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OPPORTUNITIES FOR ALTERNATIVE FUEL LOAD REDUCTION APPROACHES – SUMMARY REPORT

Mechanical Fuel Load Reduction Utilisation project

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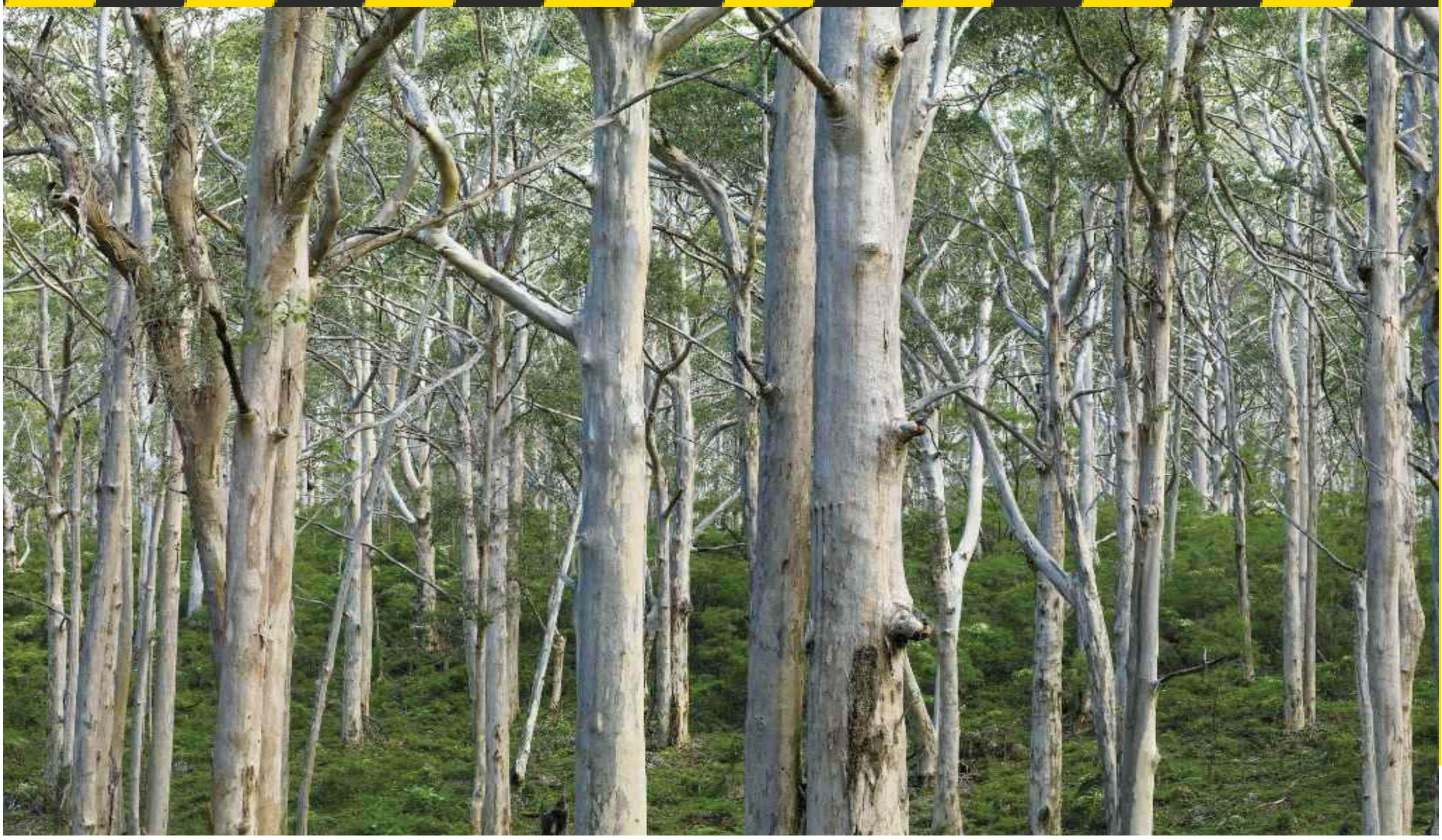

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EXECUTIVE SUMMARY

Planned burning is one of the most utilised fuel management activities, but the safe and effective application of this method is likely to be hindered by climate change (e.g. shrinking and shifting windows of opportunity) and potential adverse societal outcomes (e.g. smoke impact, risk of fire escape). For this reason, fire managers need access to detailed information to help them make informed decisions and select a fuel management strategy that is compatible with a range of factors.

This project explored the use of experts' knowledge and the UNHaRMED Decision Support System (DSS) framework (an integrated spatio-temporal model for analysing natural hazard risk within urban and rural environments) to assess the opportunities and risks associated with different approaches to reducing bushfire risk via fuel management.

This project identified:

- Areas of emerging risk in end-user defined regions of Western Australia resulting from the combination of climate change and urban sprawl.
- An increase in asset damages due to the combined effect of climate change and urban sprawl. The results indicate that losses increased dramatically more in urban residential areas compared to rural residential with increasing severity in climate change (about ten times higher).
- The relative suitability (i.e. where fuel management can technically be applied) and potential (i.e. where it is socially acceptable and economically feasible to reduce fuel loads) to apply different fuel management activities (e.g. planned burning, mechanical fuel load reduction, grazing) in achieving these outcomes. This work combined local knowledge and experience obtained through surveys and literature review with maps of current or future local conditions (e.g. land use, assets location).
- The extent to which fuel management can reduce bushfire risks. Fuel reduction led to a decrease in bushfire risk compared to a no-mitigation scenario. However, the results suggest that in cases where fuel management does significantly reduce the risk of impacts posed by bushfires, this reduction was much less than in increase in risk from climate change.

This report presents the major findings from the Fuel Load Reduction Utilisation Project and proposes future research directions identified by end-users, building on this project's results. The proposed projects could help develop policies and strategies for reducing risk in emerging bushfire risk areas at the State and national scale by offering a range of fuel management activities adapted to specific regional conditions, which could change over time.

END-USER PROJECT IMPACT STATEMENT

Tim McNaught, *Department of Fire and Emergency Services, WA*

The growing community concern regarding the impacts of a changing climate on our lives and livelihoods is impacting on the way we appreciate the interconnectedness and complexity of factors that influence the vulnerability of human populations and the things we value. Policy, planning and investment decision made today will affect the vulnerability of people and the things we value into the future. The benefit of being able to peer through a lens into a potential future and model the effect of different policy, planning or investment decisions is useful to guide those decisions to support more efficient and effective medium to long-term outcomes and understand and limit any undesirable impacts.

Importantly, research is supporting those of us who can influence policy, planning and investment decisions in further appreciating and understanding this complexity. This element of research, focusing on fuel management and assessing the opportunities and risks associated with different approaches to reducing bushfire risk from fuel management is designed to provide further knowledge into the foundational components of the UNHaRMED Decision Support System. It will assist in guiding the modelling of the effect of fuel mitigation under varied potential future scenarios.

1. INTRODUCTION

Planned burning is one of the most utilised fuel management activities, but the safe application of this method is hindered by climate change (e.g. shrinking and shifting windows of opportunity) and potential adverse societal outcomes (e.g. smoke impact, risk of fire escape). For this reason, fire managers need access to detailed information to help them make informed decisions and select a fuel management strategy that is compatible with a range of factors.

This project explored the use of experts' knowledge and the UNHaRMED Decision Support System (DSS) framework, an integrated spatio-temporal model for analysing natural hazard risk within urban and rural environments (Riddell et al., 2016), to assess the opportunities and risks associated with different approaches to reducing bushfire risk via fuel management.

The main aims of this project were to identify:

- Areas of emerging risk in end-user defined regions of Western Australia resulting from the combination of climate change and population growth (Jeanneau et al., 2021c).
- How bushfire losses due to the combined effect of climate change and population growth would change in the future (Jeanneau et al., 2021e).
- Where and under which conditions different fuel management activities (e.g. planned burning, mechanical fuel load reduction, grazing) would be suitable (i.e. where fuel management can technically be applied) and desirable (i.e. where is it socially acceptable and economically feasible) (Jeanneau et al., 2021a, Jeanneau et al., 2021f).
- The extent to which fuel management can reduce bushfire risks (Jeanneau et al., 2021e).

This report presents major findings from the Fuel Load Reduction Utilisation Project (sections 2, 3, 4 and 5) and proposes future research directions identified by end-users, building on this project's results (section 6). The proposed projects could develop policies and strategies for reducing risk in emerging bushfire risk areas at the state and national scale by offering a range of fuel management activities adapted to specific regional conditions, which could change over time.

2. IDENTIFICATION OF AREAS OF FUTURE BUSHFIRE RISK

We consulted end-users to identify key areas of emerging bushfire risk in Western Australia. We also consulted Bushfire Risk Management Plans (BRM Plans) from these areas of interest to compare the extent of current fire mitigation activities and the UNHaRMED bushfire risk outputs (see Jeanneau et al. (2021e) for details).

The discussions with end-users resulted in the selection of five major areas to focus on for this study. This selection was based on local knowledge and information presented in local BRM Plans. The five target areas for fuel management and risk reduction potential are the Gingin region, two regions in the Perth Hills (Kalamunda and Mundaring), Margaret River and the Jerramungup (Bremer Bay) region (Figure 1).

When looking at the combined impact of population growth (urban expansion) and severe climate change (RCP 8.5), areas where UNHaRMED predicted an increase in bushfire risk (Figure 2) correlated well with the location of fuel management activities currently conducted by bushfire management agencies at the rural-urban interface (see green lines on Figure 2). These findings suggest that UNHaRMED is suitable for identifying future areas of emerging risk (see

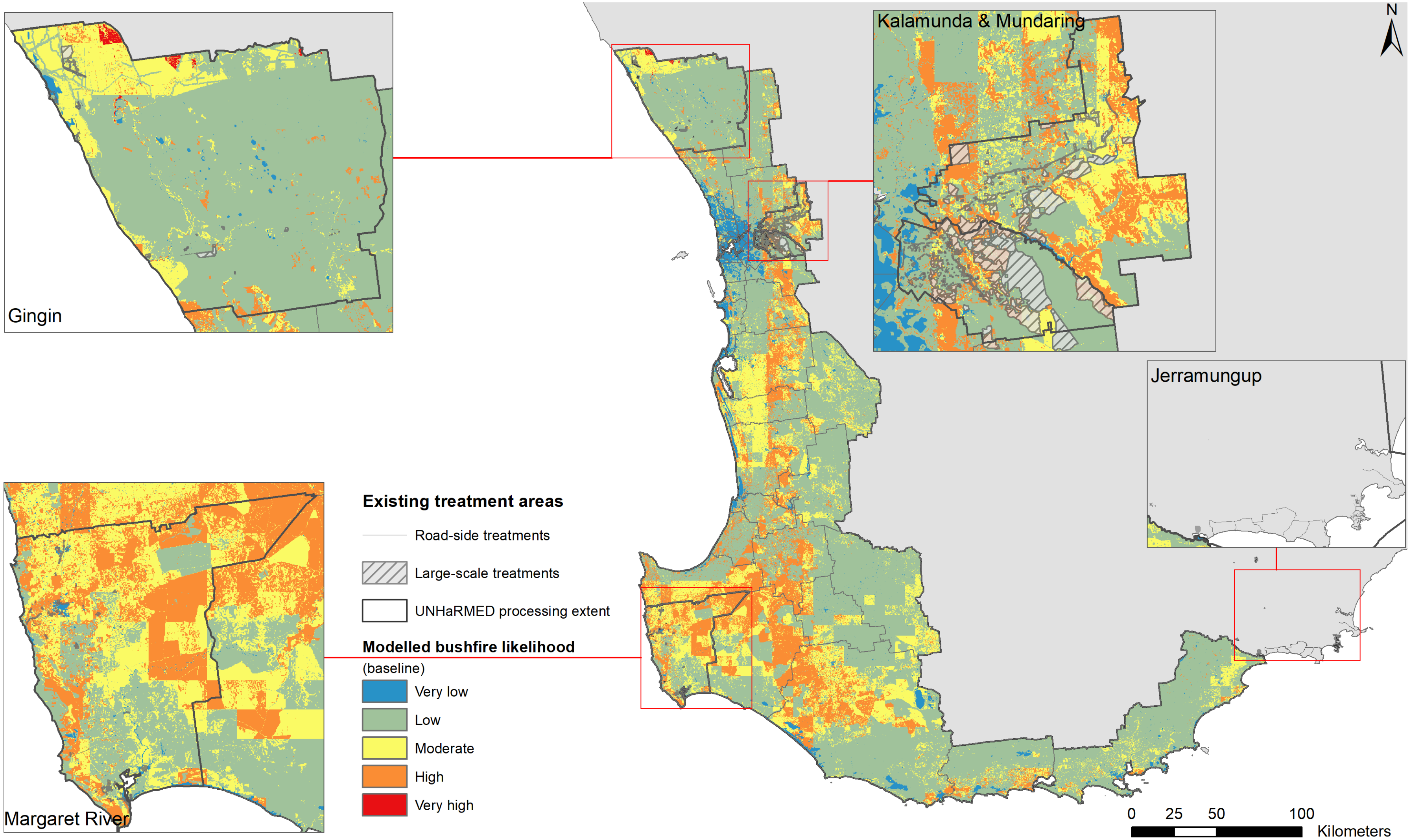

FIGURE 1. LOCATION OF THE FIVE TARGET REGIONS IN WA OVERLAYED WITH THE BASELINE BUSHFIRE LIKELIHOOD OBTAINED USING UNHARMED. NOTE THAT THE JERRAMUNGUP REGION IS CURRENTLY OUTSIDE OF THE UNHARMED PROCESSING EXTENT.

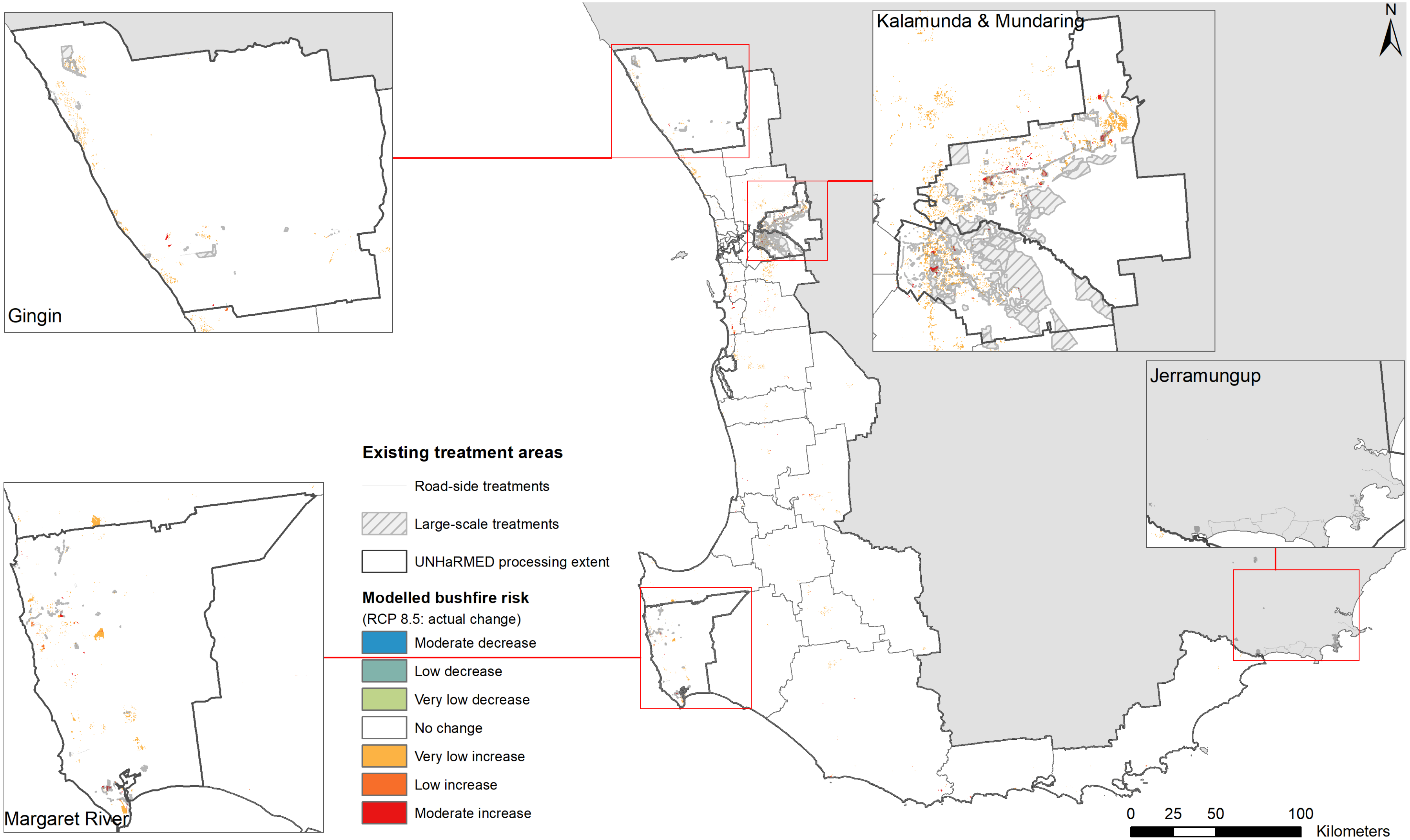

FIGURE 2. LOCATION OF THE FIVE TARGET REGIONS IN WA OVERLAYED WITH THE CHANGE IN BUSHFIRE RISK (2018 VS 2050, SEVERE CLIMATE CHANGE (RCP 8.5)) OBTAINED USING UNHARMED. NOTE THAT THE JERRAMUNGUP REGION IS CURRENTLY OUTSIDE OF THE UNHARMED PROCESSING EXTENT.

3. DETERMINATION OF FUTURE LOSSES

We ran three simulation scenarios in UNHaRMED (Table 4) and compared the resulting bushfire risk (in Average Annual Loss (AAL)) for each of the four target regions (see Jeanneau et al. (2021c) for more details). All scenarios considered the same projections for population growth and increase in area demand for a range of land use to focus on the impact of climate change on future bushfire risk.

Scenario	Description
1a	No climate change (the weather remains the same as today) and no fuel mitigation activities were conducted
2a	Moderate climate change (following RCP 4.5 emission scenarios for SW Western Australia) and no fuel mitigation activities were conducted
3a	Severe climate change (following RCP 8.5 emission scenarios for SW Western Australia) and no fuel mitigation activities were conducted

TABLE 1. DETAILS OF THE UNHARMED SIMULATION SCENARIOS. NOTE THAT ALL SCENARIOS ACCOUNT FOR POPULATION GROWTH AND AN INCREASE IN AREA DEMAND FOR A RANGE OF LAND USES.

The simulation results indicate that bushfire risk dramatically increased with the influence of climate change in three out of the four target regions (Margaret River: 42 - 57%; Mundaring: 34 - 51%; Kalamunda: 42 - 60%) (Figure 3). For the Gingin region, bushfire risk increased slightly in both climate change scenarios (RCP 4.5: 27%; RCP 8.5: 32%) compared to the first year of the simulation (Figure 3).

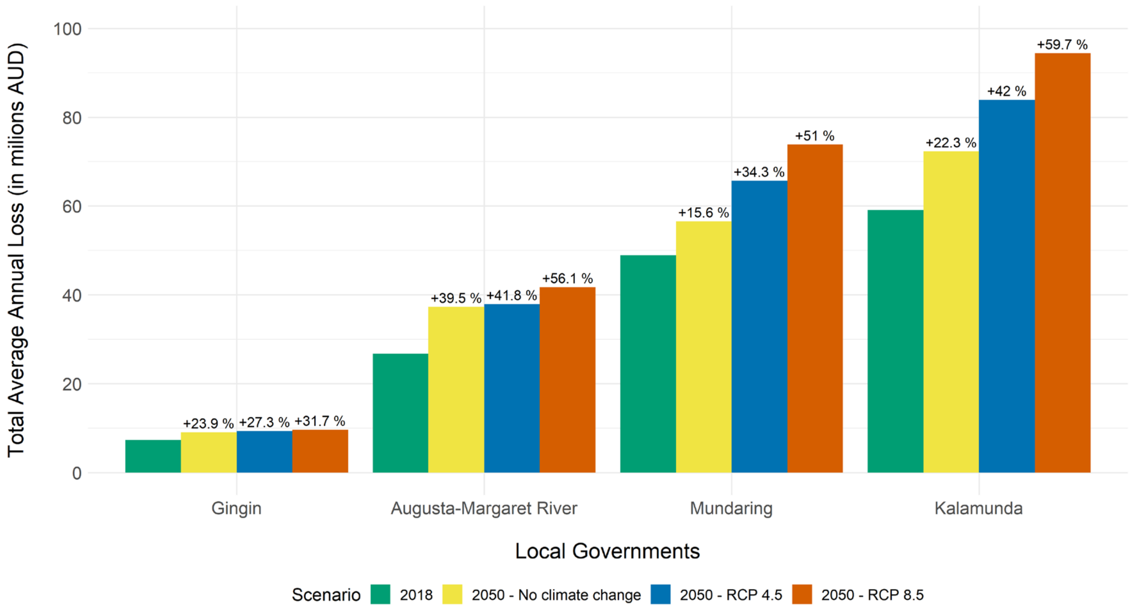

FIGURE 3. SCENARIOS 1A, 2A, AND 3A: TOTAL AVERAGE ANNUAL LOSS FROM BUSHFIRES (IN MILLIONS OF AUD) FOR THE FOUR TARGET REGIONS. NOTE THE PERCENTAGE DISPLAYED ON TOP OF EACH DIAGRAM REPRESENTS THE INCREASE IN TOTAL AAL FROM THE BASELINE YEAR OF 2018.

The "no climate change scenario" results indicate that even if the climate conditions remained the same as today, three out of the four target regions would likely observe an increase in total Average Annual Loss around 24 to 40% compared to the first year of the simulation. This observation can be correlated with urban sprawl into natural reserves, increasing the length of the rural-urban interface.

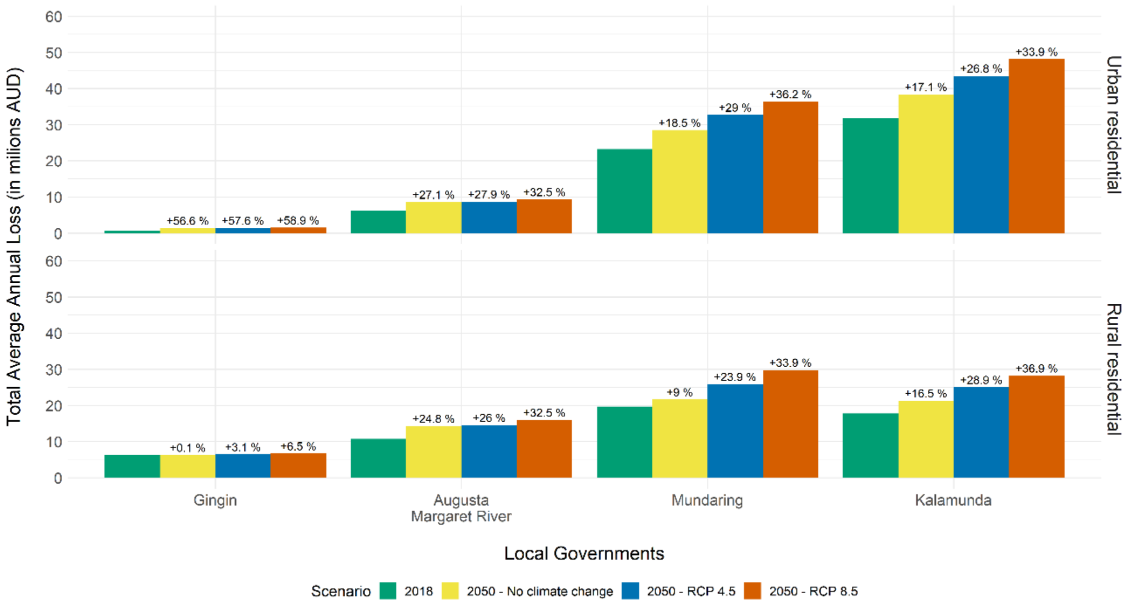

FIGURE 4. SCENARIOS 1A, 2A, AND 3A: TOTAL AVERAGE ANNUAL LOSS FROM BUSHFIRES (IN MILLIONS AUD) FOR THE FOUR TARGET REGIONS DISTINGUISHING BETWEEN RURAL AND URBAN RESIDENTIAL LAND USES. NOTE THE PERCENTAGE DISPLAYED ON TOP OF EACH DIAGRAM REPRESENTS THE INCREASE IN TOTAL AAL FROM THE BASELINE YEAR OF 2018.

Figure 4 indicates that the total AAL from bushfires was about ten times higher in the Perth Hills than that of the other two more rural regions (Gingin and Augusta – Margaret River). However, the total AAL was within the same order of magnitude for all four regions if we only consider rural residential areas. This observation highlights the need for better quantification of bushfire risk in UNHaRMED to also account for the loss of ecosystem services and other non-market value resources (see section 6.5 for more details).

4. IDENTIFICATION OF SUITABLE FUEL MANAGEMENT OPTIONS FOR MITIGATING FUTURE LOSSES

To identify where and under which conditions different fuel management activities (e.g. planned burning, mechanical fuel load reduction, grazing) would be suitable (i.e. where fuel management can technically be applied) and desirable (i.e. where it is socially acceptable and economically feasible to reduce fuel loads), we developed a general conceptual approach for the selection of fuel management strategies (the Fuel Management Suitability Tool) (Figure 5). The resulting product from this conceptual approach is a range of maps of opportunities to apply different fuel management activities (see Jeanneau et al. (2021d) for more details).

This method builds on the approach to create applicability maps for mitigation options in the European RECARE[1] project (van Delden et al., 2019) and the soil improving cropping systems potential index (SICS) in the SoilCare[2] project (van Delden et al., 2021).

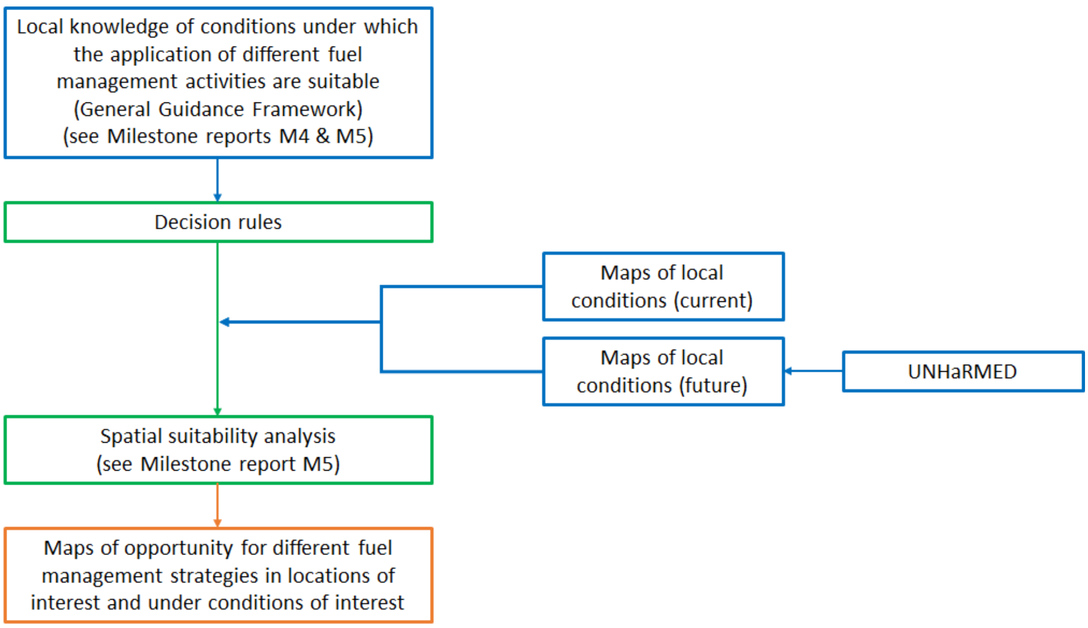

FIGURE 5. FLOW CHART REPRESENTING THE FUEL MANAGEMENT SUITABILITY TOOL GENERAL CONCEPTUAL APPROACH.

The approach combines local knowledge and experience of conditions under which the application of different fuel management strategies is suitable with maps of current or future local conditions (e.g. land use, location of assets, etc.) where fuel management would be desirable to create maps of opportunity for different fuel management activities in locations of interest (Figure 5). Local knowledge of the conditions under which different fuel management approaches are applicable can be obtained from local experts using instruments such as surveys, which can be complemented by generic information from literature, where required.

[1] https://www.recare-hub.eu/
[2] https://www.soilcare-project.eu/

An example of this local knowledge collection is the General Guidance Framework for selecting different fuel management strategies developed by Jeanneau et al. (2021b) for the case study regions of interest. This framework was developed by identifying different potential fuel management strategies and their various attributes, such as the information and knowledge needed to match different methods with particular circumstances (Appendix 1) (see Jeanneau et al. (2021b) for details). The attributes of the possible fuel management strategies were determined with the aid of a literature review and an online stakeholder survey of Local Government Bushfire Mitigation Officers in WA, thereby drawing on both general and local knowledge sources. Therefore, the framework provides information on a set of conditions bushfire mitigation officers need to consider when developing fuel management plans for a range of fuel management techniques, including planned burning, mechanical fuel reduction, or grazing.

The Fuel Management Suitability Tool was then applied to the regions of emerging bushfire risk in WA (as identified in Jeanneau et al. (2021c)) in combination with detailed local knowledge from the online survey to create maps of opportunities to apply each fuel management activity (see sample in Figure 6). Consultation with end-users and survey participants will be required to improve the accuracy of the maps of opportunity for the fuel management activities selected. This process will also help identify information that was not captured by the survey questions (e.g. social acceptability).

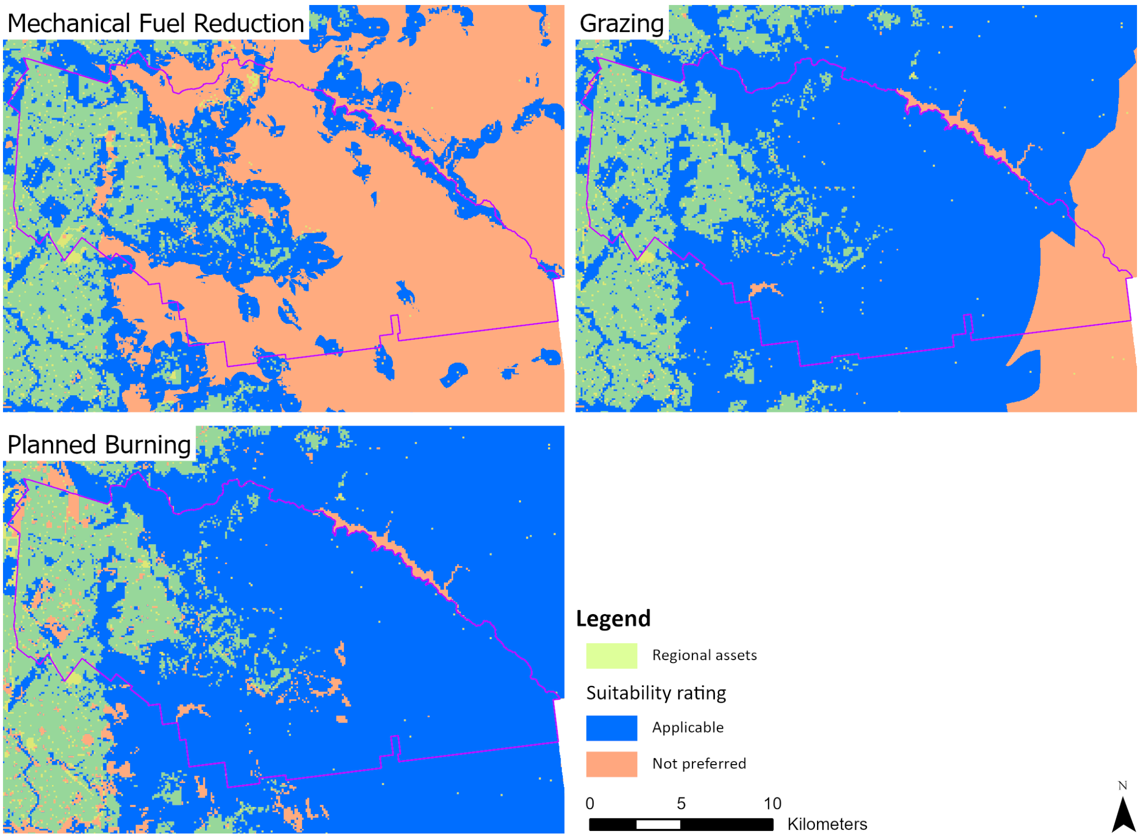

FIGURE 6. EXAMPLE OF SUITABILITY MAP FOR THE LOCAL GOVERNMENT OF KALAMUNDA.

These output maps could also be used to define fuel mitigation strategies in UNHaRMED to quantify the impact of fuel management on future bushfire losses due to population growth and climate change (see Jeanneau et al. (2021d) for details.

5. DETERMINATION OF THE EFFECTIVENESS OF FUEL MANAGEMENT FOR FUTURE LOSSES MITIGATION

To test the influence of fuel management on future losses from bushfires, we ran the three climate scenarios described in section 3 with fuel management as a mitigation option in UNHaRMED (Table 2, see Jeanneau et al. (2021e) for more details). Fuel management activities were conducted as a one-off treatment applied in the year before the end of the simulation (2049). The main aim was to quantify the potential benefit of fuel management at the rural-urban interface taking into account future urban developments and climate conditions.

Scenario	Fuel management	Climate Impact		
	Yes	*None*	*RCP 4.5 (moderate)*	*RCP 8.5 (severe)*
1b	X	X		
2b	X		X	
3b	X			X

TABLE 2. DETAILS OF THE UNHARMED SIMULATION SCENARIOS WITH FUEL MANAGEMENT. NOTE: ALL SCENARIOS ACCOUNT FOR POPULATION GROWTH AND AN INCREASE IN AREA DEMAND FOR A RANGE OF LAND USES.

Fuel management in UNHaRMED is currently intended to reset the time since last fire (fuel age) to zero. This option should then reduce the fire behaviour on the treated and neighbouring cells and reduce the AAL the year following the treatment application. Currently, the DSS does not distinguish between different fuel management approaches and defines all fuel management activities as a direct reduction in fuel load. We acknowledge that only applying a fuel treatment at the end of the simulation (year 2049) would lead to an artificially high bushfire risk due to the accumulation of fuel load over time (growth of vegetation). In a real-world environment, vegetation growth would be controlled by natural or planned burns and other fuel management activities over the years.

In this exercise, the plausible future fuel management strategies were developed based on information from future land use and bushfire risk maps produced by UNHaRMED, a geospatial dataset combining existing treatments undertaken by DFES[3] and standard practices commonly used to define fuel management strategies.

Overall, as a result of fuel management, the total AAL reduced slightly (between 0.3 to 4%) compared to the no-mitigation scenarios for all regions, demonstrating the benefit of fuel management in reducing bushfire risk at the rural-urban interface (Figure 7). The higher reduction in bushfire risk in the Shire of Mundaring and City of Kalamunda indicates that treating a larger proportion of the landscape was more effective for bushfire risk management (Table 3 and Figure 7).

[3] DFES Bushfire Risk Management System (BRMS) Assets & Treatments. https://catalogue.data.wa.gov.au/dataset/dfes-bushfire-risk-management-system-brms-assets-treatments

Although the proportional change in bushfire risk between the mitigation (scenarios b) and no-mitigation scenarios (scenarios a) decreased slightly with more severe climate change, the increase in absolute change in risk was non-negligible (Table 3). Moreover, the absolute change in total AAL with the application of fuel management was greater in the climate change scenarios (2b and 3b) than in the no-climate change scenario (1b) (Table 3). These observations suggest that fuel management can be used to reduce the impact of climate change on future bushfire risk.

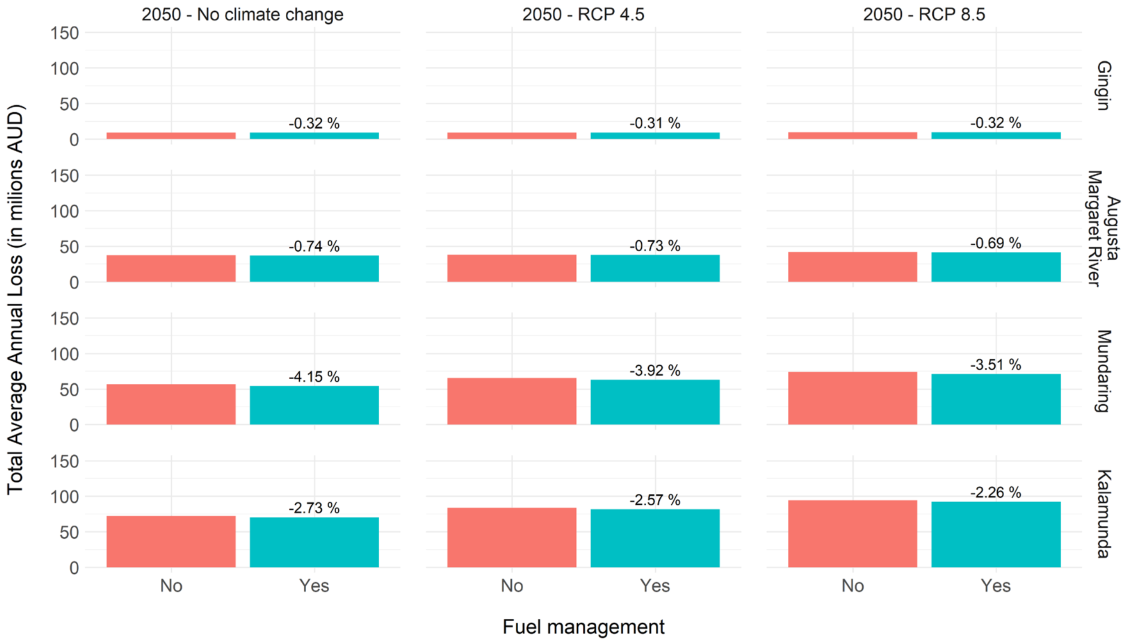

FIGURE 7. IMPACT OF FUEL MANAGEMENT ON THE TOTAL AVERAGE ANNUAL LOSS FROM BUSHFIRES (IN MILLIONS AUD) FOR THE FOUR TARGET REGIONS UNDER THREE FUTURE CLIMATE SCENARIOS. NOTE THE PERCENTAGE DISPLAYED ON TOP OF EACH DIAGRAM REPRESENTS THE RELATIVE CHANGE IN TOTAL AAL DUE TO FUEL MANAGEMENT.

However, our results suggest that in the current setting, where fuel load reduction was only applied in the last year of the simulation, even if fuel management reduced bushfire risk, this reduction was much less than the increase in risk from climate change (2b and 3b). These results could be explained by the fact that fuel load reduction was only applied to a very small fraction of the landscape (0.3 – 10%) on a single year (2049). Another potential explanation for this limited reduction could be that fuel reduction activities were not always located directly adjacent to valued assets, which the fire spread and risk calculation model in UNHaRMED might not have picked up.

Nonetheless, these observations indicate that other mitigation options will be needed to reduce bushfire risk in the future. For example, the level of fuel management will likely need to increase in light of climate change (e.g. higher revisit frequency to specific sites, increase to surface treated on a given year, etc.). Another mitigation strategy could combine different zoning strategies to limit development in high-bushfire risk areas with fuel reduction activities.

Local Government	Scenario	Fuel management	Total area (ha)	Total area treated (ha)*	Total AAL (in millions AUD)	Change in total AAL from management (%)**
Gingin	1a	No	320,705	0	9.11	
	1b	Yes		1,048 (0.3%)	9.08	-0.3 (-$28,727)
	2a	No		0	9.36	
	2b	Yes		1,048 (0.3%)	9.33	-0.3 (-$29,220)
	3a	No		0	9.68	
	3b	Yes		1,048 (0.3%)	9.65	-0.3 (-$30,754)
Augusta - Margaret River	1a	No	212,129	0	37.33	
	1b	Yes		857 (0.4%)	37.05	-0.7 (-$276,087)
	2a	No		0	37.95	
	2b	Yes		857 (0.4%)	37.67	-0.7 (-$275,429)
	3a	No		0	41.76	
	3b	Yes		857 (0.4%)	41.47	-0.7 (-$287,744)
Mundaring	1a	No	64,297	0	56.53	
	1b	Yes		2,386 (3.4%)	54.18	-4.2 (-$2,346,283)
	2a	No		0	65.66	
	2b	Yes		2,386 (3.4%)	63.09	-3.9 (-$2,570,843)
	3a	No		0	73.86	
	3b	Yes		2,386 (3.4%)	71.27	-3.5 (-$2,589,386)

TABLE 3. CHANGE IN TOTAL AAL FOR THE THREE CLIMATE CHANGE SCENARIOS AND IMPACT OF FUEL MANAGEMENT. * THE PROPORTION OF THE LOCAL GOVERNMENT AREA TREATED IN PERCENT IS PRESENTED IN PARENTHESIS. ** THE ABSOLUTE CHANGE IN TOTAL AAL (IN AUD) IS PRESENTED IN PARENTHESIS.

Local Government	Scenario	Fuel management	Total area (ha)	Total area treated (ha)*	Total AAL (in millions AUD)	Change in total AAL from management (%)**
Kalamunda	1a	No	32,394	0	72.30	
	1b	Yes		3,414 (10.5%)	70.32	-2.7 (-$1,974,400)
	2a	No		0	83.92	
	2b	Yes		3,414 (10.5%)	81.76	-2.6 (-$2,158,317)
	3a	No		0	94.35	
	3b	Yes		3,414 (10.5%)	92.23	-2.3 (-$2,129,036)

TABLE 3 (CONTINUED). CHANGE IN TOTAL AAL FOR THE THREE CLIMATE CHANGE SCENARIOS AND IMPACT OF FUEL MANAGEMENT. * THE PROPORTION OF THE LOCAL GOVERNMENT AREA TREATED IN PERCENT IS PRESENTED IN PARENTHESIS. ** THE ABSOLUTE CHANGE IN TOTAL AAL (IN AUD) IS PRESENTED IN PARENTHESIS.

6. FUTURE RESEARCH DIRECTIONS

Discussions with end-users and researchers identified five major research directions to build on the results from the current utilisation project. Two of the items relate to an expansion of the current utilisation project and two to the technical development of the DSS. The five projects are listed below and presented in more detail in the following sections:

- Improvements and expansion of the maps of opportunities for fuel management strategies
- Identification of areas of emerging bushfire risk to increase resilience at the local, regional and national scale
- Parameterisation and validation of the UNHaRMED bushfire model block
- Exploring the impact of different bushfire risk reduction strategies
- Developing new metrics to quantify the impact of bushfires.

6.1 IMPROVEMENTS AND EXPANSION OF FUEL MANAGEMENT SUITABILITY TOOL

To build on the results from the General Guidance Framework for the selection of fuel management strategies developed as part of this project (Jeanneau et al., 2021b), a refinement of the framework could be envisaged by considering local knowledge from other Australian regions (e.g. South Australia, Victoria, Tasmania) as outlined in Figure 8.

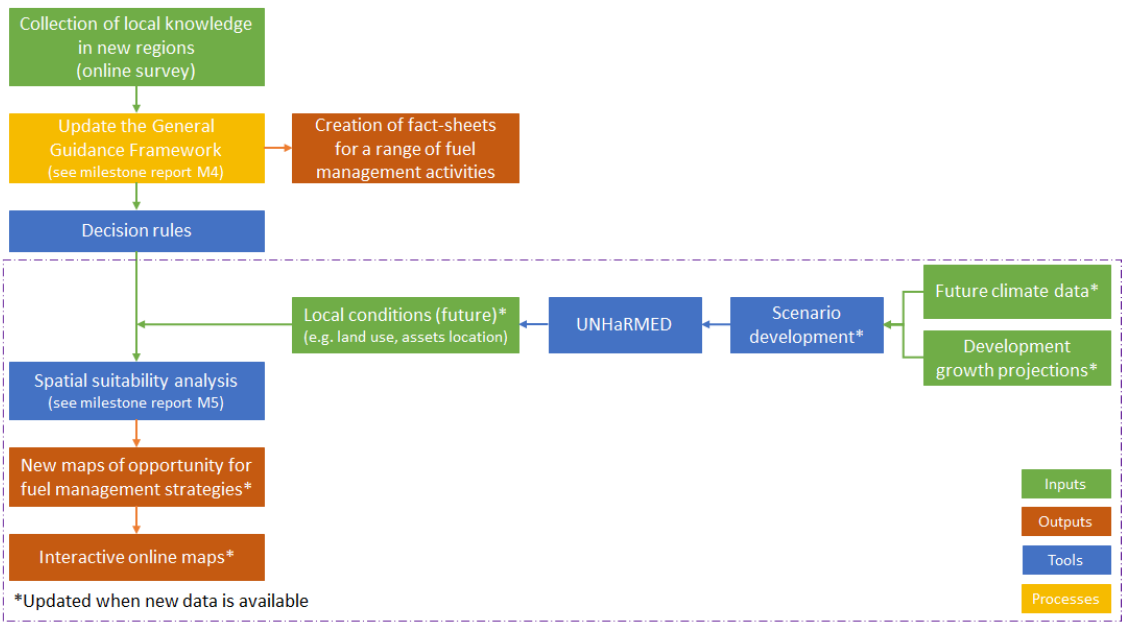

FIGURE 8. IMPROVEMENT AND EXPANSION OF THE GENERAL GUIDANCE FRAMEWORK FOR THE SELECTION OF FUEL MANAGEMENT STRATEGIES AND APPLICATION OF THE FUEL MANAGEMENT SUITABILITY TOOL WITH NEW LOCAL KNOWLEDGE IN THE NEW REGIONS.

The online survey designed for the development of the framework could be sent to Local Government Bushfire Mitigation Officers (or similar) from other States and covering a range of industries (e.g. Forestry, Department of Biodiversity, Conservation and Attractions (DBCA)). The new surveys' results would capture a broader set of local knowledge about the limitations and possibilities of applying different mitigation options to reduce bushfire risk. In parallel, up-to-date information on future climate data, population and demographics growth projections could be combined to develop a range of plausible future scenarios (see the BNHCRC Tactical Research Fund website[4] for more information). These scenarios could then be set up in UNHaRMED to produce a range of likely regional conditions for each scenario (e.g. land use, asset location, etc.). Outputs from the updated General Guidance Framework (see Jeanneau et al. (2021b) for more details) would be combined with the UNHaRMED-simulated future regional conditions and the Fuel Management Suitability Tool (see Jeanneau et al. (2021f) for more details) to create new sets of maps of opportunities for fuel management strategies in Australia (building on Jeanneau et al. (2021d)). Online interactive maps could be created (e.g. hosted in ArcGIS Online or Shiny.io) to disseminate these results to end-users.

As the process described above can be fully automated, any outputs could be updated when new data is available (e.g. climate data, development growth projections, potential technological changes).

6.2 IDENTIFICATION OF AREAS OF EMERGING BUSHFIRE RISK TO INCREASE RESILIENCE

Climate change will alter the distribution, magnitude and frequency of some natural hazards, and population growth and economic development will change the exposure of communities and built environments to these changing hazards, affecting future risk and profiles and community resilience. The combination of these factors (climate change, population growth, economic development, etc.) might result in some areas, previously considered low risk, becoming high-risk areas, as we have seen during the 2019-2020 bushfire season in Eastern Australia (Royal Commission into Natural Disaster Arrangements, 2020). This project demonstrated that the UNHaRMED DSS could be used to identify future bushfire risk hotspots in WA in the face of climate change and population growth. UNHaRMED is already applied to four sub-regions in Western Australia, South Australia, Victoria, and Tasmania. However, an extension of the DSS could be envisaged to develop a regional or national-scale decision support tool that could quantify changes in long-term bushfire risk at the scale of decades in the future.

Such a model would identify where risk is likely created with future social, ecological and economic change. In addition to this, the risk reduction, investment and adaptive capacities best suited to mitigate future risks, achieving zero preventable deaths and developing well-prepared and resilient communities.

[4] Preparing emergency services for operations in a climate-challenged world https://www.bnhcrc.com.au/research/understanding-and-mitigating-hazards/8023

A prototype integrated national decision-support system could be developed to identify areas of emerging future risk under different scenarios and mitigate that risk through investment, strategy and policy levers (see Figure 9).

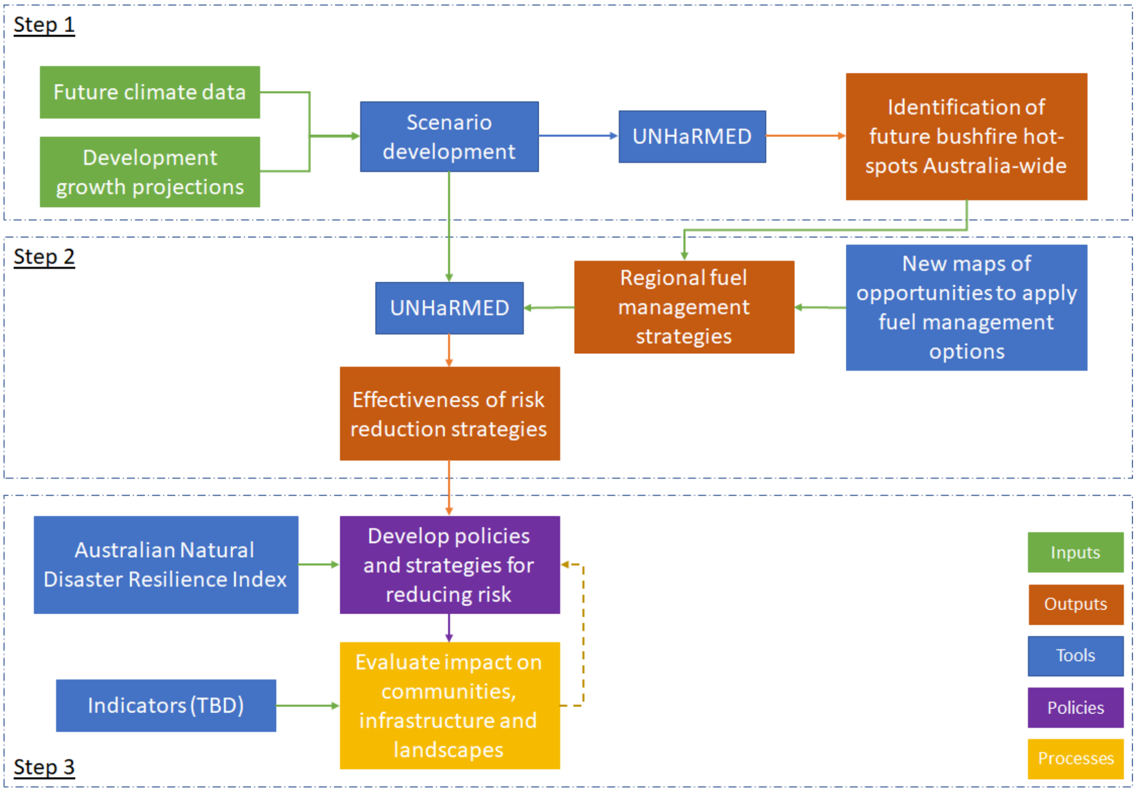

FIGURE 9. PRESENTATION OF THE PROJECT: IDENTIFICATION OF AREAS OF EMERGING BUSHFIRE RISK TO INCREASE RESILIENCE.

The first step of this project (Step 1 in Figure 9) would be to analyse future bushfire risk with UNHaRMED at the national scale (building on Jeanneau et al. (2021c)). To achieve this outcome, up-to-date information on future climate data and population and demographics growth projections would need to be collected to develop a range of plausible future scenarios (similar to those designed for 6.1 and the BNHCRC Tactical Research Fund website[4]). These scenarios would then be simulated in UNHaRMED to identify emerging bushfire risk areas for each scenario.

The second step (Step 2 in Figure 9) would be to build on the results from the project proposed in Section 6.1 to test the effect of different fuel management strategies in reducing future bushfire risk. The updated suitability maps to apply different fuel management strategies (i.e. where fuel management is technically possible, and economically and socially desirable) could be combined with information on the future bushfire hotspots identified in Step 1 (i.e. where fuel management activities are relevant) to develop potential regional fuel management plans. These strategies would then be simulated using the UNHaRMED framework with the scenarios developed in Step 1 to evaluate the effectiveness of different fuel management strategies for the emerging bushfire risk areas. This step will provide information on the different levels of emerging future risk in various locations in Australia. It will also provide visualisation tools to identify the most critical areas that require priority action through maps.

The final step (Step 3 in Figure 9) would be to implement the lessons learned from Steps 1 and 2 in a policy context and combine them with other existing indicators to develop policies and strategies for reducing future bushfire risk at the national scale. National indicators such as *The Australian National Disaster Resilience Index* (NDRI) (Parsons et al., 2020) have estimated the resilience to natural disasters for communities around Australia. This index assesses the overall capacity for communities to recover from natural disasters, their coping and adaptative capacity and eight other themes of disaster resilience across social, economic and institutional domains. The NDRINDRI's primary purpose is to highlight the strengths and barriers to disaster resilience in different communities. The most effective risk reduction strategies identified in Step 2 could be compared against results from the NDRI to evaluate the feasibility of these approaches and develop policies and plans to reduce future bushfire risk. Each policy would be evaluated by a range of indicators considering several competing objectives (e.g. cost, resilience, risk, equity) to prioritise investment in risk reduction strategies. Based on the results from these indicators, the policies and strategies could be revised based on indicator performances and trade-offs. Further work would be needed to identify the most relevant indicators to consider and how performance should be evaluated.

6.3 PARAMETERISATION AND VALIDATION OF THE UNHARMED BUSHFIRE MODEL BLOCK

Based on the results from this project (sections 2 to 5) and discussion with end-users, we identified two major avenues of improvement for the bushfire model in UNHaRMED:

- Identify new ways to collect input data to improve parameters and understand bushfire modelling processes better
- Explore manual and automatic methods to calibrate and validate the bushfire model block.

6.3.1 Identification of new ways to collect input data to improve parameters and better understand bushfire modelling processes

Capitalise on Earth Observations (EO) for new input data

The principal avenue for improving input data is by defining fuel characteristics (i.e. fuel load, fuel moisture, fuel type classification) (Figure 10). It would be possible to capitalise on the growing availability of EO data to derive these characteristics through automated methods. For example, machine learning algorithms could be developed to classify fuel types from satellite or air-borne optical imagery (Stefanidou et al., 2018, Yankovich et al., 2019) or a fusion between Light Detection and Ranging (LiDAR) instruments and optical imagery (Alonso-Benito et al., 2016, Domingo et al., 2020, Sánchez Sánchez et al., 2018). Fuel load could be estimated from vegetation indices that evaluate the vegetation structure and derive fuel amounts such as the Vegetation Structure Perpendicular Index (VSPI) (Massetti et al., 2019). It could also be estimated with the use of Synthetic Aperture Radar (SAR) sensors to estimate the canopy fuel load empirically (Brandis and Jacobson, 2003, Li et al., 2021, Saatchi et al., 2007) or directly with LiDAR instruments (Chen et al., 2017, Marselis et al., 2016). Finally, fuel moisture content could be derived from regression relationships between spectral indices derived from EO and fuel moisture measured in the field (García et al., 2020, Yebra et al., 2019, Yebra et al., 2018).

The main advantage of EO is that input data could be updated as new data becomes available and allow for improved models of bushfire risk to be developed and implemented (i.e. with a direct influence on fire behaviour modelling). These new models will be adaptive to seasonal and longer-term changes in the landscape and enable long-term scenario planning and support decision-making.

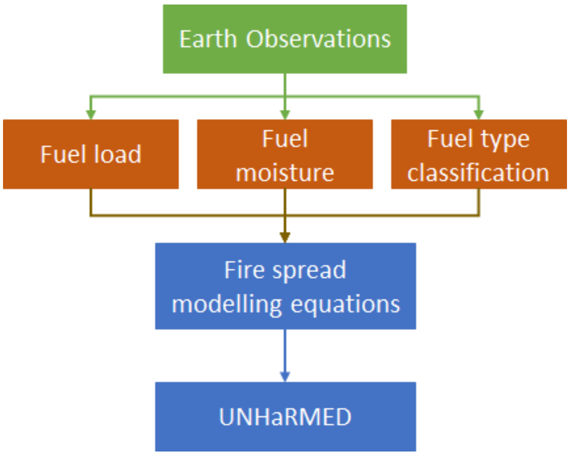

FIGURE 10. EXAMPLES OF NEW WAYS TO COLLECT INPUT DATA: CAPITALISING ON EARTH OBSERVATIONS TO DEFINE FUEL CHARACTERISTICS.

Other avenues of improvement for input data

There is currently limited information to define the vulnerability of assets to bushfire damages (i.e. vulnerability curves). The principal source of information comes from Bushfire Attack Levels (BAL) assets that would have been constructed based on their age and the modelled fire intensity at that location (Australian Standard AS 3959[5]). The vulnerability calculation considers the built strength versus the modelled intensity in a cell to determine whether the asset would be subject to damage. If the fire intensity is greater than constructed strength, it is assumed that the entire asset is lost. Historical data from past bushfire events could be used to improve the way vulnerability is captured in the UNHaRMED framework (Figure 11). For example, information on damages to assets and infrastructure for a range of events could be correlated with the estimated total AAL from UNHaRMED under similar conditions to refine the bushfire damage index curves and the expected fatality maps.

[5] https://www.abcb.gov.au/news/2020/open-access-bushfire-standard

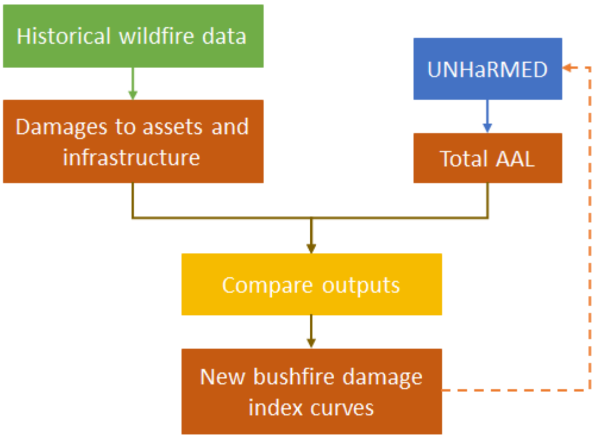

FIGURE 11. EXAMPLES OF NEW WAYS TO COLLECT INPUT DATA: USING HISTORICAL DATA TO IMPROVE UNDERSTANDING OF ASSETS VULNERABILITY TO BUSHFIRES.

6.3.2 Exploration of manual and automatic ways to calibrate and validate the bushfire model block

Given that the testing phase of the UNHaRMED DSS for WA is close to completion, there would be significant merit to undertake a detailed simulation study to validate and evaluate the modelling results. There could be two ways to approach this question: manual (e.g. comparing UNHaRMED outputs with historical fire data) and automated methods (e.g. fire behaviour modelling).

Manual calibration and validation methods for bushfire risk modelling

Historical data from past bushfire events could be used to extract information on damages incurred from bushfires (e.g. loss of assets, infrastructure, cost of fire events) and directly compare these metrics with UNHaRMED simulation results for the same conditions (e.g. land use, building types, weather)(Figure 12a). This comparison method could be used to corroborate UNHaRMED outputs and identify how plausible the simulation results can be compared to real-world data.

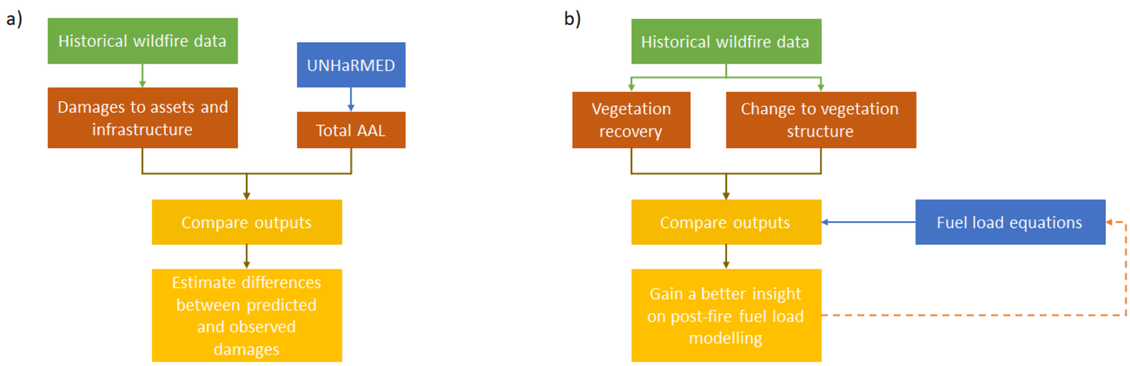

FIGURE 12. EXAMPLES OF MANUAL CALIBRATION AND VALIDATION METHODS FOR BUSHFIRE RISK MODELLING.

Another way to use historical data would be to examine how vegetation structure changes after a fire event and how it recovers (in terms of growth rate and structure) (Figure 12b). This information could be used to gain a better insight into how fuel load should change after an event and could lead to conceptual modifications of the fuel load equations.

Automated calibration methods for fire behaviour modelling

There is a need to better understand the processes involved in bushfire modelling and the current limitations of each approach. This knowledge could be used to explore potential avenues to improve how fire behaviour is implemented in UNHaRMED.

One example could be to use physically-based dynamic bushfire models such as Phoenix (Tolhurst et al., 2008), Spark (Miller et al., 2015) or Aurora (Steber et al., 2012) (Figure 13). These models are instrumental in predicting the intensity and spread of particular fire events under a given set of environmental conditions (e.g. temperature, relative humidity, wind speed, wind direction etc.). When coupled with Monte Carlo Simulations (MCSs), they can identify the most likely fire paths and fire front direction for a set of environmental conditions (Alcasena et al., 2017, Parisien et al., 2019, Ager et al., 2017). Results from MCSs could also help to define new fire spread weighting functions, accounting for a greater spread in directions of more likely fire paths. Combining these improvements with further fuel information from EO (see 6.3.1) would help define a new fire spread model for use within UNHaRMED. The MCSs could also be used to account for the effects of fire shadows or ember attacks. These results combined with better input data on assets vulnerability (see 6.3.1) could help to improve the current BAL based vulnerability functions in UNHaRMED.

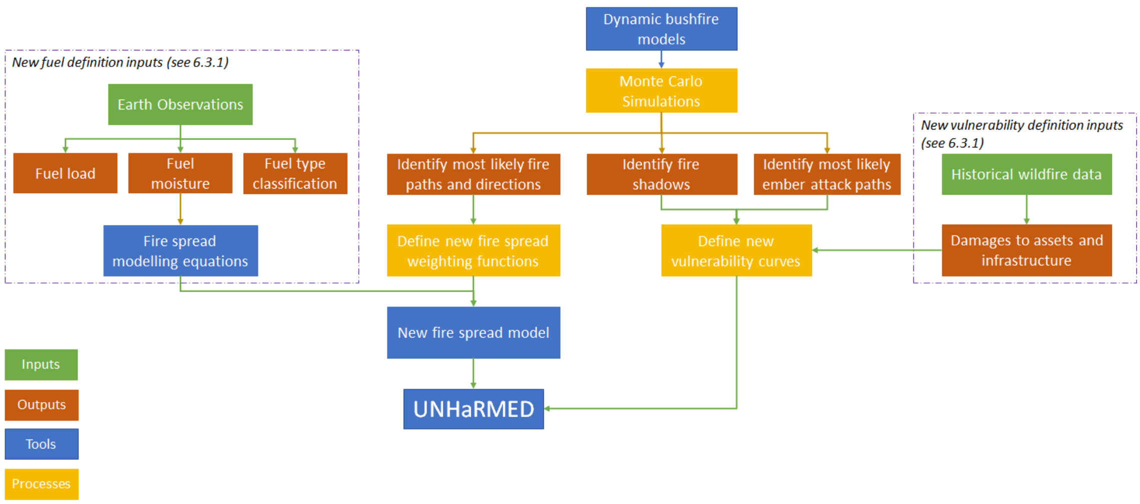

FIGURE 13. EXAMPLES OF AUTOMATIC CALIBRATION METHODS FOR FIRE BEHAVIOUR MODELLING.

6.4 EXPLORATION OF THE IMPACT OF DIFFERENT BUSHFIRE RISK REDUCTION STRATEGIES

This project has looked at how fuel management at the rural-urban interface, defined as a direct reduction in fuel load, could impact future bushfire risk. Other fuel management strategies could be explored in the future to increase the resilience of future bushfire risk management planning in the face of climate change. For example, further work could explore the influence of landscape-scale mitigation strategies on future bushfire risk by testing the effect of different fuel management mosaics at strategic locations in the landscape (e.g., changing the amount of the landscape treated) or testing the influence of treatment distance from specific assets. The exploratory analysis presented in

Section 5 could also be expanded to consider treatment strategies over longer time frames. For instance, different fuel reduction strategies could be compared with UNHaRMED to evaluate the effectiveness of reducing fuel load at regular intervals (e.g. every year, 5-years, etc.). Because fuel management in non-grass fuels will have a longer lasting effect (> 1 year) as fuel re-accumulation is slow (between 5-20 years, depending on the fuel type and layer), the timing of different fuel reduction treatments could be adjusted for a range of vegetation types.

Another example of a risk management strategy to explore within the UNHaRMED framework could be to assess the effect of policy changes on future bushfire losses. For example, by modifying building codes, zoning restrictions and future infrastructure development or through increased asset hardening, and education and engagement of community leaders.

The community already has growing concerns regarding the side effects and social and environmental acceptability of different fuel treatments (e.g. smoke taint of grapes from planned burns). However, these will need to be balanced with the potential co-benefits of these same treatments (e.g. fuel management, safer access, seed regeneration, weed control, etc.). Further work could use the methodology developed for the General Guidance Framework for the selection of different fuel management strategies to identify the benefits and limitations of a range of fuel management options (Jeanneau et al., 2021b) and run a cost-benefit analysis for each method.

Another avenue for research could also explore the impact of climate change on the drying of vegetation (i.e. curing)), as this would influence the ability of vegetation to catch on fire. Currently, the UNHaRMED bushfire model considers that vegetation is completely dry (100% curing). However, with the improvement of input data proposed in section 6.3.1, it should be possible to test the influence of different fuel moisture levels on fire behaviour with a range of climate scenarios.

6.5 DEVELOPMENT OF NEW METRICS TO QUANTIFY THE IMPACT OF BUSHFIRES

Currently, the bushfire risk in UNHaRMED is estimated from a combination of bushfire likelihood, exposure (i.e. value and the number of assets exposed to fires), and vulnerability (i.e. functions that describe building vulnerability to fires) and is expressed as an Average Annual Loss (AAL, in AUD).

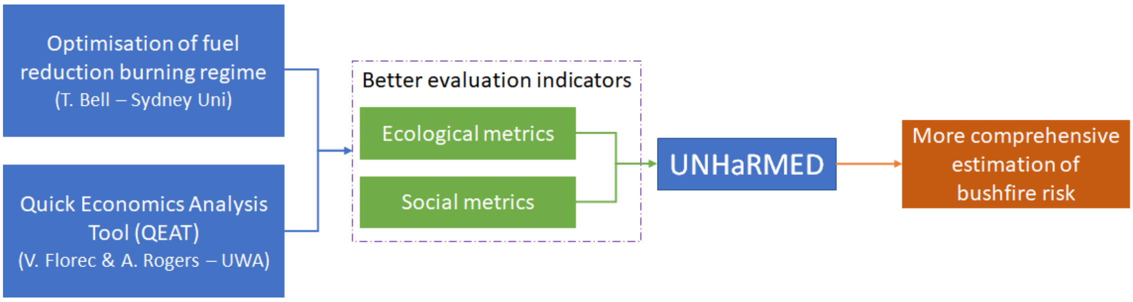

FIGURE 14. DESCRIPTION OF POSSIBLE NEW BUSHFIRE RISK METRICS FOR UNHARMED.

While critical for comparability with the other hazards modelled within UNHaRMED, the use of AAL makes it difficult to quantify the ecological and social impact of bushfires in each regional application. To address this issue, exploratory work (e.g. literature review) could identify a range of indicators available to complement the AAL metric. This scoping will need to be done in consultation with end-users to determine which ones would be the most relevant to them and how flexible they would be to adopt new evaluation approaches. A possible outcome of this investigation could be to propose a new conceptual approach quantifying the impact of bushfires on non-market assets (e.g. human health, ecosystems, cultural heritage, etc.) that could be applicable at a regional scale across various States.

For instance, two examples from other Bushfire and Natural Hazard CRC projects could be investigated: *Optimisation of fuel reduction burning regime* and *Economics of natural hazards* BNHCRC projects (Figure 14). The former produced a framework to quantify the effects of planned burning on a range of environmental services (e.g. carbon and nutrient stocks, water quality, vegetation diversity) (Gharun et al., 2017). This approach could add new ecological indicators in the UNHaRMED framework and help end-users develop new fuel mitigation scenarios that maximise environmental services. The second project developed the Quick Economics Analysis Tool (QEAT) (Florec et al., 2019) and a searchable database called the Value Tool (Rogers et al., 2018). The QEAT tool compares different fuel management treatments by estimating each option's economic, social and environmental benefits. This method could be adapted to our application and transferred to the UNHaRMED framework to compare the benefits of a range of fuel management options. The Value Tool is a database listing non-market valuation studies for intangible values affected by natural hazards and their management (e.g. fire, floods, earthquakes). The methods presented in these studies could be used as a guide to define social, environmental, and human health values to complement the AAL estimates in UNHaRMED (i.e. the exposure and vulnerability components). These new indicators could then be used to look at the costs and benefits of different fuel management options in the light of climate change on future social, environmental and infrastructure risks.

In addition to non-market assets, further work could examine the indirect impact of bushfires on other economic or social aspects. For example, in agriculture, when bushfires ravage crops or smoke taint spoils grapes ready for harvest, these events indirectly impact the entire food chain and lead to direct losses for farmers. Another indirect impact worth exploring could be the effect of smoke on community health (e.g. asthma or other respiratory diseases), which might only develop several years after catastrophic bushfire events.

Another aspect that could be explored in the future would be to look into the possibility, and time it takes, to recover from a fire event. For instance, assets (e.g. houses and infrastructure) could be rebuilt relatively quickly after an event, while it might take 50 years or more for an ecosystem to recover from a fire if it was not devastated beyond rehabilitation.

7. SUMMARY

Overall, this project demonstrated that UNHaRMED could be used to (i) identify areas of emerging bushfire risk, (ii) quantify the impact of climate change on future losses due to bushfires, and (iii) quantify to what extent fuel management strategies are able to mitigate future bushfire losses.

This project also developed a novel approach to identify where different fuel management approaches could be applied in different areas using a combination of local knowledge/experience and spatial data analysis. The method was tested in four areas of emerging bushfire risk in Western Australia and led to the development of interactive maps for seven fuel management activities. These maps indicate where particular fuel management approaches can technically be applied (= suitable) and where they are socially acceptable and economically feasible. These maps can be obtained for current and future conditions with the aid of UNHaRMED, therefore providing an assessment of which fuel management options are available to mitigate the impact of bushfires in areas of emerging risk. The approach is generic and flexible and can be tailored to different locations based on local knowledge and experience.

This utilisation project was a proof of concept for the UNHaRMED Decision Support System (DSS) and could be refined through five principal research directions. First, the suitability analysis presented in this report could be easily expanded to other regions in Australia by considering local knowledge from other Australian regions outside of WA. Second, a prototype integrated national decision-support system, similar to the one presented here, could be developed to identify areas of emerging future risk under different scenarios and mitigate that risk through investment, strategic and policy levers. Third, improving data collection (e.g. Earth Observations, historical data) and understanding of fire behaviour processes could contribute to the parameterisation and validation of the bushfire model. Fourth, although this project explored the effect of fuel reduction on future bushfire risk, additional work could investigate the impact of different risk reduction strategies. Such work could look at landscape-scale mitigation strategies, the co-benefits and side-effects of a range of fuel management activities, and explore the impact of climate change on the drying of vegetation. Finally, new indicators and metrics could be included to better assess the impact of bushfires on non-market assets (e.g. ecological and social impacts) and indirect losses (e.g. impact on the entire food chain).

TEAM MEMBERS

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END-USERS

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Department for Environment and Water (DEW)	Mike Wouters Simeon Telfer
Tasmanian Fire Services (TFS)	Louise Mendel

APPENDIX 1: THE GENERAL GUIDANCE FRAMEWORK

TABLE 4. PRESENTATION OF THE GENERAL ANALYTICAL FRAMEWORK MECHANICAL FUEL MANAGEMENT ACTIVITIES). THE TEXT IN BLACK REPRESENTS INFORMATION COLLECTED THROUGH THE ONLINE SURVEY, IN BLUE INFORMATION COLLECTED FROM THE LITERATURE ONLY, AND IN ORANGE INFORMATION FOUND IN THE LITERATURE REVIEW AND THE ONLINE SURVEY.

	Forest thinning	Scrub rolling/ Brush-cutting	Mulching	Mowing/Slashing	Fire breaks and strategic access	Parkland clearing
Cost	US: $87 to $3000/ha	US: $90 to $110/ha	- Australia: highly variable[6] $100 to $280/hour, up to $3,000/ha; $6,000/ha in heavy forested fuels - US: $40 to $400/ha	- Australia: $100 to $120/hour - US: $10 to $16/ha	Australia: highly variable[6] $120/km to $1,000/ha	Australia: highly variable[6] $150 to $400/hour, up to $1,500/ha or $8,000/ha
Benefits	- Reduce the potential for active crown fire spread - Can be chipped and used as bio-fuel to generate energy - Sale of woodchips can reduce initial cost - Can remove invasive species (e.g. mistletoe, beetles, etc.)	- Fuel reduction - Blade-up and Chopper Rolling are much easier to manage around sensitive sites	- Fuel reduction - Reduce the potential for active crown fire spread - Improve the visual amenity of the area - Improve the amenity value - Improve ecological function of the area - Create a temporary buffer/fire	- Fuel reduction - Provide mulch and minimise risk of fire - Improve the visual amenity of the area - Manage vegetation on verges and expanses of undeveloped land - Weed control - Productivity 3 to 5 times greater than mulching	- Fuel reduction - Improve ecological function of the area - Improve the visual amenity of the area - Create better access for future mitigation and suppression activities or for the search of missing person - Limit fire spread and size	- Fuel reduction - Improve the visual amenity of the area - Alteration of fuel structure - Easy to maintain once established - Create a physical barrier between interfaces (e.g. rural-urban interface) - Easy to maintain once established

[6] Will depend on depends on terrain, fuel load, state of existing tracks, contractor, type of treatment, extent of the area to treat, etc.

			break (for planned burning or wildfires)		- Create a physical barrier between interfaces (e.g. rural-urban interface) - Easy to maintain	- Minimal soil disturbance

TABLE 4. (continued) PRESENTATION OF THE GENERAL ANALYTICAL FRAMEWORK (MECHANICAL FUEL MANAGEMENT ACTIVITIES). THE TEXT IN BLACK REPRESENTS INFORMATION COLLECTED THROUGH THE ONLINE SURVEY, IN BLUE INFORMATION COLLECTED FROM THE LITERATURE ONLY, AND IN ORANGE INFORMATION FOUND IN THE LITERATURE REVIEW AND THE ONLINE SURVEY.

	Forest thinning	Scrub rolling/ Brush-cutting	Mulching	Mowing/Slashing	Fire breaks and strategic access	Parkland clearing
Benefits (continued)					- Low impact on bush land - Reduce the perceived bushfire risk of neighbours.	
Limitations	- Soil moisture (for machinery accessibility) - Cost increases with distance to access roads - Transportation cost of hauling biomass - Nutrient removal	- Increases surface fuel density and continuity - Works better with dry or dead vegetation Only cost-effective if applied in strips of about 20m wide	- Risk of damaging trees when pruning (which can result in pathogen entry points for fungi) - Can be visually unappealing if unsuitable equipment is used or if site is left untidy after treatment - Cost increases with distance to access	- Not species-specific - Risk of reducing the ecological function of the area if total vegetation removal (e.g. biodiversity, wildlife habitat) - Risk of causing fire with the mowing equipment - Limited to fine fuels - Limited equipment	- Increased erosion risk - Allows possible unauthorised access to area - Loss of vegetation - Increased maintenance costs - Not an effective fire break if not maintained properly (e.g. summer/during restricted period)	Expensive

			roads and tree diameter - Steep topography and poor site conditions (e.g. uneaven surface) - Does not produce merchantable forest products (e.g., saw logs or woodchips)	manoeuvrability in steep topography - Equipment availability - Dry roads to allow machinery access	- People may also assume fire breaks may actually stop all fires from progressing	

TABLE 4. (continued) PRESENTATION OF THE GENERAL ANALYTICAL FRAMEWORK (MECHANICAL FUEL MANAGEMENT ACTIVITIES). THE TEXT IN BLACK REPRESENTS INFORMATION COLLECTED THROUGH THE ONLINE SURVEY, IN BLUE INFORMATION COLLECTED FROM THE LITERATURE ONLY, AND IN ORANGE INFORMATION FOUND IN THE LITERATURE REVIEW AND THE ONLINE SURVEY.

	Forest thinning	Scrub rolling/ Brush-cutting	Mulching	Mowing/Slashing	Fire breaks and strategic access	Parkland clearing
Equipment	- Feller-bunchers - Chainsaw (hand felling) - Skidders and forwarders	- Large steel drums with cutting knives mounted on the face of the drum - Drums can be towed behind a wheeled or tracked by a tractor, or they can be pulled on a winch cable (for steeper slopes)	- Track and tyre based skid steer/Bobcat machines fitted with rotary drum nibbling heads - Excavators with a mastication head - Horizontal or vertical shaft cutting heads	- Ride on mowers - Whipper-snippers - Brush cutters - Chainsaws - Mulchers - Tractor mounted slashing equipment (3-point linkage equipment) - Steel-track tractor with a front-mounted rotating toothed drum	- Loader - Excavator - Skid Steer - Grader - Disc plough - "Posi-track" machines with mulching head - Bobcats - Chainsaws - Slashers - Chemical spray unit	- Mulching head - Bobcat

Experience and training	Machine operator	Machine operator	- Experienced machine operators - Understanding of forest types, environment and biodiversity - Fire and Land Management Training	- No specific training required - Conservation and Horticulture certificates. - Safety courses for equipment - Knowledge of machinery operations	- Understanding of the local regulations (e.g. Firebreak Notice, Bushfire Act, Environmental Protection Act, Biodiversity conservation Act, Aboriginal Heritage Act, etc.) - Experience in mapping and understanding the local topography - Contract management	- Very good machine operators - Background in horticulture and forestry

TABLE 4. (continued) PRESENTATION OF THE GENERAL ANALYTICAL FRAMEWORK (MECHANICAL FUEL MANAGEMENT ACTIVITIES). THE TEXT IN BLACK REPRESENTS INFORMATION COLLECTED THROUGH THE ONLINE SURVEY, IN BLUE INFORMATION COLLECTED FROM THE LITERATURE ONLY, AND IN ORANGE INFORMATION FOUND IN THE LITERATURE REVIEW AND THE ONLINE SURVEY.

	Forest thinning	Scrub rolling/ Brush-cutting	Mulching	Mowing/Slashing	Fire breaks and strategic access	Parkland clearing
Experience and training (continued)					- Project management - Knowledge of local fire activity/conditions to be able to take the path of least environmental damage	

Timing	- Autumn - Winter - Spring	When fuel is dry	- Summer[7] - Autumn[7] - Winter - Spring	- Summer[7] - Autumn - Winter - Late spring	- Late spring[7] - Summer[7] - Autumn - Winter	- Spring - Summer - Early autumn[7]
Vegetation	- Plantation forests (e.g. pine) - Overstory vegetation (for biomass harvesting)	- Shrubland - Plantation forests (e.g. eucalypts) - Mallee - Mallee-heath	- Forests (small hardwood species up to 25cm in diameter) - Shrubland - Woodland - Grassland	- Shrubland - Grassland - Spinifex	- Forests - Woodland - Shrubland - Grassland	- Woodland - Open forests
Driving factors	- Slope - Distance to access roads - Presence of protected biodiversity elements	- Terrain - Fuel dryness	- Slope - Distance to access roads - Distance to assets - Presence of protected biodiversity elements - Land use	- Terrain - Distance to access roads - Distance to assets - Distance to conservation areas -	- Terrain - Slope - Distance to assets - Distance to conservation areas - Presence of protected biodiversity elements	- Slope - Terrain - Distance to access roads - Distance to assets - Presence of protected biodiversity elements

TABLE 4. (continued) PRESENTATION OF THE GENERAL ANALYTICAL FRAMEWORK (MECHANICAL FUEL MANAGEMENT ACTIVITIES). THE TEXT IN BLACK REPRESENTS INFORMATION COLLECTED THROUGH THE ONLINE SURVEY, IN BLUE INFORMATION COLLECTED FROM THE LITERATURE <u>ONLY</u>, AND IN ORANGE INFORMATION FOUND IN THE LITERATURE REVIEW <u>AND</u> THE ONLINE SURVEY.

	Forest thinning	Scrub rolling/ Brush-cutting	Mulching	Mowing/Slashing	Fire breaks and strategic access	Parkland clearing
Driving factors (continued)			- Vegetation type - Fuel structure - Amount of fuel	- Presence of protected biodiversity elements - Land use type - Fuel structure	- Fuel structure - Amount of fuel - Soil conditions	- Amount of fuel - Size of the area to treat

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[7] Seasons supporting the highest likelihood of an effective fuel management program (maximum consensus amongst the survey participants).

			- Size of the area to treat	- Amount of fuel - Soil conditions - Size of the area to treat	- Ability to keep burn within containment lines	
Landscape	- Slopes: 0 – 30% - Treatment scale: > 10 ha	- Slopes: 0 – 35% - Treatment scale: 20 – 200 m wide strips	- Slopes: 0 – 16% (up to 35% with adapted machinery) - Treatment scale: 5 – 20 m wide	- Slopes: 0 – 16% - Treatment scale: small plots	- Slopes: 0 – 30% - Treatment scales: o Land vacant or over 4000 m² require fire breaks; o 3 – 5 m wide directly adjacent to assets o Slope 0-5% → 30m wide o Slope 5-15% → 40m wide o Slope>15% → 50m wide o Within 30 to 100 m from building zones - Within 300 m from plantation forests	- Slopes: 0 – 10% - Treatment scales: 20 m wide starting from structures and around the boundary of reserves within townsites

TABLE 4. (continued) PRESENTATION OF THE GENERAL ANALYTICAL FRAMEWORK (MECHANICAL FUEL MANAGEMENT ACTIVITIES). THE TEXT IN BLACK REPRESENTS INFORMATION COLLECTED THROUGH THE ONLINE SURVEY, IN BLUE INFORMATION COLLECTED FROM THE LITERATURE ONLY, AND IN ORANGE INFORMATION FOUND IN THE LITERATURE REVIEW AND THE ONLINE SURVEY.

	Forest thinning	Scrub rolling/ Brush-cutting	Mulching	Mowing/Slashing	Fire breaks and strategic access	Parkland clearing
Land use	- Plantation forests - Nature reserves and conservation forests	- Plantation forests	- Vacant plots	- Vacant plots	- Vacant plots	- Nature reserves and conservation forests

		- Nature reserves and conservation forests - Mixed farming and grazing	- Nature reserves and conservation forests - Recreational areas - Residential and rural residential - Industrial	- Nature reserves and conservation forests - Recreational areas - Residential and rural residential - Industrial - Pasture - Horticulture - Mixed farming and grazing	- Nature reserves and conservation forests - Residential and rural residential - Industrial - Plantation forests - Intensive agriculture - Livestock grazing - Mixed farming and grazing	- Residential and rural residential - Industrial - Utilities and infrastructure
Other considerations	- Removal of fine fuel in the understory to limit fire hazard - Set minimum distance and maximum surface treated in the presence of protected or endangered species - Consider combining with planned burning to maximise fuel reduction	- Can be used as a treatment for wildlife habitat improvement - Cost-effective if there is a commitment to ongoing management/maintenance to maintain risk reduction benefits over time	- Can be used to complement planned burning to reduce fuels in the landscape adjacent to assets - Follow up maintenance program to remain effective in the longer term - Vertical shaft cutting heads are generally lighter	- Prefer hand slashing where sensitive/endangered species are identified - Only apply where there is a significant need rather than removing all the vegetation	- Use contours and appropriate water runoff (e.g. fallen tree branches) to limit erosion risks - Consider offset planting to limit erosion risks - Use gates to reduce un-authorised access - Develop consistent firebreak specifications across different Local Governments	- Apply treatment as close as possible from assets to maximise fuel reduction Consider combining with planned burning to maximise fuel reduction

TABLE 4. (continued) PRESENTATION OF THE GENERAL ANALYTICAL FRAMEWORK (MECHANICAL FUEL MANAGEMENT ACTIVITIES). THE TEXT IN BLACK REPRESENTS INFORMATION COLLECTED THROUGH THE ONLINE SURVEY, IN BLUE INFORMATION COLLECTED FROM THE LITERATURE ONLY, AND IN ORANGE INFORMATION FOUND IN THE LITERATURE REVIEW AND THE ONLINE SURVEY.

	Forest thinning	Scrub rolling/ Brush-cutting	Mulching	Mowing/Slashing	Fire breaks and strategic access	Parkland clearing
Other considerations (continued)			- Horizontal shaft cutting heads provide more mulching action		- Promotion of property requirements, active annual property inspections, education programs and enforcement practices to minimise complacency risk	
Sources	Endress et al. (2012) Forestry Tasmania (2001) Hunter et al. (2007) Loudermilk et al. (2014) Metlen and Fiedler (2006) Nader et al. (2007) Stephens et al. (2009) Stephens et al. (2012) Volkova et al. (2017) Windell and Bradshaw (2000)	Burrows (2015) OBRM (2018) Rummer (2010) Windell and Bradshaw (2000)	Halbrook et al. (2006) Hunter et al. (2007) Jain et al. (2018) Kane et al. (2006) Kreye et al. (2014) Martorano et al. (2021) OBRM (2018) Rummer (2010) Windell and Bradshaw (2000)	Nader et al. (2007) OBRM (2018) Potts and Stephens (2009) Pyke et al. (2014)	Burrows (2015) Leask and Smith (2011) Partners in Protection (2003)	OBRM (2018)

TABLE 5. PRESENTATION OF THE GENERAL ANALYTICAL FRAMEWORK (OTHER FUEL MANAGEMENT ACTIVITIES). THE TEXT IN BLACK REPRESENTS INFORMATION COLLECTED THROUGH THE ONLINE SURVEY, IN BLUE INFORMATION COLLECTED FROM THE LITERATURE ONLY, AND IN ORANGE INFORMATION FOUND IN THE LITERATURE REVIEW AND THE ONLINE SURVEY.

	Planned burning	Pile burning	Chipping	Herbicide	Grazing
Cost	- Australia: highly variable[8] $500/ha to less than $100/ha - US: $14 to $120/ha	US: $18 to $300/ha	US: $1600/day	- Australia: highly variable[8]; less than $150/km to up to $500/ha - US: $10 to $100/ha	US: $25 to $30/ha
Benefits	- Fuel reduction - Improve ecological function of the area - Cheapest fuel management method	- Wider window of opportunity than planned burning - Low risk of fire escape - Minimal damage to surrounding trees	- Good alternative to pile burning if piles have already been constructed - Chips can be used for erosion protection - Promotes nutrient cycling - Selling of wood by-product	- Fuel reduction - Improve ecological function of the area - Improve the visual amenity of the area - Reduce invasive weeds into bushland - Can target specific plant species	- Fuel reduction - Short-term treatments to reduce flammable vegetation - Hoof incorporation of fine fuels (burial, mixing with soil)
Limitations	- Risk of damaging fire-sensitive vegetation - Burn cost per hectare is higher on small areas - Difficult to control (risk of fire escape) - Impact air quality - Limited window of opportunity	- Cost increases with distance to access roads	- Expensive technique - Towed chippers are limited to roadside processing	- Risk of killing vegetation outside the range of intended species - Can increase fuel load if left and not removed	- Removal of native species - Spread of weeds - Risk of overgrazing - Grazing in non-palatable environments (e.g. conifer forests) can result in an increase in fuel loads

[8] Will depend on depends on terrain, fuel load, state of existing tracks, contractor, type of treatment, extent of the area to treat, etc.

	- Difficult to implement if fuel load is too high			- Cost increases with distance to access roads - Contamination risk (leaching)	- Livestock cannot effectively control mature bush plants - Risk of trampling/soil compaction (if stock density is too high)

TABLE 5. (continued) PRESENTATION OF THE GENERAL ANALYTICAL FRAMEWORK (OTHER FUEL MANAGEMENT ACTIVITIES). THE TEXT IN BLACK REPRESENTS INFORMATION COLLECTED THROUGH THE ONLINE SURVEY, IN BLUE INFORMATION COLLECTED FROM THE LITERATURE ONLY, AND IN ORANGE INFORMATION FOUND IN THE LITERATURE REVIEW AND THE ONLINE SURVEY.

	Planned burning	Pile burning	Chipping	Herbicide	Grazing
Equipment	- Utility mounted flamethrower - Hand firelighters - Aerial ignition with drip torches - Four wheel drive mounted water firefighting units and larger truck mounted units	-	- Swing machine with a brush-cutter or saw-head attachment - Self-levelling feller-buncher (for slopes > 50%)	- Tank hose - Spray gun and backpacks - Fixed-wing aircraft or helicopter	- Livestock (e.g. cattle, goats, sheep) - Vehicles to transport stock
Experience and training	- Highly skilled operation officers (e.g. senior firefighter)	-	-	- Accredited supervisors and applicators - Experienced operator	Knowledge of livestock and local poisonous plant species
Timing	- Autumn[9] - Spring[9] - Winter	- Autumn - Winter	- Spring - Summer - Autumn - Winter	- Spring - Summer[9] - Autumn[9] - Winter	- Spring - Summer - Autumn - Winter
Vegetation	- Forests - Shrubland - Grassland	- Biomass resulting from thinning operations (up to 1.5m height, 8.5m diameter)	- Small trunks and branches - Piled wood	- Shrubland - Forests - Spinifex	- Forests - Grassland - Rangelands

[9] Seasons supporting the highest likelihood of an effective fuel management program (maximum consensus amongst the survey participants).

	- Woodland			- Grassland	
Driving factors	- Slope - Distance to assets - Distance to conservation areas - Presence of protected biodiversity elements	- Distance to access roads - Fuel structure - Amount of fuel	- Slope - Distance to access roads	- Presence of protected biodiversity elements - Distance to riparian environments - Vegetation type - Distance to access roads	- Presence of protected biodiversity elements - Vegetation type - Structure of the fuel - Soil conditions - Size of the area to treat

TABLE 5. (continued) PRESENTATION OF THE GENERAL ANALYTICAL FRAMEWORK (OTHER FUEL MANAGEMENT ACTIVITIES). THE TEXT IN BLACK REPRESENTS INFORMATION COLLECTED THROUGH THE ONLINE SURVEY, IN BLUE INFORMATION COLLECTED FROM THE LITERATURE ONLY, AND IN ORANGE INFORMATION FOUND IN THE LITERATURE REVIEW AND THE ONLINE SURVEY.

	Planned burning	Pile burning	Chipping	Herbicide	Grazing
Driving factors (continued)	- Ability to keep burn within containment lines - Fuel structure - Amount of fuel			- Distance to conservation areas - Land use type - Soil conditions - Size of the area to treat	
Landscape	- Slopes: 0 – 16% - Treatment scales: o < 200 ha around townships; o > 200 ha on Crown lands, National Parks and Nature reserves	-	Slopes: 0 – 10%	- Slopes: 2 – 15% - Treatment scale: 3 – 10 m wide	- Slopes: 0 – 30% (possible up to 60 in alpine environments) - Treatment scale: 1.5 to 65 ha
Land use	- Vacant plots - Nature reserves and conservation forests - Recreational areas	- Nature reserves and conservation forests - Allowed near residential areas	-	- Vacant plots - Nature reserves and conservation forests	- Plantation forests - Intensive agriculture - Pasture - Livestock grazing

	- Residential and rural residential			- Recreational areas - Residential and rural residential - Industrial - Plantation forests - Horticulture	- Horticulture - Mixed farming and grazing - Allowed near residential areas
Other considerations	- Ensure good planning to limit the risk of fire escape - Check weather conditions to control when to start/stop planned burning activities - Encourage the development of post-fire landscape mosaics	-	-	- Removal of dead fuel loads after treatment - Training to limit risk of off-target damages - Use chemicals as per label	- Consider combining with other management activities to maximise fuel reduction - Consider nutritional value of the feed

TABLE 5. (continued) PRESENTATION OF THE GENERAL ANALYTICAL FRAMEWORK (OTHER FUEL MANAGEMENT ACTIVITIES). THE TEXT IN BLACK REPRESENTS INFORMATION COLLECTED THROUGH THE ONLINE SURVEY, IN BLUE INFORMATION COLLECTED FROM THE LITERATURE ONLY, AND IN ORANGE INFORMATION FOUND IN THE LITERATURE REVIEW AND THE ONLINE SURVEY.

	Planned burning	Pile burning	Chipping	Herbicide	Grazing
Other considerations (continued)	- Potentially combine with other management activities				- Control stocking density during grazing; grazing duration; plant secondary compounds; and animal physiological state
Sources	Cirulis et al. (2020) Clarke et al. (2019) Dwire et al. (2016) Furlaud et al. (2018) Gazzard et al. (2020) Hartsough et al. (2008) Howard et al. (2020) Hunter et al. (2007) Leavesley et al. (2013) Morgan et al. (2020) OBRM (2018) Rummer (2010)	Hunter et al. (2007) Rummer (2010)	Rummer (2010) Windell and Bradshaw (2000)	Hunter et al. (2007) Nader et al. (2007) Pyke et al. (2014)	Bruegger et al. (2016) Davies et al. (2010) Davies et al. (2020) Endress et al. (2012) Fuhlendorf and Engle (2004) Nader et al. (2007) Porensky et al. (2018) Ruiz-Mirazo and Robles (2012)

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