Final report

Development of carbon sequestration methods for savanna fire management in Northern Australia

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Abstract

This project aimed to develop a revised method for the sequestration of carbon through savanna fire management in the low rainfall area of Northern Australia (600-1000mm average annual rainfall zone). The existing Savanna Burning Methodology accredited under the Commonwealth's Emissions Reduction Fund (ERF) concerns (a) abatement (reduction) of greenhouse gases (methane, nitrous oxide), (b) sequestration of carbon in non-living debris (litter), through the implementation of strategic fire management essentially to reduce the extent, intensity, and thereby resultant emissions, from late dry season wildfires. That methodology applies to around 1.2 million km^2 of Northern Australian savannas, in two contiguous Rainfall Zones, High (>1000 mm y-1) and Low (1000 – 600 mm y-1). These zones are broadly described by the region stretching north from Broome in the west, to Townsville in the east, less the Queensland Wet Tropics and substantial areas of pastorally productive grasslands that are ineligible under this ERF methodology. If the revised method developed through this project is accepted, the potential for landholders in Northern Australia to earn income from savanna fire management could be increased.

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Executive summary

Background

The currently available Savanna Burning methodology accredited under the Commonwealth's Emissions Reduction Fund (ERF) concerns (a) abatement (reduction) of greenhouse gases (methane, nitrous oxide), (b) sequestration of carbon in non-living debris (litter), through the implementation of strategic fire management essentially to reduce the extent, intensity, and thereby resultant emissions, from late dry season wildfires. The development of new carbon accounting methodologies for savanna fire management based on carbon sequestration will dramatically increase the viability of savanna fire management projects in the northern rangelands and provide new opportunities for sustainable sources of income in the longer term for pastoral properties. Funding of this research phase was supported by significant Investment involving the MLA Donor Company in partnership with the Indigenous Land & Sea Corporation and The Nature Conservancy.

Objectives

Building on substantial investment associated with the development of the original Savanna Burning abatement methodology, this project aimed to support the development of:

- A detailed scientific assessment of the potential for additional storage of carbon in Living Tree Biomass (LTB) through implementing strategic fire management in fire-prone savanna landscapes—with that assessment to be provided as a scientific paper submitted to an appropriate international journal for peer review.
- Developing a roadmap for incorporation of LTB carbon sequestration in future ERF Savanna Burning methodologies—with development of the roadmap involving key institutional stakeholders and submitted as part of final reporting requirements.

Methodology

A detailed scientific assessment was undertaken to potential for additional storage of carbon in Living Tree Biomass through implementing strategic fire management in fire-prone savanna landscapes. Plot locations were chosen to sample the strong latitudinal rainfall gradient in the central region of the tropical savannas. The statistical program R was used for all statistical analysis and a simple individual demographic model was implemented in R to stimulate tree recruitment.

Results/key findings

The scientific assessment demonstrated strong support for the inclusion of a LTB sequestration component in future development of ERF-accredited Savanna Burning methodologies. Research into the potential for additional storage of carbon in living tree biomass through implementing strategic fire management in fire-prone savanna landscapes has demonstrated that:

- Significant potential exists for developing an ERF-accredited methodology in the next few years for managing fire-carbon stocks in prone woody vegetation types across the Northern Savannas.
- A roadmap was developed involving all current partners and the engagement of key Commonwealth agency stakeholders.

Benefits to industry

An updated methodology would provide substantial economic and environmental benefits for northern savanna pastoral enterprises operating especially in marginally productive, fire-prone, woody landscapes.

Future research and recommendations

Although an updated Savanna Burning methodology incorporating a Living Tree Biomass component is unlikely to be available until 2022/2023 assuming a successful development pathway, implementing a preparatory R&D and extension program could be implemented to better inform Northern Savanna pastoral stakeholders of associated enterprise opportunities and challenges.

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1. Background

The development of new carbon accounting methodologies for savanna fire management based on carbon sequestration will dramatically increase the viability of savanna fire management projects in the northern rangelands and provide new opportunities for sustainable sources of income in the longer term for pastoral properties.

Effective savanna fire management reduces the impacts of wildfires on pastoral production, assets and infrastructure, biodiversity and other environmental values, thereby improving natural capital and rangeland condition more generally. This will lead to productivity improvements and increases in profit for pastoral enterprises. Further, with the introduction of sequestration methodologies, there will be increased incentives for all landholders in the northern rangelands to conduct savanna fire management on their properties, regardless of tenure. This is likely to lead to improved landscape scale fire management and increased cooperation amongst neighbours.

The currently available Savanna Burning methodology accredited under the Commonwealth’s Emissions Reduction Fund (ERF) concerns the abatement (reduction) of greenhouse gases (methane, nitrous oxide) through the implementation of strategic fire management essentially to reduce the extent, intensity, and thereby resultant emissions, from late dry season wildfires. That methodology applies to ~1.2 million km2 of Northern Australian savannas, in two contiguous Rainfall Zones, High (>1000 mm y-1) and Low (1000 – 600 mm y-1), broadly described by the region stretching north from Broome in the west, to Townsville in the east, less the Queensland Wet Tropics and substantial areas of pastorally productive grasslands that are ineligible under the ERF methodology.

The present project aimed to increase the potential for landholders in Northern Australia to earn income from savanna fire management through supporting the development of future ERF methodologies incorporating additional sequestration of carbon in Living Tree Biomass (LTB).

The project was undertaken by the Darwin Centre for Bushfire Research, Charles Darwin University (CDU), with coordination and project management support from the North Australia Indigenous Land & Sea Management Alliance Ltd (NAILSMA). Funding was contributed under an equal partnership arrangement involving the MLA Donor Company, Indigenous Land & Sea Corporation, and The Nature Conservancy.

2. Objectives

The LTB research component aims to develop a robust methodology for carbon accounting based on a statistical modelling approach using data observations over 20 years from the 130 monitoring plots in the higher rainfall region used in previous assessments (Murphy et al. 2009, Cook et al. 2015), plus additional observations over at least 5 years from 260 plots in the lower rainfall region (located in the NT/QLD Gulf of Carpentaria, and the Kimberley). This will include field sampling of at least an additional 60 plots from low rainfall areas to finalise the dataset. As for previous analyses undertaken on the high rainfall dataset, a minimum of 5 years of observations is required to assess fire regime effects on tree biomass dynamics. This will include undertaking a final analysis of assembled available higher rainfall Three Parks data and lower rainfall plot data to derive statistical models describing relationships between a minimum set of variables including savanna tree biomass parameters (stem recruitment, increment and mortality), fire regime parameters (e.g. fire frequency, severity), and mean annual rainfall and/or latitude.

CDU research work outputs:
1) Project Commencement 14th March 2018
   a. Field sampling
   b. Data collation, cleaning and refining ready for analysis
   c. Plans for initial technical workshop

2) Mid-Term Report 31st August 2018
   a. Outcomes of technical workshop 1
   b. Update on ongoing data analysis and refinement
   c. Plans for second technical workshop

3) Final Report 30th April 2019
   a. Outcomes of technical workshop 2
   b. Final report on MLA template
   c. submission of paper(s) for publication in peer-reviewed scientific journal/s by June 2019 describing: Research and analysis work of the project, and a formal framework for implementing a LTB methodology

The further development and revision of the data and conclusions from this research project will be conducted by the DoE as outlined in the proposal. There is very close collaboration between project proponents and the federal Department of Environment on previous methodologies. The DoE need this research to complete the two methodologies for submission to the Emissions Reduction Assurance Committee."

All technical objectives were met fully with minor adjustments. With reference to those agreed objectives we specifically note:

- Data for a further 70 plots incorporating at least five years of observations in the Lower Rainfall Zone were assembled, as against the 60 plots specified
- For analysis, based on critical assessment of the integrity of the Higher Rainfall Zone (HRZ) dataset, 126 plots were used versus the 130 plots originally specified
- Both scientific workshops were held as proposed, involving participation of key Commonwealth ERF agency personnel, national and international scientific colleagues, industry and funding partners
- All assembled data have been made available to the Commonwealth's National Greenhouse Gas Inventory team for independent assessment and utilisation in the NGGI's FullCam modelling
- Final Milestone reporting documents were completed as required, including (a) submission of a scientific paper to an appropriate and leading international journal for peer review (Appendix 9.1), and (b) an agreed Roadmap Framework outlining future R&D requirements (Appendix 9.2)

However, we also observe that final reporting was unavoidably delayed given the very late start to fieldwork (refer CDU Research output1 above) associated with extensively delayed signing (by over a year and a half) of all agreement documents by contributing partners.

3. Methodology

A detailed scientific assessment was undertaken to potential for additional storage of carbon in Living Tree Biomass through implementing strategic fire management in fire-prone savanna landscapes. Plot locations were chosen to sample the strong latitudinal rainfall gradient in the central region of the tropical savannas. The statistical program R was used for all statistical analysis and a simple individual demographic model was implemented in R to stimulate tree recruitment

3.1 Living Tree Biomass sequestration research component

Full details are given in Appendix 8.1 the draft manuscript “Recruitment, growth and mortality of trees in Australian savannas: predicting effects of fire management on tree biomass” Whitehead et al. submitted to Ecological Monographs in December 2019. Only salient details are summarised below.

The LTB research component aimed to develop a robust methodology for carbon accounting based on a statistical modelling approach using data observations over 20 years from 126 monitoring plots established in the higher rainfall zone (HRZ—>1000 mm y-1) and as used in previous assessments (Murphy et al. 2009, Cook et al. 2015), plus additional observations of up to 12 years from 330 plots in the lower rainfall zone (LRZ—1000 – 600 mm y-1) located in the NT/QLD Gulf of Carpentaria, and the Kimberley. All plots were subject to non-experimental (i.e. ambient) fire and ambient low intensity grazing regimes, and located in situations devoid of flammable exotic grasses. Fire occurrence and severity observations typically were undertaken annually on all plots. Observations of stem growth (based on diameter at breast height—DBH), height, and health were undertaken on tagged stems every 5 years for plots in the HRZ, and annually in the LRZ.

Detailed statistical analyses were conducted on the assembled data set (including 12,344 tagged trees) in order to characterise relationships between fire regimes and key demographic rates of trees: recruitment into large sapling size classes (≥5 cm diameter at breast height); stem diameter growth; and mortality. These relationships were then used to build a process-explicit demographic model of an Australian savanna tree population.

3.2 Developing the Roadmap

The ongoing LTB sequestration development roadmap was developed as part of undertaking two programmed workshops, in November 2018 and July 2019, involving scientific (including international colleagues), Commonwealth agency, funders, and industry stakeholder participants). A draft Roadmap document was circulated after the July 2019 workshop to participants for their comments before finalisation.

4. Results

4.1 Living Tree Biomass sequestration research component

Full details are given in Whitehead et al. (submitted), refer Appendix .1—only salient details are summarised below.

- Mortality—Tree mortality rate displayed a clear unimodal relationship with stem diameter, with mortality greatest in the smallest and largest stems. Mortality increased with increasing fire frequency, and this effect became more pronounced as severity increased (i.e. mild < moderate < severe).

- Recruitment—Only one fire variable was related to recruitment rate, severe fire frequency, with this variable included in all well-supported models. The models suggested that recruitment was reduced as the frequency of severe fires increased. Recruitment was also clearly influenced by mean annual rainfall (positively related) and vegetation class.
- Stem growth—Stem diameter increment was clearly affected by the frequency of mild, moderate and severe fires. All three of these variables were included in all well-supported models of stem diameter increment. There was evidence of a slight unimodal relationship between fire frequency and diameter increment, with diameter increment tending to peak when the frequency of moderate and severe fires was around 0.25 fires year–1. The apparent peak may be an artefact of the quadratic model. At fire frequencies greater than this, diameter increment declined markedly, with the effect most pronounced as severity increased (i.e. mild < moderate < severe). There was also strong evidence of a longer-term reduction in diameter increment following severe fires. Time since severe fire was a highly significant term when added to the best model. Predicted diameter increment increased linearly by a relatively modest 0.023 mm year–1 for each year after the last severe fire in the plot, with no indication of a plateau after 25 years. In contrast, adding time since last mild or moderate fire did not improve the best model.

Demographic model—

- The demographic model, integrating the relationships we have identified between fire regime variables and tree demographic rates, suggests that frequent moderate to severe fires lead to large reductions in tree abundance over time. Annual severe fires reduce tree basal area and total biomass to near-zero (≥99% reduction relative to unburnt) at long-term equilibrium, in all three vegetation classes modelled: Open forest (mixed grasses), Woodland (mixed grasses) and Open woodland (mixed grasses). Annual moderate fires reduce tree basal area and total biomass by ≥41% (relative to unburnt) in Open forest (mixed grasses), ≥61% in Woodland (mixed grasses) and ≥75% in Open woodland (mixed grasses). However, annual mild fires have a much more modest effect: reducing tree basal area and total biomass by 2–47% (relative to unburnt).
- Although frequent severe and moderate fires have a large negative effect on tree abundance, the relatively low frequencies of moderate and severe fires experienced by our monitoring plots have a relatively modest effect overall. For example, Woodland

(mixed grasses) was the most frequently burnt vegetation class, with mild, moderate and severe fires experienced at a rate of 0.38, 0.16 and 0.04 fires year–1, respectively. The demographic model predicted that this would lead to a 19% reduction in both basal area and total biomass (relative to unburnt).

- The effect of ambient fire regimes on tree abundance was greatest, in relative terms, in the least productive vegetation classes (i.e. Open woodland > Woodland > Open forest). At the most productive open forest/mixed sites, tree abundance was not suppressed by the ambient fire regime, relative to unburnt. In this vegetation class, under this fire regime, tree basal area is expected to be at a water-limited upper bound. In marked contrast, the demographic rates estimated from our monitoring data, suggest that Woodland (mixed grasses) and Open woodland (mixed grasses) could be expected to have tree basal area well below the water- limited upper bound under ambient fire regimes.
- All three of the demographic processes in the model (mortality, recruitment, growth) made a substantial contribution to the negative effect of ambient fire regimes on tree basal area and total biomass. The effect of a fire-driven reduction in recruitment was slightly larger than the effect of fire-driven mortality. The effect of a fire-driven reduction in growth was smallest of the three demographic effects, though still a substantial contributor to the overall impact of fire.
- The demographic model predicts that a realistic improvement in fire management would result in a substantial increase in tree abundance over time, in at least some vegetation classes. In Woodland (mixed grasses), total tree biomass (including belowground biomass) is predicted to increase most, by 21.7 t DM ha–1 (18%) once a long-term equilibrium has been reached. However, our model predicts that such an equilibrium would take a very long time to reach: somewhere in the order of 200 years. Even so, a rapid increase in total tree biomass (12.9 t DM ha–1) in the first century following a shift in fire regimes due to improved fire management, would see Woodland (mixed grasses) sequester about 6.3 t C ha–1.
- In both the most productive and least productive vegetation classes (Open forest [mixed grasses] and Open woodland [mixed grasses], respectively), increases in tree abundance, in absolute terms, due to improved fire management are likely to be much less than in woodland/mixed. In open forest/mixed, total tree biomass is predicted to increase by just 1.4 t DM ha–1 (<1%) once a long-term equilibrium has been reached. The small magnitude of this increase reflects that under ambient fire regimes, Open forest (mixed grasses) is already close to the water-limited upper bound to tree basal area. In Open woodland (mixed grasses), total tree biomass is predicted to increase by 6.8 t DM ha–1 (39%) once a long-term equilibrium has been reached.

4.2 Developing the Living Tree Biomass sequestration development Roadmap

The final agreed roadmap is presented in full in Appendix 8.2

5. Conclusion

5.1 Key findings

This initial R&D program has demonstrated the necessary scientific underpinnings for the development of an updated ERF-accredited Savanna Burning methodology accounting for carbon sequestration in Living Tree Biomass. Development of an accompanying agreed Roadmap sets out further R&D components which need to be undertaken in preparation for the development of an accredited ERF methodology.

Significant potential exists for developing an ERF-accredited methodology in the next few years for managing fire-carbon stocks in prone woody vegetation types across the Northern Savannas.

An updated methodology would likely provide substantial economic and environmental benefits for northern savanna pastoral enterprises operating especially in marginally productive, fire-prone, woody landscapes.

5.2 Benefits to industry

Although an updated Savanna Burning methodology incorporating a LTB component is unlikely to be available until 2022/2023 assuming a successful development pathway, as noted above MLA might usefully consider implementing a preparatory R&D and extension program to better inform Northern Savanna pastoral stakeholders of associated enterprise opportunities and challenges.

6. Future research and recommendations

It is recommended that MLA consider the undertaking of (a) a preparatory R&D program to critically examine the physical landscape and enterprise conditions under which an updated Savanna Burning methodology might be of benefit to pastoral enterprises in different Northern Savanna regions, and (b) based on that research, implement an extension program in order to better inform regional pastoral stakeholders about opportunities and potential benefits, costs and challenges associated with implementing a commercial Savanna Burning project as part of a diversified pastoral enterprise.

As noted above, the present project effectively has addressed all research challenges and objectives as agreed. Based on the findings of the submitted scientific paper (Appendix 8.1), and especially the Framework Roadmap (Appendix 8.2), the major foreseen challenges associated with development of an updated Savanna Burning methodology incorporating a LTB component are:

- Climate change issues (especially CO2 fertilisation, increased temperature, possibly more variable rainfall) need to be considered In future modelling of fire regime effects
- The longevity of carbon pools involving standing dead biomass needs to be accounted for in the methodology
- Further work is required to address seasonal inputs to fuel loads (e.g. leaf litter, woody debris), and enhanced quantification of fine fuel (litter, grass) and coarse woody fuel accumulation generally

- Given the importance of severe fire effects on LTB stocks as demonstrated in Appendix 9.1, a major challenge is to develop a robust remote sensing approach for mapping fire severity—this would have the added benefit of replacing the arbitrary seasonal cut-off date (31 July) which is currently used to discriminate between relatively less severe fires in the early dry season versus typically more severe late dry season fires
- Integrating above components in a workable and transparent new Savanna Burning methodology combining emissions abatement and carbon sequestration components

Agreed funding for ongoing a Phase 2 R&D program addressing issues identified in the Roadmap (Appendix 8.2) has been approved by a partnership involving the Indigenous Land & Sea Corporation, The Nature Conservancy, and ConocoPhillips Ltd. It is the intention of the ongoing R&D partnership to keep MLA informed of all developments.

Based on the likelihood of expanded Savanna Burning opportunities derived from an updated methodology, of more immediate relevance to MLA and industry partners is the need to undertake preparatory research, extension, and engagement activities with the Northern Savanna pastoral sector. This would involve a detailed assessment of the economic opportunities that might be available to pastoral enterprises in different regional landscape settings. In the recent past MLA has undertaken an analogous assessment focusing on a broader range of carbon market opportunities (Wiedemann et al. 2016). Despite industry scepticism about the value of diversified enterprise opportunities concerning carbon markets generally, an updated Savanna Burning methodology may be attractive to enterprises operating in marginally productive settings given the dire financial circumstances facing many in the northern pastoral industry (McLean et al. 2014; Holmes et al. 2017; Russell-Smith and Sangha 2018, 2019).

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8. Appendix

8.1 DRAFT manuscript submitted to Ecological Monographs, December 2019 - Recruitment, growth and mortality of trees in Australian savannas: predicting effects of fire management on tree biomass

Submitted as a separate file.

8.2 Developing the Living Tree Biomass sequestration development Roadmap

Submitted as a separate file.

Appendix 8.2: Project Roadmap

Framework for implementing a Living Tree Biomass Sequestration method as part of ongoing revision and updating of the current (2018) Savanna Burning methodology

final updated version December 2019

Report prepared by:

Darwin Centre for Bushfire Research

Charles Darwin University

For:

North Australian Indigenous Land & Sea Management Alliance Ltd

As part of contractual Milestone reporting requirements to:

Indigenous Land & Sea Corporation's Australian Indigenous Agribusiness

Meat & Livestock Australia's MLA Donor Company Ltd

The Nature Conservancy

1. Background

This “framework report” is a required deliverable as part (b) of Milestone 4 of the project:

Key research to assist the development of Emissions Reduction Fund carbon sequestration methods for savanna fire management in Northern Australia

in relation to the contractual agreement between the North Australian Land and Sea Management Alliance Ltd (NAILSMA), and funding partners—(a) the Indigenous Land & Sea Corporation’s (ILSC) Australian Indigenous Agribusiness (AIA); (b) Meat & Livestock Australia’s (MLA) MLA Donor Company Ltd; and (c) The Nature Conservancy.

The scope of this report extends upon that originally required (i.e. Milestone 4(b)—"describing…a formal framework for implementing a Living Tree Biomass sequestration method”), as it sets out a pathway for reporting both on the status of the Living Tree Biomass (LTB) sequestration method, as well as on other related matters addressing ongoing revision and updating of the current (2018) Savanna Burning methodology[1] as part of renewed Phase 2 contractual arrangements[2]. Specifically, these new contractual arrangements require finalisation of the scientific bases both for the LTB sequestration method, as well as addressing:

- analysis of remnant tree biomass decay after stem death
- availability and reliability of national-scale tree biomass mapping products
- assessment of fuel load accumulation over the seasonal cycle, accounting especially for late dry litterfall inputs
- methodological issues associated with inputs and decay of coarse woody debris fraction in fuel loads
- remotely-sensed methods to assess fire severity—both for direct application in an LTB method, as well as potentially replacing the early / late dry seasonal cut-off date of 1 August as applies in the current (2018) methodology.

2. Development pathway

2.1 National Greenhouse Gas Inventory (NGGI) and Emissions Reduction Fund (ERF) process

At the project methodology development workshop held in Darwin, July 2019, undertaken in fulfilment of Milestone 3 of the current contractual arrangement, Mark Newnham of the Department of Environment & Energy (DEE) outlined the formal conceptual process for ERF methodology development (as summarised in Fig.1). *Note that the timeframes provided in Fig.1 are conceptual only and, as noted below, do not represent the actual timeframes being addressed by the Phase 2 project*.

As illustrated in the schematic, the process for inclusion of LTB as a component of an updated and revised Savanna Burning methodology is at an early stage in the assessment and implementation

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[1] CoA (Commonwealth of Australia) 2018. Carbon Credits (Carbon Farming Initiative—Savanna Fire Management—Emissions Avoidance) Methodology Determination 2018. Dept Environment and Energy, Australian Government, Canberra.

[2] Phase 2 Project Title: Finalising the Savanna Burning Living Tree Biomass (LTB) methodology, and updating and refinement of current Emissions Abatement and Dead Organic Matter methods

process—specifically, the undertaking and publishing of the fundamental scientific research, and early evaluation by the National Inventory team.

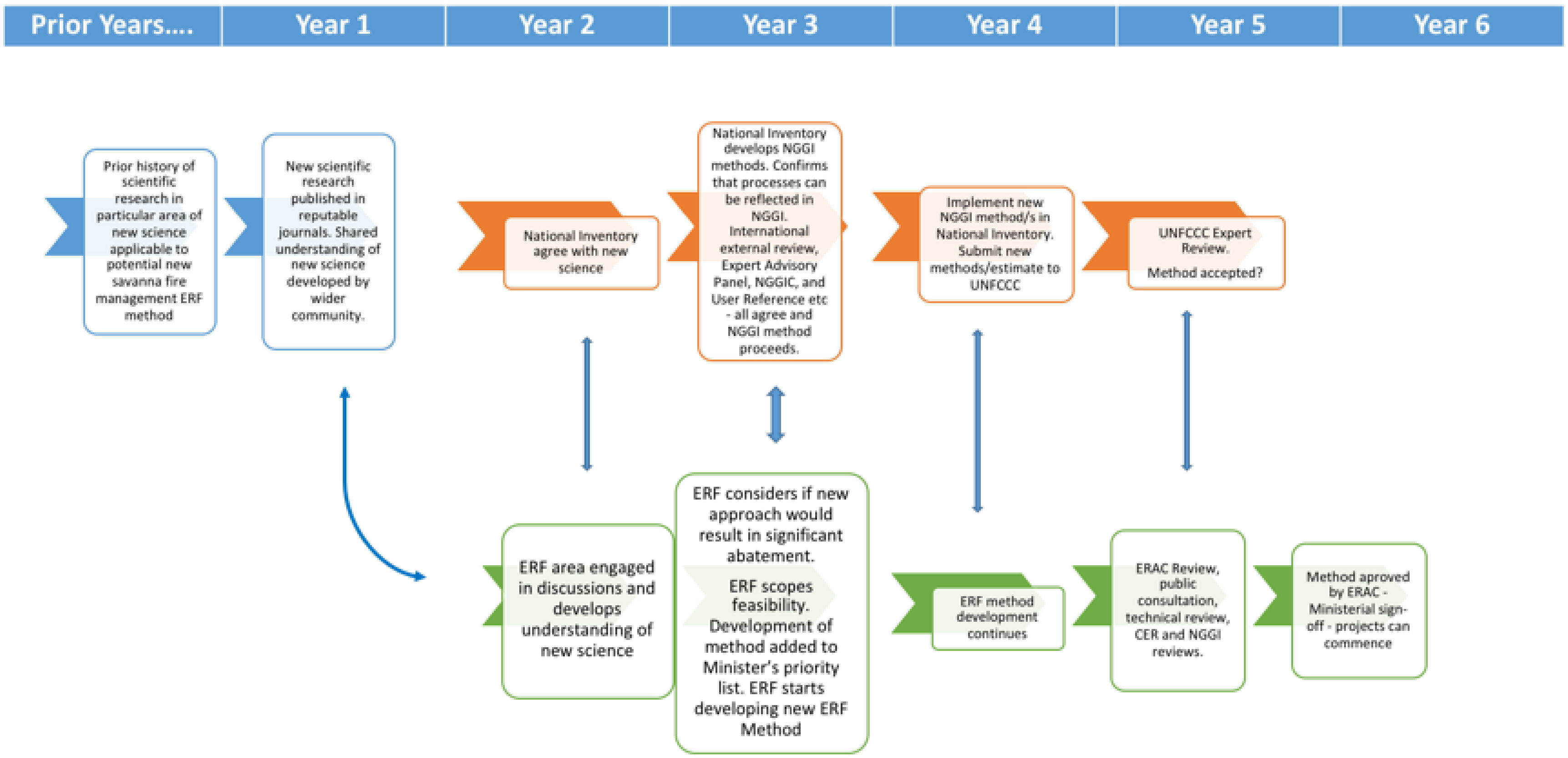
Further steps in the process are reliant firstly on that initial assessment, subsequent discussions with the ERF and assessments by pertinent international bodies, and ultimately independent review and evaluation by the Emissions Reduction Assurance Committee (ERAC).

In relation to the 'framework' process outlined in following sections, key timeframes for the development and implementation of an updated and revised savanna Burning method which incorporates an LTB component, comprise:

- *by December 2019*—submission of scientific papers describing basis of effects of fire regime on LTB to appropriate international journals for review
- *by April/June 2020*—submission of ancillary papers and reports addressing issues relevant to proposed LTB method (e.g. fate of 'standing dead trees'), and related Savanna Burning methods issues (e.g. seasonal litter fall; fire severity mapping)
- *by mid 2020*—preliminary evaluation by NGGI team complete and, if deemed warranted, (a) ongoing work on inclusion of Savanna Burning LTB processes in National Accounts, (b) ongoing discussions with ERF concerning Savanna Burning methods development
- *by end of 2021 (or thereabouts)*—assuming above processes support implementation of a Savanna Burning method incorporating LTB sequestration, submission of a revised and updated draft method for independent review by the ERAC

Note that the timeframes proposed above reflect current Phase 2 project commitments as at December 2019.

Fig. 1: Process map for new savanna science → inclusion in National Inventory → development of new ERF Method



Prior history of scientific research in particular area of new science applicable to potential new savanna fire management ERF method

New scientific research published in reputable journals. Shared understanding of new science developed by wider community.

National Inventory agree with new science

National Inventory develops NGGI methods. Confirms that processes can be reflected in NGGI. International external review, Expert Advisory Panel, NGGIC, and User Reference etc - all agree and NGGI method proceeds.

Implement new NGGI method/s in National Inventory. Submit new methods/estimate to UNFCCC

UNFCCC Expert Review.

Method accepted?

ERF area engaged in discussions and develops understanding of new science

ERF considers if new approach would result in significant abatement.

ERF scopes feasibility. Development of method added to Minister's priority list. ERF starts developing new ERF Method

ERF method development continues

ERAC Review, public consultation, technical review, CER and NGGI reviews.

Method aproved by ERAC - Ministerial sign-off - projects can commence

2.2 Savanna Burning R&D pathway

The current and new contractual arrangements, and additional tasks concerning the furnishing of relevant available datasets to the National Inventory team as agreed at the July 2019 workshop, collectively set out 11 core tasks to be addressed over the next 12 or so months (ending mid-2020). The timeframes for the undertaking and completion of these core tasks are summarised schematically in Table 1.

Brief descriptions of respective tasks are provided in following sections, where numbering of tasks follow the numbering as set out in Table 1.

3. Core Tasks—as listed in Table 1

(1) Datasets provided to NGGI

1.1 LTB dataset—all tree stem and fire regime data from 236 plots (451 including grouped subplots) across the savanna rainfall gradient to be provided to NGGI team—this has been undertaken (September 2019)

1.2 Fuel accumulation and related datasets for high (>1000 mm mean annual rainfall) and low (1000 – 600 mm mean annual rainfall) rainfall zones—these datasets, already incorporated in earlier (2012, 2015) and current (2018) Savanna Burning methodologies, to be provided to NGGI team—this has been undertaken (September 2019)

(2) Living tree Biomass science basis

2.1 Paper: data description, statistical analysis—This paper, coordinated primarily by Prof Peter Whitehead and Assoc Professor Brett Murphy, deals with fire effects on the dynamics of trees in savannas. Rates of growth in size (stem diameter), mortality and recruitment to the 5 cm diameter size class will be related to the frequency and severity of fires. The final version of this paper is to be submitted to *Ecological Monographs*, in mid-December 2019. As at time of writing (mid-December 2019) the Title and Abstract of the finished paper is as follows:

Recruitment, growth and mortality of trees in Australian savannas: predicting the effects of fire management on tree biomass

Peter J. Whitehead, Brett P. Murphy, Jay Evans, Cameron P. Yates, Andrew C. Edwards, Harry J. MacDermott, Dominique Lynch and Jeremy Russell-Smith

Abstract: Tropical savannas are characterised by high primary productivity and high fire frequency, such that much of the carbon captured by savanna vegetation is rapidly returned to the atmosphere. Hence, there have been suggestions that management-driven reductions in fire frequencies and/or intensities in savannas might significantly increase carbon storage in tree biomass. We analysed a large, long-term tree monitoring dataset (236 plots, monitored for 3–24 years, including 12,000 tagged trees) from the tropical savannas of northern Australia, in order to characterise relationships between fire regimes and key demographic rates of trees: recruitment into large sapling size classes (≥5 cm diameter at breast height); stem diameter growth; and mortality. We used these relationships to build a process-explicit demographic model of an Australian savanna tree population. We found that savanna fires, especially high-severity fires, significantly reduce tree

recruitment, survival and growth. Despite these negative effects of fire on the demographic rates, tree biomass appears to be suppressed by only a relatively small amount by ambient fire regimes. Despite this relative stability of tree biomass, there is substantial scope for fire managers to generate carbon credits from increased carbon storage in tree biomass. We found that plausible, management-driven reductions in fire frequency and severity could lead to increases in total tree biomass, including belowground biomass, of about 12.9 t DM ha^{-1} over a century. Accounting for the increase in carbon storage could generate significant tradeable carbon credits, on average is worth annually 3–4 times those generated by current savanna greenhouse gas (methane and nitrous oxide) abatement projects and much more on sites presently affected by high frequencies of severe fire. If appropriate carbon accounting methodologies can be developed, sequestration by tree biomass has the potential to significantly increase the economic viability of fire/carbon projects in Australian savannas. This burgeoning industry has the potential to bring much-needed economic activity to tropical savanna landscapes, without compromising important natural and cultural values.

2.2 Report: Biomass benchmarking—this assessment, being undertaken primarily by Cameron Yates, explores the reliability of available coverages describing standing tree biomass across northern Australia for use in independent benchmarking of biomass change. At the time of writing the following summary report has been submitted for milestone reporting:

Outline – Availability of reliable national-scale biomass mapping products which could be used to provide (a) a baseline biomass estimate at the start of projects, (b) ongoing monitoring of biomass change

Introduction

A methodology for living biomass in savanna trees will offer options to recognise increases in carbon stored in Australian tropical savannas through improved management of fire. Over much of the northern savannas, fire presently suppresses tree biomass below levels ultimately fixed by water availability and competition. A living tree biomass method is being developed for northern Australia, using measurements of stems and records of fire frequency and severity spanning up to 25 years in several hundred field sites. The method will be built on empirically-determined models of change in stem recruitment, growth and mortality under different fire regimes.

Under existing savanna burning methodologies both abatement and coarse woody debris rely on spatially derived burnt area mapping from the North Australia Fire Information (NAFI) website, and vegetation fuel type mapping as inputs to calculate emissions. Mapping of fire is at a minimum pixel size of 250m x 250m, using the MODIS satellite sensor. While vegetation-fuel type mapping at large spatial scales is based in part on MODIS or higher resolution Landsat 30m x 30m imagery, mapping is validated at the project scale by local descriptions assigning at least 250 sites to one of the 9 eligible vegetation-fuel types.

Tree cover and hence tree biomass may vary substantially within vegetation-fuel types, potentially contributing to differences at the rates in which they accumulate new biomass. Predictive models applicable to savanna burning take account of such variation where attributable to variation in rainfalls. They are also likely to be applied to deliver very conservative estimates of biomass benefits of improved fire management to reduce risks of over-estimation.

It has been suggested that estimates of biomass and change through time relevant to savanna burning projects might be provided by presently available or emerging developments in remote sensing. In this paper we consider that proposition, based on a review of relevant literature, supplemented by our experience in deriving and applying a number of remote sensing platforms and approaches to interpretation to fire management in northern Australia.

Deriving a baseline biomass estimate at the start of projects

Biomass or surrogate spatial products are typically derived from one of four methods; 1. Process models, 2. Optical satellite sensors, 3. Radar, and 4. LIDAR:

1. Process models typically use digitised generalisations or extrapolations of field-based measurements as surrogates for or indicators of spatial variation in ecological processes which can be applied individually or in combination to derive new spatially-defined layers relevant to biomass production. Typical inputs to such synthetic surfaces include aspects of rainfall or greenness (NDVI). Current relevant available layers at continental scale are:
    a. The Commonwealth Department of Environment and Energy reports on Australia's greenhouse emissions through the National Greenhouse Gas Inventory (NGGI) for energy, industrial processes, agriculture, land use, land use change, forestry, waste, and other. The NGGI uses layers for continental scale process models including maximum above ground biomass (Roxburgh 2019), forest productivity (Kesteven 2004), land cover change (Lowell 2003), net primary productivity (Ruimy 1994).
    b. The Queensland Government, through the Long Paddock web site, provides pasture-based and other coverages derived from a process model building on rainfall surfaces (Carter 2010).

The current models available for the savannas' do not directly measure living tree biomass. They estimate total maximum biomass. The various enhancements or re-interpretations which relate to tree dynamics, e.g. forest productivity, net primary productivity and others are derived and/or presented at scales of 1km x 1km up to 5km x 5km, which are poorly matched to the size of typical savanna burning projects.

2. A myriad of optical satellite sensors of varying characteristics - including pixel sizes from sub-1m x1m to 10km x 10km, overpass rates from daily to twice a month, number of bands and their spectral characteristics, and temporal length of satellite series – offer some potential to estimate biomass. For example, the NOAA-AVHRR and Landsat satellite series both date to the early 1970's but operate at very different spatial scales. There is currently no tree biomass layer derived from optical satellite sensors for the tropical savannas. However, several surrogates are available:
    a. Two pixel-based fractional cover products have been applied to the tropical savannas, a MODIS and Hyperion product (Guerschman 2009) derived from one image a year, and a Landsat product for Queensland and the Northern Territory, derived by the Queensland Government (Armston 2009). There is also a Landsat continental persistent green layer (Gill 2017). Optical satellite sensors with few bands in the red and near-infra red do not discriminate green vegetation from the tree, shrub and ground layer making it difficult to estimate only the tree component.
    b. Optical satellites have been used to classify vegetation and fuel classes at many scales across the tropical savannas for decades, including for: NT vegetation mapping, Queensland's Regional Ecosystem Mapping, the National Vegetation Information System NVIS, Vegetation Fuels Mapping (SavBat), and individual Savanna Burning Projects. This approach groups areas of similar habitat and vegetation types into classes, rather than a pixel-based approach. The classification of optical satellite imagery into vegetation fuel classes is used in the current methodology.

Although optical satellite sensors provide a range of spatial scales, some of which may be applicable to savanna burning projects, current products have difficulties separating green tree, shrub and grass layers. This is particularly problematic in the monsoonal tropical savanna, with an annual cycle of greening in the wet season and curing through the dry season, compounded by fire activity removing grass and scorching tree canopies. Therefore, pixel-based products of living tree biomass or surrogates are not appropriate for savanna burning methodologies.

3. Radar can overcome some important limitations of optical sensors (Sinha 2015) but can be costly and there is no current system in place for radar-based mapping of biomass in northern savannas and no prospects of an agreed platform emerging.

4. There has been lot of resent research and investment into tree biomass estimation from Lidar with good results at a fine scale (e.g. resolution of less than 50cm from ground Lidar and 5m from aircraft; Zolkos 2012; Lee 2007). Ground-based application typically covers sites of up to 1 ha and would require a huge effort to sample typical project areas. Effective stratification to minimise costs of application would itself require biomass mapping to standards and resolution presently

unavailable. Airborne-borne application generates additional costs and processing demands limit practical application to relatively small mapped areas. Although it is an emerging technology with real future potential, it has no present practical application for current savanna-scale biomass estimation or application at the project scale.

(b) ongoing monitoring of biomass change.

The change in living tree biomass at any given location through time is small with average tree growth rates of under 2 mm annually, and associated small annual changes in basal area and biomass. Annual rates of recruitment and mortality are also a small proportion of standing biomass. Whilst the cumulative effect of shifts in all of these processes on biomass is substantial at time scales relevant to savanna burning projects, none of them are readily measurable by remote sensing that can be applied at scale. Given complexities with mapping biomass spatially as described above, realistically a drawing together of empirical (statistical) summaries of all of these influences into an integrated model, such as outlined in the forthcoming paper by Whitehead et al. (in prep.), provides the most amenable approach for assessing living tree biomass status and change at project and broader scales.

Further reporting

A more comprehensive report is in development. Some papers or reports cited in the National Inventory Reports 1,2, and 3 are not readily accessed. If they become available, details will be included in the review report.

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2.3 “Standing dead stems” assessment—this assessment tracks the fate of tagged stems that were observed to die within respective assessment periods in high and low rainfall zone plots, and also fallen stems that were tagged and measured in the aftermath of Cyclone Monica in 2006 and remeasured 10 years later. The annual fire histories are available for all plots, including for Cyclone Monica stems. The program of works for this assessment is as follows:

- current measurement records (stem diameter, height) describing the fate of all dead standing and fallen stems at high and low rainfall zone, and Cyclone Monica, plots are up-to-date
- a further field assessment round will be undertaken for all standing and dead stems at long-term monitoring plots in Kakadu, Litchfield and Nitmiluk National Parks, over October and November 2019—these data will be combined with existing data for analysis
- Analysis and write-up of these data will be undertaken in early 2020, with a paper submitted to an appropriate international journal by end of April 2020

(3) Fire severity mapping algorithm development

3.1 Fire severity mapping—this detailed assessment program of works (refer Table 1) will be undertaken by a team involving Dr Andrew Edwards, Dr Stefan Maier, Patrice Weber, in collaboration with international colleagues Prof David Roy (University of South Dakota), Prof Luigi Boschetti (University of Idaho), Prof Jose Pereira (University of Lisbon) amongst others. The program of works is planned to be completed by mid-2020 with submission of scientific paper(s) to appropriate international journal(s).

Note that the undertaking of this work will also inform the assessment of the feasibility of generating a reliable fire severity mapping product to replace the current arbitrary early / late dry season cut-off date of 1st August (refer core task 4.3).

Dr Andrew Edwards has provided the following detailed outline addressing the development of an automated process to create a fire severity mapping methodology based on globally available and regionally created datasets, calibrated by local information.

3.1.1 Background

Fire Severity in the tropical savannas is here defined by the relative scorch height [1]. The energy of a fire is due to the length of the fire front, the available cured fuel and wind speed. The energy released by fire directly affects a proportion of photosynthetic vegetation (PV), predominantly foliage, scorching in a vertical direction. Upper canopy scorch markedly effects tree growth (Whitehead *et al.* in press) and is described as “severe”. Fire affected areas with unaffected canopy are “mild”. This binary classification is the basis of the remotely sensed detection and classification of fire severity mapping previously defined [2] and to be applied in this research.

A fire severity mapping algorithm has been in train since 2011. To simplify the large amount of processing required to derive the product, the algorithm used all available calibration data to derive a simple threshold of the relative difference of the near infrared (RdNIR). This has meant that the classification is less accurate in the earliest and latest parts of the fire season, and similarly in the highest and lowest tree structural classes. Although this provides a reasonable average accuracy in any given year, to improve the accuracy of the fire severity map throughout a year we have developed this dynamic calibration method to adjust the algorithm throughout the season and across vegetation structural classes.

3.1.2 Methods

Fire severity classes, unlike burnt areas, are not readily discernible from satellite imagery, relying on algorithms using satellite imagery, ancillary and calibration data. Accuracy using traditional methods is notoriously low (see Table 1 in [2]), whereby modern sophisticated machine learning algorithms require thousands of points for reliable and acceptable classification accuracy [3].

An extensive series of 6,478 waypoints were collected via aerial survey across regions of north Australia from 2011-16, Figure 3.1. The standard survey method [4] was applied at all times, flying in a helicopter (R44) at approximately 400 feet Above Ground Level, travelling at approximately 70 knots. These data, when randomly split, provide both calibration and validation data for the fire severity map classification. At each waypoint the level of fire effect, the severity, was assessed for an area approximating 3 ha, approximately half the area of a MODIS 250 m pixel (6.25 ha), in a detailed range of fire severity classes from patchy through to extreme.

The aerial survey data are being further attributed post-survey to characterise the date the fire occurred, using the North Australia Fire Information (NAFI) MODIS 250 m derived semi-automated burnt area mapping (BAM) and active fire data known as Hot Spots. The Hot Spot information is available from the University of Maryland data portal (http://modis-fire.umd.edu/af.html) and Landgate WA (https://firewatch-pro.landgate.wa.gov.au/home.php) but are edited daily by Dr Peter Jacklyn from the NAFI team to remove false positives.

Maitec (https://www.maitec.com.au/) is a satellite image data provider operated by Dr Stefan Maier and a contributor to this study. Maitech have developed MODIS image download and post-processing capabilities using Bidirectional Reflectance Distribution (BRDF) modelling to remove reflectance change due to look-angle and sun reflectance phenomena by using multiple multi-angular observations of surface reflectance [5]. The effect of fires on chlorophyll slowly changes post-fire and is not usually strongly apparent in the first 1 or 2 days. Therefore, a variety of post-fire image dates from 3 to 7 days will be selected. Reflectance information from multiple MODIS bands will extracted from the image archive at the locations and dates provided by the calibration data pre- and post-fire, for ± 7 days.

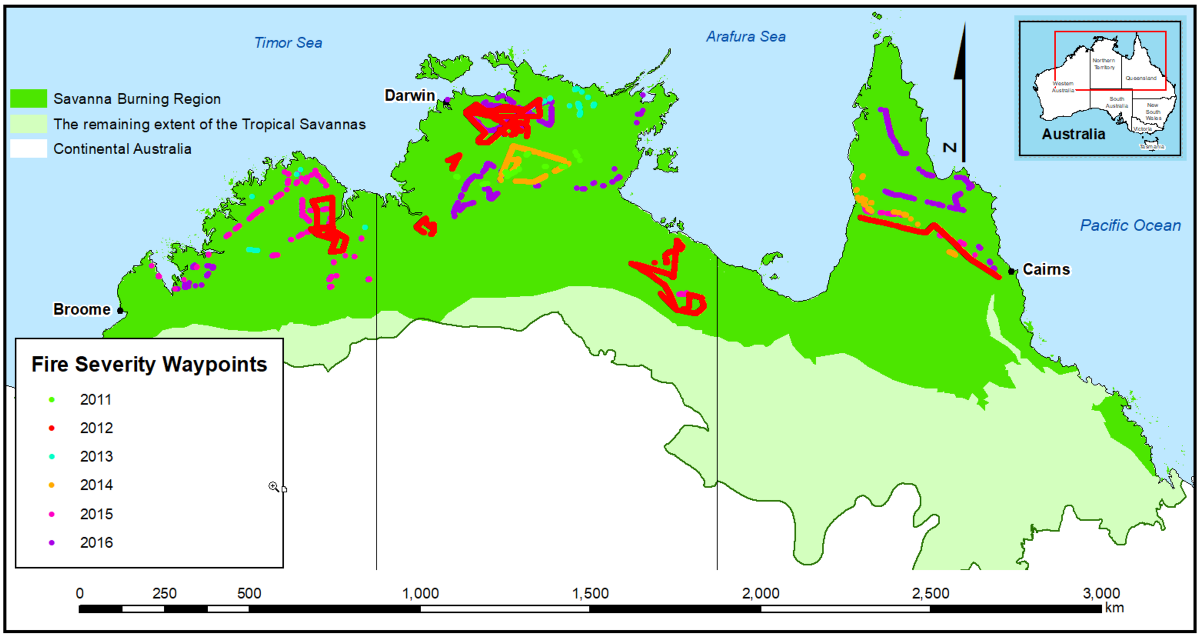

Figure 3.1. Extent of the Fire Severity aerial surveys 2011-16 over the Savanna Burning region in the tropical savannas of north Australia.

Two image products will be derived. The first is the relative difference in the near infrared (RdNIR) developed in previous research to incorporate the highest resolution MODIS image data, the NIR with 250 m pixels, whilst encapsulating the greatest, and most parsimonious, spectral information discriminating fire severity, again in the NIR. The second product will assess the pre-fire BRDF modelled image and a series of post-fire high-look-angle images, as a means of minimising the ground layer whilst maximising the canopy layer to look for change in known burnt areas, with the expectation that if no change is detected then the canopy has been minimally, or not, scorched, whilst a change would indicate fire effect in the canopy, and thus a severely burnt area.

To determine the most appropriate geographical stratification, within which we will derive separate RdNIR thresholds, we are creating ancillary surfaces, including a burnt area mask from NAFI. The NAFI mapping is highly regarded by the fire management community who monitor the mapping in the field, and it has annually achieved overall mapping accuracy > 90% for the many years independent and extensive aerial observations have been collected, often in conjunction with the fire severity calibration/validation data, to purposefully assess it. Stratification will also be assessed using a fire radiative power surface derived from the edited active fire waypoints, and Landsat-scale derived multi-year foliage projective cover (FPC) surfaces (https://www.longpaddock.qld.gov.au/forage/report-information/foliage-projective-cover/).

The outputs will be a combination of the stratification layers, the multiple RdNIR layers (3, 5 and 7 days) and the ΔBRDF layers to ascertain, with the validation subset of the field observations, the most accurate fire severity mapping algorithm.

3.1.3 Result

The last, but by no means the simplest, phase of the project will be the automation of the best result of the processes. Dr Patrice Weber has been employed to work with the assessment team, Drs Stefan Maier and Andrew Edwards, to automate many of the processes described in the above methods. But also includes the processes undertaken by the BAM team from NAFI to select and tabulate the BAM images used to delineate fire scars and the multiple products derived (annual fire frequency, late dry season fire frequency, time-since-last-burnt, patch size distribution and patchiness indices, etc).

The potential for these methods to be globally adaptable depends on either the utility of the Hot Spot surface information or the pre-fire BRDF versus post-fire off-nadir analyses to characterise the fire severity.

3.1.4 References

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2. Edwards, A.C., J. Russell-Smith, and S.W. Maier, *A comparison and validation of satellite-derived fire severity mapping techniques in fire prone north Australian savannas: Extreme fires and tree stem mortality.* Remote Sensing of Environment, 2018. **206**: p. 287-299.

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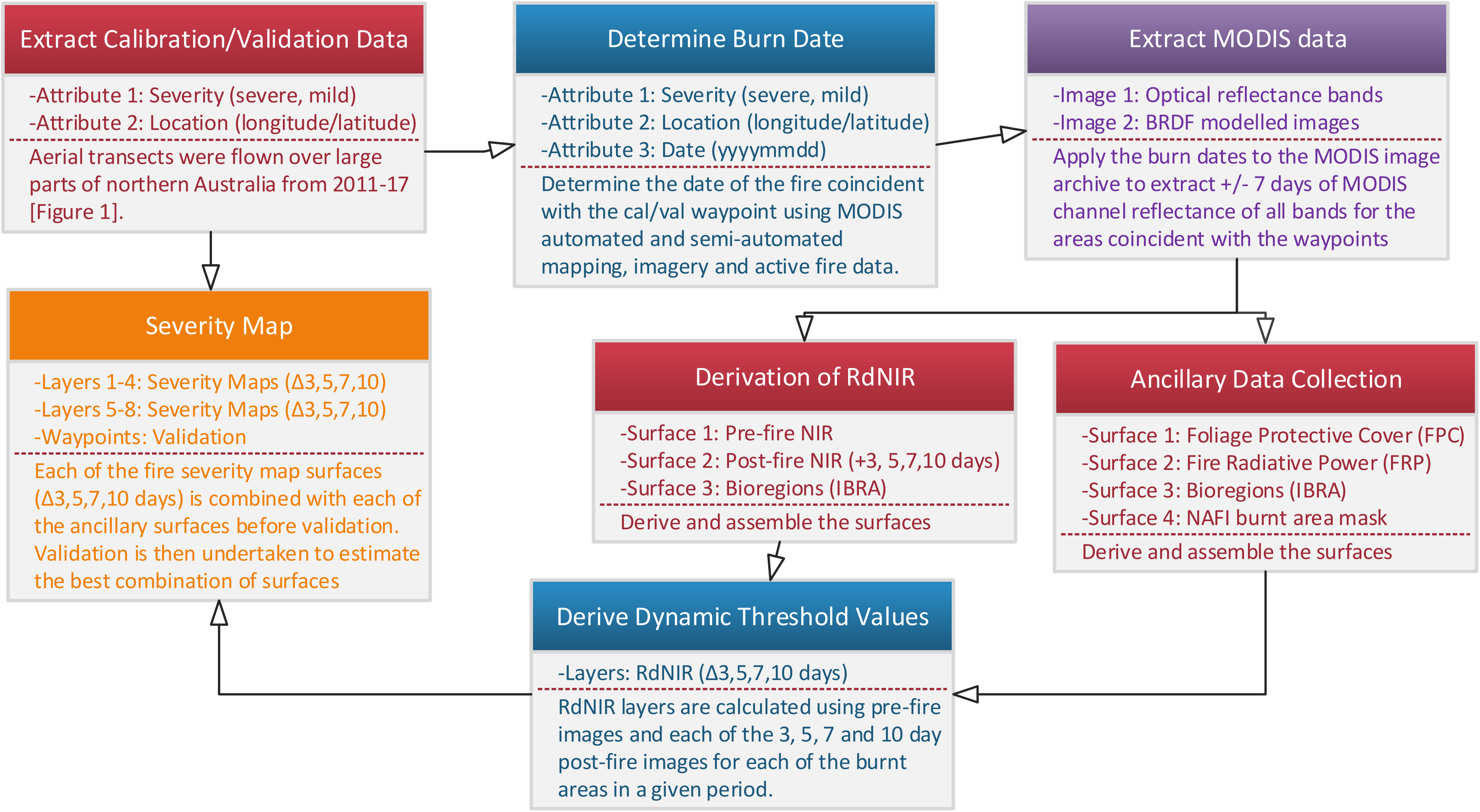

Extract Calibration/Validation Data

-Attribute 1: Severity (severe, mild)
-Attribute 2: Location (longitude/latitude)

Aerial transects were flown over large parts of northern Australia from 2011-17 [Figure 1].

Determine Burn Date

-Attribute 1: Severity (severe, mild)
-Attribute 2: Location (longitude/latitude)
-Attribute 3: Date (yyyymmdd)

Determine the date of the fire coincident with the cal/val waypoint using MODIS automated and semi-automated mapping, imagery and active fire data.

Extract MODIS data

-Image 1: Optical reflectance bands
-Image 2: BRDF modelled images

Apply the burn dates to the MODIS image archive to extract +/- 7 days of MODIS channel reflectance of all bands for the areas coincident with the waypoints

Derivation of RdNIR

-Surface 1: Pre-fire NIR
-Surface 2: Post-fire NIR (+3, 5,7,10 days)
-Surface 3: Bioregions (IBRA)

Derive and assemble the surfaces

Ancillary Data Collection

-Surface 1: Foliage Protective Cover (FPC)
-Surface 2: Fire Radiative Power (FRP)
-Surface 3: Bioregions (IBRA)
-Surface 4: NAFI burnt area mask

Derive and assemble the surfaces

Derive Dynamic Threshold Values

-Layers: RdNIR (Δ3,5,7,10 days)

RdNIR layers are calculated using pre-fire images and each of the 3, 5, 7 and 10 day post-fire images for each of the burnt areas in a given period.

Severity Map

-Layers 1-4: Severity Maps (Δ3,5,7,10)
-Layers 5-8: Severity Maps (Δ3,5,7,10)
-Waypoints: Validation

Each of the fire severity map surfaces (Δ3,5,7,10 days) is combined with each of the ancillary surfaces before validation. Validation is then undertaken to estimate the best combination of surfaces

Figure 3.2. The methods: from top left, “Extract Calibration/Validation Data”, moving clockwise to the final “Severity Maps” and the validation.

(4) Revising and updating current (2018) Savanna Burning method

4.1 Seasonality of fuel accumulation—the current Savanna Burning methodology does not take seasonality of litter fall into account, despite substantial, if mostly unpublished, evidence to the contrary. To address this, this core task involves five associated activities, including the publication of at least two papers, as follows:

- ***Seasonal fuel load data accumulation down the rainfall gradient***—Jay Evans is overseeing this component and has provided the following notes:

  "Currently there is a gap in the scientific data relating to the seasonal accumulation of litter and coarse woody debris, particularly for sandstone woodlands and heaths. These data underpin our ability to improve the current Savanna Emissions Abatement and Coarse Woody Debris methodology components. For example, the latest methodology does not take into account seasonal inputs of litter although we know from various studies that litter fuel loads are substantially greater in the late dry season due to leaf fall from around the middle of the year. Including seasonal estimates of litter and coarse woody debris will improve the methodology by showing that early season prescribed burning substantially reduces greenhouse emissions under reduced seasonal fuel load conditions. The objective is to (a) demonstrate seasonality in fine (leaves, small <5mm diameter twigs) fuel inputs, and (b) investigate seasonality inputs for coarse fuels (>5mm <5cm) in north Australian savannas. To achieve this a field program is being undertaken over 2019 at more-or-less monthly intervals, to monitor fuel inputs at permanent sites covering various veg-fuel classes located down the northern rainfall gradient sampling both Savanna Burning methodology rainfall zones."

- ***Paper: write-up of seasonal fuel accumulation associated with curing data***—Cameron Yates is undertaking this component and has provided the following notes:

  "Northern savanna fuels accumulate after a fire over progressive years and, in some cases such as with hummock grasses (ie. spinifex), accumulation has been shown to be decadal. For many fuel types, accumulation is most prominent in the fine fuels (leaf and twig) component, particularly in the first five years since fire. The monsoonal northern savannas have a distinct wet and dry season with annual rainfall in the summer months followed by droughting over the winter months. This study documents the seasonality of fine fuel accumulation down a rainfall gradient (1700mm – 700mm) under tree canopy cover conditions ranging from 48% – 5% projective foliage cover (PFC). Based on three years of sampling, the program demonstrated an average 7% increase of fine fuels in the late dry season in the lower rainfall zone, and 25% increase in the late dry season in the higher rainfall zone. A paper describing the study will be submitted for publication in early 2020."

- ***Litterfall data collection, Litchfield NP***—Dr Stefan Maier has been undertaking this field-based study at permanent sites in Litchfield NP, collecting leaf litter samples monthly since 2011. Sampling will be maintained throughout the remainder of 2019, and assembled data used to help inform the seasonal analysis described below.

- ***Paper: synthesis of available seasonal fuel load data***—using all datasets described above, and any others available, Dr Stefan Maier will undertake analysis of assembled data and prepare a scientific paper for publication in an international journal by end of April 2020. Dr Maier has provided the following notes describing the study:

> “This project will use the nearly one decade-long dataset of monthly leaf fall measurements at the Savanna Supersite in Litchfield National Park together with more recent leaf litter decomposition measurements to develop a mathematical model describing leaf litter fuel dynamics, i.e. seasonal variations in leaf litter fuel loads. The model will then be calibrated for other locations across Australia's tropical savanna using all available seasonal leaf litter fuel load measurements. From the detailed model a simplified model will be developed for predicting seasonal leaf litter fuel accumulation for the different vegetation fuel classes, for use in estimates of greenhouse gas emissions from savanna fires. The same models will be investigated for their utility in predicting coarse fuel accumulation.”

4.2 Paper / Report: Revision of fuel load accumulation parameters in current (2018) method—as noted in previous submissions to the ERF, the currently applied Olson curve relationships describing fuel accumulation (a) grossly underestimate fuel accumulation for most, if not all, vegetation fuel types relative to the empirical data that were supposedly used to derive them, (b) apply unsupported (inflated) estimates of fuel residues immediately post-fire (which leads to significant under-estimation of fuel accumulation subsequently), and (c) as widely acknowledged in the scientific literature, are inappropriate for applications where fuel accumulation occurs under non-equilibrium conditions[3] (ie. marked seasonal fluctuations of fuel component inputs [as described above] and decay [e.g. as described by Rossiter-Rachor *et al*.][4]). By mid-2020, a detailed report will be submitted addressing these issues, and making informed recommendations as to how these relationships should be revised / amended.

4.3 Paper / Report: Revision of current seasonal cut-off date, and replacement with fire severity approach—for pragmatic reasons the current and preceding Savanna Burning methods have all applied a seasonal early / late dry season cut-off as 1 August. While this generally has been found to be useful and applicable to climatic circumstances across the northern savannas, it does not take into account that severe fires can occur under early dry season conditions, and fires of much less severity can occur in the late dry season period (including management prescribed fires). As noted above under core task (**3**), there is a realistic requirement to incorporate fire intensity / severity to account for effects on LTB sequestration, and it follows that, if feasible, such technical fire severity mapping advances need to be applied generally throughout the Savanna Burning methodology. A report addressing these issues will be provided mid-2020, in association with reporting generally on the feasibility and reliability of an appropriate fire severity mapping product.

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[4] Rossiter-Rachor NA, Setterfield SA, Hutley LB, McMaster D, Schmidt S, Douglas MM (2017) Invasive *Andropogon gayanus* (Gamba grass) alters litter decomposition and nitrogen fluxes in an Australian tropical savanna. *Scientific Reports* **7**: Article number: 11705

4.4 Inclusion of Pindan as new vegetation fuel type—this recommendation follows the study as reported by Lynch *et al*. 2018[5].

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[5] Lynch D, Russell-Smith J, Evans J, Yates CP, Edwards AC (2018) Incentivising fire management in Pindan (Acacia shrubland): a proposed vegetation fuel type for Australia's savanna burning greenhouse gas emissions abatement methodology. *Ecological Management & Restoration* **19**:230-238.

Table 1: Timeframe for undertaking and completion of core tasks as identified in contractual agreements and related arrangements. Note: cells highlighted in dark grey refer to milestone delivery timeframes; cells highlighted in light grey refer to additional timeframes likely required to complete tasks (e.g. finalisation of scientific paper review process, and publication)

Action		**2019**					**2020**											
No.	***Activity***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Jan***	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
(1) Datasets provided to NGGI																		
1.1	Living tree biomass data	▓																
1.2	High and Low rainfall zone datasets underlying earlier Methods	▓																
(2) Living Tree Biomass science basis																		
2.1	Paper: data description, statistical analysis	▓	▓	▓	▓	▓	░	░	░									
2.2	Report: Biomass benchmarking	▓	▓	▓	▓	▓	░	░	░									
2.3	"Standing dead stems" assessment																	
	• ongoing field assessment	▓	▓	▓	▓													
	• data assembly, analysis	▓	▓	▓	▓	▓	▓	▓										
	• Paper							▓	▓	▓	░	░	░	░	░	░		
(3) Fire severity mapping algorithm development																		
3.1	Data collection, analysis, write-up of proposed method																	
	• ongoing field assessment	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	░	░	░	░	░	░	░
	• remote sensing assessments			▓	▓	▓	▓	▓	▓	▓	▓	░	░	░	░	░	░	░

Action		**2019**					**2020**											
No.	***Activity***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***	***Jan***	***Feb***	***Mar***	***Apr***	***May***	***Jun***	***Jul***	***Aug***	***Sep***	***Oct***	***Nov***	***Dec***
										▓	▓	▓	░	░	░	░	░	░
(4)	**Revising and updating current (2018) Savanna Burning method**																	
4.1	Seasonality of fuel accumulation																	
	• Seasonal fuel load data accumulation down rainfall gradient	▓	▓	▓	▓	▓	░	░	░	░	░	░	░	░	░	░	░	░
	• Paper: write-up of seasonal fuel accumulation associated with curing data	▓	▓	▓	▓	▓	▓	▓	░	░	░	░						
	• Litterfall data collection, Litchfield NP	▓	▓	▓	▓	▓	░	░	░	░	░	░	░	░	░	░	░	░
	• Paper: synthesis of available seasonal fuel load data						▓	▓	▓	▓	░	░	░	░	░			
4.2	Revision of fuel load accumulation parameters in current method																	
	Paper / Report						▓	▓	▓	▓	▓	▓	░	░	░	░	░	░
4.3	Revision of current seasonal cut-off date, and replacement with fire severity approach—refer **(3)**																	
	Paper / Report						▓	▓	▓	▓	▓	▓	░	░	░	░	░	░
4.4	Inclusion of Pindan as new vegetation fuel type—refer Lynch *et al*. 2018												░	░	░	░	░	░