average frequency from 2004-2019)	9,344,675	4, 610,688	6,232,244	20,187,607
Australian Carbon Credit Units (ACCUs; 1 tonne of GHG emissions abatement = 1 ACCU)	3,856,404	2,150,812	1,166,330	7,173,546
ACCUs from Indigenous projects only	3,445,652	893,554	833,725	5,172,931
ACCUs from pastoral lands only	207,802	1,109,083	304,262	1,621,147
ACCUs from conservation lands only	202,950	148,175	28,343	379,468

Within the Northern Territory, fire management under Indigenous land use accounts for 75%, pastoral 7.5%, and conservation 17.5%, of the total SB area. Within Queensland, fire management for GHG emissions abatement accounts for 46% of the area under Indigenous land use, 50% under pastoral, and only 4% under conservation land use, of the total SB area. Within Western Australia, 55% of total managed area is under Indigenous land use, 11% pastoral and 34% under conservation land use (Table 1).

Since 2012, savanna fire management has abated 7 $Mt.CO_2$-e, with a total of 7,173,546 ACCUs issued since the commencement of SBM. Of this total, 5 $Mt.CO_2$-e (72%) has been abated on Indigenous lands (Table 1). Fire management on pastoral and conservation lands has delivered 23% and 5% of total abatement, respectively. SBM has led to a significant reduction in the area burnt under extensive, severe, LDS fires, estimated at $>$8 M ha/yr since 2013, along with a significant reduction in overall fire frequency (Fig. 2ab) and approximately 1.3 Mt of GHG emissions (Edwards et al. 2021).

3.3. ES account—the value of fire management for enhancing Indigenous well-being, abating GHG emissions, affording opportunity costs, and maintaining ES

3.3.1. Marketable benefits: Indigenous well-being, GHG emissions abatement, and the opportunity cost of fire management

The market value of fire management was assessed for: i. well-being benefits for Indigenous people living in remote locations; ii. abatement of GHG emissions for delivering tradable carbon credits over the seven year period, 2013-2019; and iii. opportunity costs associated with foregone fire management benefits over the preceding seven year period. The total value of tangible (marketable) benefits, accounting for these three components, was estimated at USD 288 million/yr, as described below:

3.3.1.1. Indigenous well-being benefits. Total well-being benefits for three welfare sectors (economic participation, healthy lives, and community support and welfare), were estimated at USD 189 million/yr, considering one-sixth of the eligible workforce in Qld, and a quarter each in the NT and WA, in line with carbon projects on Indigenous lands (Table 2). Applied to the total eligible workforce, the estimated value of benefits is ~USD 1 billion/yr.

Additonally, Indigenous peoples accrue a wide variety of social, cultural and spiritual, learning and ceremonial benefits, associated with cultural and natural resource management activities (Grieves 2007; Altman et al. 2011). Enhanced fire management through carbon projects creates culturally appropriate jobs in remote communities where, currently, >400 rangers are employed in the NT, and >100 in Qld and WA respectively (Table 2).

3.3.1.2. GHG emissions abatement benefits. The total monetary value of ACCUs issued following the commencement of SBM in 2013 was estimated at USD 74.6 million over seven years, using an average carbon price of USD 10.4 per ACCU. In the NT, the total value of carbon credits was USD 5.73 million/yr, where Indigenous fire management comprised 90% of the total (Table 2). In Qld, total carbon credits were worth USD 3.19 million/yr, including 42% Indigenous, and in WA the total value was USD 1.73 million/yr, including 71% Indigenous (Table 2). The average annual value of carbon credits across all the SB projects was USD 10.65 million/yr.

Table 2
Carbon credits for all the selected land uses, and well-being benefits derived by Indigenous peoples (values in USD 2020) from managing fire in savanna landscape above the 600 mm rainfall isohyet region.

	Northern Territory	Queensland	Western Australia
Carbon benefits per year (values in USD, applying recent C price from ERF auction at AUD 16.14, and a conversion rate of 0.64 on 19 May 2020 i.e. @ USD 10.40/tonne of GHG abatement)			
ACCUs from Indigenous lands over the last 6 years	3,445,652	893,554	833,725
Average value (USD)/year (@USD10.4/ACCU)	5,972,463	1,548,826	1,445,123
Jobs# (number of people employed)	>400	>100	>100
Well-being benefits for 25% of the 'eligible workforce' (USD/yr) to be able to work on-*country**			
1. Safe and supportive communities: using sub-sector community support and welfare for saving welfare costs of USD 3,994 /person*	19,475,914	22,744,534	6,822,162
2. Economic opportunities: for saving welfare costs of USD5,340/person*	26,038,620	30,408,651	9,120,993
3. Healthy lives: for saving welfare costs USD 6,086/ person*	29,674,166	34,654,346	10,394,478
Total well-being benefits for working on country in terms of welfare cost savings for the government (USD)	75,188,700	87,807,531	26,337,633
Total benefits (USD/yr)	81,161,164	89,356,358	27,782,757
Overall total benefits (USD/ yr) to the local Indigenous people			198,300,278

*the average welfare benefits at AUD 44,886/person/yr [values in 2015–16]) were adjusted and updated for the selected three out of six welfare sectors. The AUD values were converted to USD using a conversion rate of 0.64 as on 19 May 2020. One quarter of the eligible workforce in the NT and WA, and one-sixth in Qld was considered for estimating total benefits in proportion with Indigenous projects in the respective state/territory.

#these are rough but conservative estimates as the number of rangers working on fire management projects vary significantly due to seasonal availability of work, and cultural, social, or ceremonial responsibilities.

3.3.1.3. Opportunity costs of GHG emissions, soil C, and carbon sequestration in living tree biomass. Since 2013, savanna fire management has contributed significantly to GHG emissions abatement, and reducing the loss of carbon in soils and living tree biomass (Edwards et al. 2021). When accounting for the seven year pre-SB period, these represent an opportunity cost of USD 81.5 million/yr (Table 3). The opportunity cost of GHG emissions abatement alone was estimated at USD 40.4 million/ yr. Due to wildfires, the rate of soil erosion and related soil C loss—estimated considering topography, wildfire frequency, and land use (following Edwards et al. 2015)—represents an opportunity cost of USD 23 million/yr. The opportunity cost of C sequestration in living tree biomass, applying a conservative value of 0.6 tonnes of C sequestered/ ha/yr (following Murphy et al. 2021), was estimated at USD 17.9 million/yr (Table 3).

3.3.2. Non-marketable benefits: ES values using regional Australian studies

The value of ES delivered from fire management under SB projects (i. e. ~29 M ha area) was estimated at USD 10.54 billion/yr (applying standard ES valuation techniques, and accounting for 25% of total ES values). Of that total, the value of ES delivered on Indigenous lands was estimated at USD 7.29 billion/yr, pastoral lands at USD 1.61 billion/yr, and conservation USD 1.63 billion/yr (Table 4).

Areas under prescribed fire management in the NT delivered most benefits at USD 6.76 billion/yr, followed by Qld USD 2.11 billion/yr, and WA USD 1.66 billion/yr (Table 4). Prescribed fire management on Indigenous lands in the NT has delivered ES benefits estimated at USD 5.4 billion/yr, followed by WA ~ USD 1 billion/yr, and Qld USD 0.95 billion/yr. The value of ES delivered from pastoral and conservation lands in the NT under carbon projects was relatively modest, USD 0.35 and 1.05 billion/yr, respectively. In Qld, areas under fire management on pastoral lands accounted for ES benefits estimated at USD 1.08 billion/yr, followed by Indigenous lands USD 0.954 billion/yr. In WA, Indigenous and conservation lands delivered ES benefits estimated at USD 0.98 and 0.49 billion per year, respectively (Table 4).

Table 3
Opportunity costs of GHG emissions, Soil C loss, and C sequestration in living tree biomass, for indigenous, pastoral and conservation land uses.

Opportunity costs	Northern Territory	Queensland	Western Australia	Total value (USD in 2020)
Opportunity cost of annual GHG emissions (avg for 2006–2012 period, before implementing SBM)[1]				
Indigenous	16,396,487	4,301,206	4,186,752	
Pastoral	2,308,013	5,036,456	2,865,775	
Conservation	3,166,404	403,286	1,776,926	**40,441,305**
Opportunity cost of Soil C loss[2]				
Indigenous	7,929,790	1,298,239	4,865,232	
Pastoral	1,089,019	1,957,244	2,083,877	
Conservation	1,463,784	406,215	2,077,089	**23,170,489**
Opportunity cost of C sequestration in live tree biomass[3]				
Indigenous	6,443,655	2,062,155	2,683,533	
Pastoral	649,967	2,250,683	526,494	
Conservation	1,507,356	189,031	1,650,640	**17,963,515**
TOTAL opportunity costs				**81,575,309**

[1] Average GHG emissions ($NO_2$and CH_4) were calculated using SavBat v3 for 2006–2012 period when SBM was not available for the land managers. The opportunity costs were estimated applying recent C price (USD 10.4/tonne) from ERF auction in March 2020.

[2] Soil C loss due to wildfires was estimated applying losses considering topography (>5% slope) and LDS fire frequency, and the costs were estimated applying the recent C price (USD 10.4/tonne) from ERF auction in March 2020.

[3] C sequestration in living tree biomass was estimated for the area under each land use class, applying an average rate of 0.6 t/ha/yr, and a C price of USD 10.4/tonne from ERF auction.

Table 4
Annual value of ES from fire managed land area under active carbon projects above the 600 mm rainfall isohyet in tropical savannas of Australia.

			Northern Territory			Queensland			Western Australia		
Dominant land use	Ecosystem type	ES value (USD values in 2020)/ ha/yr	Ecosystem area (ha)	Total value of ES (USD M)	Fire management-related ES values (1/4th of the total ES values) (USD M)	Ecosystem (area in ha)	Total value of ES (USD M)	Fire management-related ES values (1/4th of the total ES values) (USD M)	Ecosystem (area in ha)	Total value of ES (USD M)	Fire management-related ES values (1/4th of the total ES values) (USD M)
Indigenous	Tropical rainforest	4158	3,722,094	15,476.47	3,869.12	223,864	930.83	232.71	57,113	237.48	59.37
	Woodlands	896	6,103,949	5,469.14	1,367.28	2,814,343	2,521.65	630.41	4,007,239	3,590.49	897.62
	Shrublands	448	137,537	61.62	15.40	44,837	20.09	5.02	0	0.00	0.00
	Grasslands	445	41,548	18.49	4.62	43,679	19.44	4.86	137,319	61.11	15.28
	Wetlands	2078	187,909	390.47	97.62	155,242	322.59	80.65	0	0.00	0.00
	Others	223	133,333	29.73	7.43	22,770	5.08	1.27	98,863	22.05	5.51
	Total		***10,326,370***	***21,445.92***	**5,361.48**	***3,304,735***	***3,819.67***	***954.92***	***4,300,534***	***3,911.12***	***977.78***
Pastoral	Tropical rainforest	4158	149,218	620.45	155.11	334,062	1,389.03	347.26	0	0.00	0.00
	Woodlands	896	760,209	681.15	170.29	3,147,395	2,820.07	705.02	843,741	755.99	189.00
	Shrublands	448	1,310	0.59	0.15	8,701	3.90	0.97	0	0.00	0.00
	Grasslands	445	107,256	47.73	11.93	14,697	6.54	1.64	0	0.00	0.00
	Wetlands	2078	23,621	49.08	12.27	33,367	69.34	17.33	0	0.00	0.00
	Others	223	-	0.00	0.00	68,642	15.31	3.83	0	0.00	0.00
	Total		***1,041,614***	***1,399.00***	**349.75**	***3,606,864***	***4,304.18***	***1,076.04***	***843,741***	***755.99***	***189.00***
Conservation	Tropical rainforest	4158	599,709	2,493.59	623.40	20,363	84.67	21.17	96	0.40	0.10
	Woodlands	896	1,679,798	1,505.10	376.27	277,680	248.80	62.20	1,745,909	1,564.33	391.08
	Shrublands	448	17,775	7.96	1.99	-	0.00	0.00	0	0.00	0.00
	Grasslands	445	15	0.01	0.00	4,016	1.79	0.45	882,174	392.57	98.14
	Wetlands	2078	100,811	209.49	52.37	397	0.82	0.21	0	0.00	0.00
	Others	223	17,527	3.91	0.98	478	0.11	0.03	17,078	3.81	0.95
	Total		***2,415,635***	***4,220.05***	**1,055.01**	***302,934***	***336.19***	***84.05***	***2,645,257***	***1,961.11***	***490.28***
TOTAL					**6,766.24**			**2,115.01**			**1,657.05**

*Carbon returns estimated @ AUD 16.14 or USD 10.4 (using a conversion rate on 19 May 2020) per tonne of abatement applying C price from ERF auction in March 2020.

4. Discussion

Implementation of incentivised fire management since 2013 on 29 M ha of land across north Australian savannas has transformed fire regimes resulting in at least 30% less GHG emissions, and better conservation and land management outcomes that are now delivering a diverse range of ES, estimated here at USD 10.54 billion/yr. This study underlines the socio-economic and environmental importance of incentivised fire management, especially for highlighting the diversity of benefits that flow to local, regional and global communities. Indigenous well-being benefits, estimated at USD 189 million/yr, carbon benefits at USD 10.65 million/yr, and the opportunity costs of SB, estimated at USD 81.6 million/yr, indicate the tangible value contributed by SB fire management. Contributions of SBM extending beyond GHG emissions abatement are well recognised for improving employment opportunities (Whitehead et al. 2005; Whitehead et al., 2009; Altman et al., 2011; Whitehead and Oliver, 2014; Russell-Smith and Sangha, 2018), socio-economic and health outcomes (Grieves, 2007; Burgess et al., 2009; Buergelt et al., 2017; Sangha et al., 2017a; Sangha et al., 2019a; Sangha et al., 2019b), and protecting biodiversity, water and soil resources (Legge et al., 2011; Ansell et al., 2020; Evans and Russell-Smith, 2020; Edwards et al., 2021). This is the first study of its kind to integrate socio-economic and ecological data to highlight the total value of a diverse range of benefits derived from effective and inclusive management of fire in savannas, as a means for informing development of appropriate social, educational, public, and health sector policy frameworks, in addition to GHG emissions abatement.

In sections below, we address various cost savings, socio-economic benefits of SB for Indigenous and wider regional and global communities, methodological limitations, and future propsects.

4.1. Cost savings for implementing SBM

In the absence of incentivised SBM, the costs of effective land and fire management to protect natural and cultural assets, and maintaining the flow of ES across the savannas are high and logistically challenging (Edwards et al. 2021). Applying average on-ground land management costs to Indigenous, pastoral and conservation lands of USD 499/km^2 (Sangha et al. 2019c), USD 168/km^2 (Russell-Smith et al., 2019a), and USD 553/km^2 (Sangha et al. 2017a) respectively, the total cost of managing highly fire-prone northern savannas was estimated at USD 12 billion/yr (Table 5). As an illustrative example, the Australian Government spends > USD 12.8 million/yr to manage Australia's premier savanna conservation reserve, the 20,000 km^2 World Heritage-listed Kakadu National Park, yet significant fire and associated biodiversity conservation management issues remain unaddressed (Woinarski and Winderlich 2014; Russell-Smith et al. 2017). If applied across the entire savanna landscape, these costs alone equate to a total of USD 1.28 billion/yr. In addition, substantial investment is afforded by State and Territory Governments to manage feral animals, weeds and other

Table 5
The cost of managing Indigenous, pastoral, and conservation land across the Australian tropical savannas (using management cost-related hard data from > 100 National Parks, IPAs, pastoral and other conservation lands [data obtained from relevant NP Departments in three studied jurisdictions, and Taylor et al., 2014).

Cost (USD values, in 2020) of managing land under	Northern Territory	Queensland	Western Australia
Indigenous	5,154,883,968	1,650,127,565	2,147,553,907
Pastoral	176,023,542	609,415,741	142,558,479
Conservation	1,337,412,899	167,704,262	1,464,791,277

environment related problems in respective jurisdictions. This clearly indicates that incentivised SB/Indigenous land management offers a more cost-effective approach when compared to conventional land/conservation management programs (Sangha et al. 2019d).

The opportunity cost of USD 81.6 million/yr (Table 3) illustrates the magnitude of benefits foregone in the seven year period prior to the implementation of the regulated SBM program in 2012, the remaning 75% of the eligible SBM region where SB projects are not being undertaken, and potentially very extensive fire-prone rangelands below the 600mm rainfall isohyet envelope outside the current SBM.

4.2. Socio-economic and cultural benefits of SB

Apart from SB carbon projects and ranger programs, economic opportunities for Indigenous communities are very limited in northern Australia (Altman and Kerins 2012; Sangha et al. 2020). SB projects have led to development of economic enterprises that support local Indigenous aspirations and cultural responsibilities, empower local communities, and provide many socio-economic benefits to the broader non-Indigenous community (Russell-Smith et al. 2019c).

SBM has greatly enabled Indigenous peoples in remote communities to strengthen their connections to their land, visit and maintain their cultural sites, and to regain control of their affairs, outside of governmental welfare restrictions (Russell-Smith et al. 2009; Whitehead and Oliver 2014; Social Ventures Australia, 2016; Sangha et al. 2017a). A consistent and reliable flow of funds from carbon contracts, as well as other government and philanthropic resources, has been instrumental in supporting other small innovative businesses/activities such as art centres, weed and feral animal control programs, rock art conservation, and bi-cultural school programs (Social Ventures Australia, 2016; Ansell et al., 2020; Cooke 2019; Warddeken Land Management Ltd., 2018-19).

Improved public health due to reduced bushfire impacts is an important outcome of SB projects, including benefits such as a healthier population, less pressure on public health systems, and better work outcomes (in contrast to widely reported wildfire-related health impacts such as asthma or cardio-vascular illness [Abram et al. 2021; Borchers Arriagada et al., 2020; Johnston et al. 2002; Johnston, 2020]). Increasing incidents of respiratory illness are directly correlated with the occurrence of bushfires in the NT (Johnston et al. 2002; Lewis and Corbett 2002). These impacts are particularly pronounced and concering for Indigenous communities in the north (Hanigan et al. 2008). The estimated costs of bushfires to Sydney health services were $8.2million (Deloitte Access Economics, 2014). Without doubt, a reduction in hot, extensive LDS fires across the north contributes to save significant health costs.

Internationally, the success of the SBM program has encouraged the Australian Government to support the development of SBM in southern Africa, particularly Botswana and surrounding countries (https://www.isfmi.org/portfolio-2). Using fire as a critical tool to sustainably manage natural and semi-natural fire-prone rangelands and savanna landscapes is increasingly being recognised globally (Ryan et al., 2013; Lipsett-Moore et al., 2018; Mistry et al., 2019; Moura et al., 2019; Russell-Smith et al., 2021; https://globalrangelands.org/topics/rangeland-ecology/fire-tool-land-management). North Australian experience demonstrates that similar wide-reaching economically beneficial approaches to manage wildfires, biodiversity, land degradation, pests, and weeds can be developed in consultation with local and Indigenous communities across the globe.

4.3. Limitations of ES valuation methodology

Two methodological concerns are often raised with respect to ES valuations: 1. the importance of ES monetary assessments; 2. the legitimacy of the basic value transfer (BVT) method, such as applied here. For assessing ES values, Costanza et al. (1997; Costanza et al., 2014), de Groot et al. (2012), and others have emphasised that ES estimates can help us understand the importance of managing natural and semi-natural systems typically ignored in conventional policy development contexts. Realising the monetary value of ES directly informs policy regarding the economic significance of preserving natural resources towards a market economy. For example, at registered SBM project sites, the proportion of land area affected by wildfire has halved (from 36% to 18%), on average, when comparing pre-project (2006-12) with implementation (2013-19) periods (Edwards et al. 2021). Such achievement underlines ancillary benefits accruing to the safety and security of agricultural production systems, infrastructure, and other assets, as well as many ecological benefits (as highlighted by Edwards et al. 2021, and others listed in Appendix 1). Overall, our estimated ES valuation of USD10.54 billion/yr highlights the value of prescribed fire management for regulating climate, water and soil resources, biodiversity and other ecological functions, for underpining all regional agricultural and related production systems, including: free-range beef industry, worth >USD 6.4 billion/yr across northern Australia (Meat and Livestock Australia 2019); horticulture and crops, worth USD 160 million/yr (NT Farmers 2015); and fisheries and related industries, worth USD 140 million/yr (Sangha et al. 2019d), in the NT alone. Such critical links between maintaining ES and long-term sustainability of major economy sectors have been highlighted recently by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES, 2019), and earlier by the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005).

Regarding the application of the BVT technique to interpret the value of ES (Boyle et al. 2009; Plummer 2009; Rosenberger and Loomis 2017; Rogers et al. 2019), we have used only local and regional values relevant to Australian savannas, and conservatively attributed a quarter of maintenenace of ES values to fire management. However, our well-being estimates, although relatively small, reflect the actual value of fire management for local people. It is important to note that Indigenous well-being benefits extend far beyond the three welfare sectors considered here. For example, self managed land-based opportunities contribute to reduce domestic violence, incarceration rates, and other social and health problems predominant in remote Indigenous communities, costing >USD 6.4 billion/yr to Australian and Territory/State Governments (Australian Law Reform Commission (ALRC) 2017; Hamburger et al. 2016; PwC's Indigenous Consulting 2017; Sangha et al. 2019c). Jones et al. (2018) provided a 'proof of concept' stating that Indigenous Rangers working on *country* achieve much better life satisfaction and family well-being than other unemployed (non-Rangers) members in remote central Australian communities. We suggest that a parallel non-monetary assessment of ES in the future, conducted through workshops or focus group discussions with local Indigenous peoples, will improve these estimates and lend further support for holistic policy development.

4.4. Future prospects

Establishing equitable financial arrangements such as Payments for Ecosystem Services (PES) in consultation with Indigenous peoples and other relevant stakeholders is important not only for achieving conservation but also for business development and climate change mitigation outcomes. In northern Australia, PES arrangements can assist to address the Australian Government's 'Developing the North' and 'Closing the Gap' Indigenous development agendas. The latter is an ongoing national program worth >USD 15 billion/yr established since 2008, with little success to date [CoA 2020]). As well, PES can self-empower remote Indigenous peoples, and ensure the delivery of ES to enhance the well-being of local and wider communities. The economic rationale for such initiatives is discussed in detail by Sangha et al. (2019b), identifying multiple benefits and cost-savings for the Australian Government (USD 2.56-11.5 billion per yr).

Given that >60% of the savanna landscape is managed by Indigenous stakeholders, the value of fire management in terms of Indigenous well-being and carbon benefits, estimated at USD 198 million/yr (Table 2), indicates that there are potentially huge benefits for the Australian Government to invest in further development and expansion of SBM and similar land management programs across the entire north where biodiversity and Indigenous cultural assets are highly prone to wildfires (Russell-Smith et al., 2019b; Russell-Smith et al., 2019c; Sangha et al., 2019b). Such an investment is also justified if we apply a social cost of carbon at USD 56/tonne of abatement for savannas, calculated at USD 401 million, using recent figures (£51 per tonne C, at a conversion rate of 0.9, as of 30 May 2020) from the UK's Department of Business, Energy, and Industrial Strategy (2019). Realising the SB program's contributions beyond GHG emissions abatement is an important first step, which can then help progress its application to broader social, cultural and natural resource management contexts across northern Australia and worldwide.

Currently, there is ongoing development in Australia towards a co-benefits framework that aims to recognise the integrated value of socio-economic, cultural, and other environmental benefits, in addition to GHG emissions abatement (Aboriginal Carbon Foundation 2019; Queensland Land Restoration Fund 2019). This will add to the carbon price by incorporating co(core)-benefits for future land management investments. Such an inclusive, co-developed framework will build confidence and reliability in developing sustainable and innovative land management enterprises, attract international investors, and particularly philanthropic groups focused on achieving conservation and social benefits (Salzman et al. 2018).

5. Conclusion

SBM projects in northern Australia have effectively demonstrated that stewardship arrangements for managing fires can deliver many successful and quantifiable ES outcomes, including significant reduction of GHG emissions and wildfires, enhancing the well-being of local communities, and supporting social and built infrastructure development across the region (Russell-Smith et al. 2015; Ansell et al., 2020; Russell-Smith et al., 2019b; Russell-Smith et al., 2019c; Sangha et al., 2017a; Sangha et al., 2019a).

Estimating ES values from a vast, largely Indigenously managed landscape, with a majority of benefits beyond any market measures, is a challenge but our comprehensive approach applying a mix of the standard BVT technique and a locally-relevant well-being assessment, offers a good start but does not pretend to be exhaustive.

Expanding SBM to the entire savanna region—an area of high conservation significance, but sparse population (Woinarski et al. 2007; Russell-Smith and Sangha 2018)—would provide significant further benefits. Other feasible regional complementary approaches include: enhanced sustainable land use practices whereby pastoral land managers match the real carrying capacity of production to supporting natural systems (Russell-Smith and Sangha 2018); improved pest and weed control (Radford et al. 2020); providing better protection for seasonally critical waterbodies (Warddeken Land Management Ltd., 2018-19); sustainable management and exploitation of coastal and freshwater resources (Sangha et al. 2019d); support for Indigenous and local cultural and ceremonial activities (Russell-Smith et al. 2013); and continuing to adapt and apply traditional knowledge systems for effective land management (Russell-Smith 2016; Whitehead et al. 2005). Such initiatives, when encouraged by private, state and international actors, could help achieve Sustainable Development Goals for many local and Indigenous communities both regionally and globally, and effectively help address climate change, biodiversity decline, land degradation, and potentially many other serious environmental concerns that we face today.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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