Power Network Bushfire Risk Characterisation – Powerlink, Queensland

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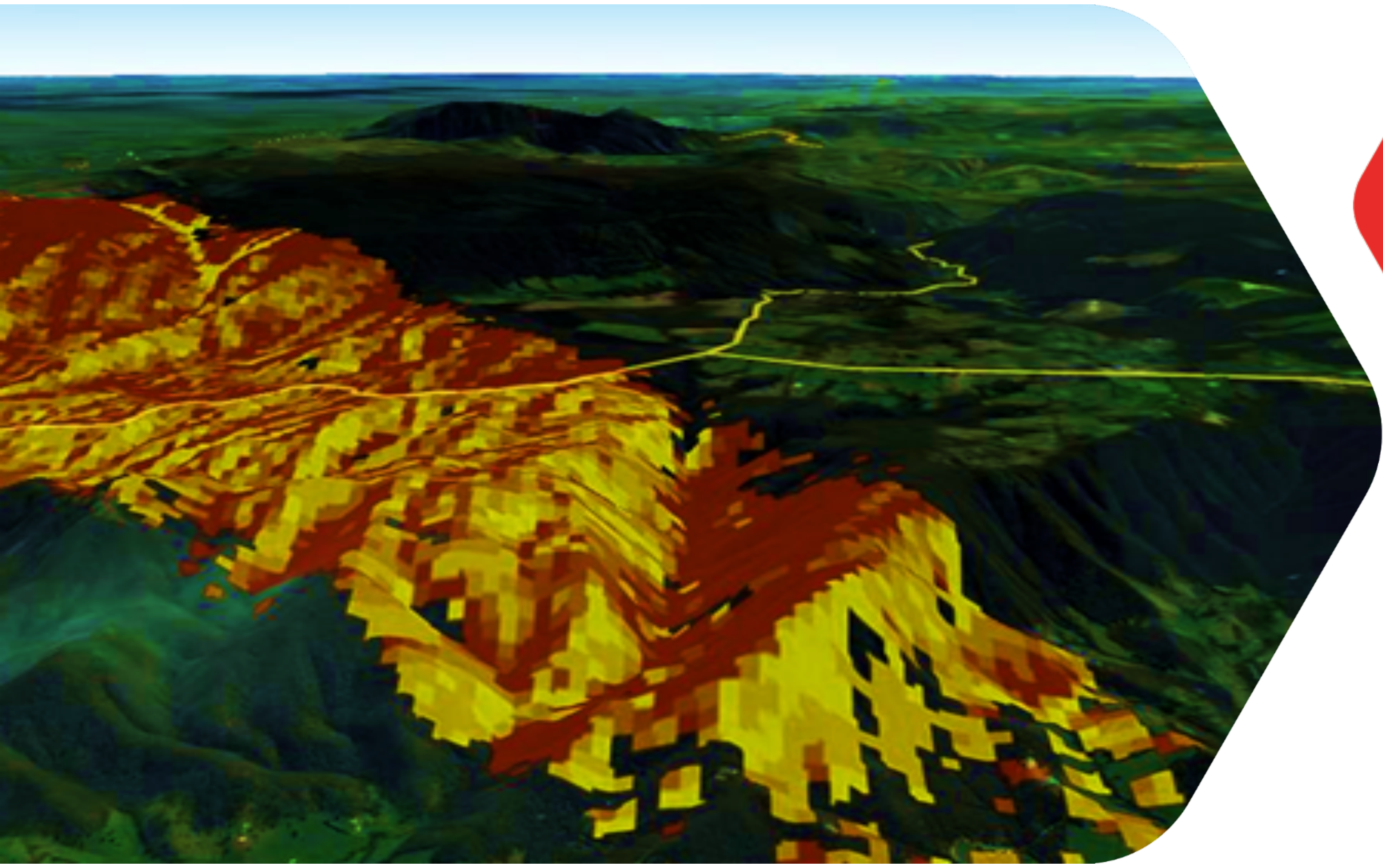

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We acknowledge the traditional custodians across all the lands on which we live and work, and we pay our respects to Elders both past, present and emerging. We recognise that these lands and waters have always been places of teaching, research and learning.

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Cover: PHEONIX RapidFire

(Example of a single bushfire simulation generated by PHOENIX)

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Guide to this report

This report outlines the methodologies and key results from the PHOENIX fire simulations and Bayesian Network (BN) modelling as led by the FLARE team. As part of the BN modelling, we integrate a series of economic outputs for the Queensland region, as provided by Dr Veronique Florec. The process for integrating these data into the modelling is detailed in this report, however a more detailed methodology and key results for the economic analyses is provided as a separate document.

Detailed additional results to accompany this report include:

- Annualised loss from the network (FLARE) - Appendix A.
- Annualised cost from the network (FLARE) - Appendix B.
- Measuring bushfire impacts: economic values (Dr V Florec) - Appendix C.

Executive summary

Natural Hazards Research Australia and Powerlink commissioned the FLARE Wildfire Research Group at The University of Melbourne to apply fire risk modelling methods to quantify the potential impacts to and from the Powerlink power transmission network. This research builds on the methodology developed as part of Project IGNIS, considering for the first time a Queensland case study. Outcomes from this research will help to identify high-risk locations and support decision-making processes toward bushfire risk mitigation across the Powerlink network.

Understanding the potential consequences of ignitions starting from energy network assets is a key concern for the energy industry and fire management agencies alike, especially as the climate changes and we see increases in fire occurrence, severity and frequency. Transmission networks are the high-voltage components of energy distribution systems, carrying electricity over vast distances to meet the increasing demands of an expanding society. Transmission networks are essential for ensuring a reliable power supply, however they also traverse diverse natural and human-modified landscapes, often passing through remote and fire-prone areas. As such, there is an urgent need to comprehensively assess and manage the risks associated with energy networks to safeguard lives, property, and the environment. A better understanding of future fire risk from energy networks, including where in the landscape ignition risk is highest and under what conditions the consequences will be greatest, is critical for ensuring effective and timely management for bushfire prevention.

The aim of the project was to improve the scientific underpinning for characterising risk from bushfire to the power transmission network and has been quantified as the Annualised Loss considered using two approaches:

1. **Annualised Loss from the power transmission network** - characterised as the impacts which could result from an ignition on the Powerlink network, helping to identify parts of the network which could present a higher risk to human and environmental assets.
2. **Annualised Loss to the power transmission network** - characterised as the likelihood of a bushfire in the landscape resulting in damage to the Powerlink power transmission network, helping to identify parts of the network that are more vulnerable to impacts from bushfires. Across both approaches, impacts have been assessed for multiple assets including houses, human lives, agriculture, environment, and infrastructure.

PHOENIX RapidFire was used to determine predominant landscape-scale fire risk from and to the entire Powerlink network which covers large areas of Queensland. This was achieved by simulating two different ignition scenarios: powerline ignitions from all transmission towers in Queensland along the network (n = 25,886); and landscape scale ignitions (2km gridded ignitions within a 15km buffer of the network) (n = 39,309). A series of weather-days were selected from Automatic Weather Station (AWS) records based on the Forest Fire Danger Index (FFDI) to capture variation in weather and associated effects on fire behaviour. Economic data was also derived for the greater Queensland region, and these values integrated into the modelling to help quantify annualised costs (more detailed economic methods and key results are presented separately in Appendix C).

Overall, annual area burnt from ignitions starting on the Powerlink transmission network was found to be greater around Townsville and Gladstone compared to the greater Brisbane region. These regions correlate with areas of urban settlements and higher housing density (and hence powerline density). These areas occur where a complex urban interface exists in a topographically diverse landscape covered with fire prone vegetation. Higher risk locations were also present in the far west of the network (north-west of Brisbane, and north-west of Rockhampton).

Interestingly, ignitions that result in the greatest annual area burnt do not always correlate with the areas of highest annualised cost. In general, ignitions near population centers result in fires with higher annualised cost, as the cost of assets such as housing and human lives significantly increase the calculation of annualised cost. This is most likely driven by the different land uses between regional and urban centers, in particular with housing distributed across the urban-wildland interface.

In terms of annualised risk to the Powerlink network from fires starting elsewhere in the landscape, we found that the highest probability of loss (of the network) occurs around the coastal and highly urbanised regions (i.e., around Brisbane and Rockhampton). These areas of higher risk may, in part, be explained by the presence of forested regions to the west of both locations. While energy networks have little ability to influence the amount of fuel management that occurs beyond their assets, this information will be useful for guiding future fire risk mitigation efforts along the Powerlink network. The areas of highest risk may require additional management in the lead up to potentially high-risk fire seasons.

Results from this project will support Powerlink business operations, justifying ongoing commitment and investment to bushfire risk mitigation activities. The ability to predict where the highest risks are from (and to) the network and surrounding assets is important for determining where management actions can be implemented in an attempt to reduce those vulnerabilities.

End-user/Project partner statement

Stephen Martin, Senior Strategist Land Assets, Research and Development, Powerlink Queensland

"Powerlink Queensland highly regards the results of this research and it will be applied directly to multiple use cases immediately across the business. Management of risks and assets are integrally linked to risks associated with bushfires, including investment, maintenance and operational decisions across the business. Our internal Bushfire Mitigation Working Group will review and coordinate the implementation of this research across the business. This will include consideration of integration with strategic partners like Queensland Fire and Emergency Services (QFES) and Queensland Fire and Biodiversity Consortium (QFBC). There are enhancements and additional questions that would add further value and we will explore further with NHRA and its research partners."

Figures

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1. Introduction and background

Natural Hazards Research Australia and Powerlink Queensland commissioned the FLARE Wildfire Research group at The University of Melbourne to apply fire risk modelling methods to quantify the potential impacts to and from the Powerlink power transmission network. Outcomes from this research will help identify high-risk locations and support decision-making processes toward bushfire risk mitigation across the network.

1.1. Project driver

Effective disaster resilience thinking acknowledges the complexities and interconnections that exist at all societal levels, including that of a variety of different critical lifeline utilities that contribute to a complex web of risk ownership and management. It is also best understood as a process with an outcome that has at its core an understanding and willingness to negotiate with others to allow a balance of complexities that influence society.

Australia's electricity networks are one part of the electricity system, providing the infrastructure that connects generators to customers who purchase their electricity from a retailer. All of these players operate in a highly regulated framework to ensure a reliable and cost-effective supply of electricity. The most recent Royal Commission into bushfires supported the common knowledge that electricity is an essential service that other services are dependent on.

Due to changes in the frequency and intensity of many natural hazards such as bushfires, networks have progressively been making changes to the design and operations of their network to reduce risks to their network caused by natural hazards and to strengthen supply. Regulators have asked for networks to build resilience into their business and their assets – so that they can better defend their decisions into the future, networks have had to perform these mitigation activities within strict regulatory and legislative requirements. The regulatory and legislative requirements and therefore business imperatives can be at odds with community expectations of networks during natural events. These expectations include that networks will provide access to a stable supply and protect assets to minimize disruption to that supply and therefore the impact on communities.

Within this complex environment, networks need to understand and articulate the benefits of undertaking continued bushfire mitigation investment. Whilst it is relatively easy to identify and estimate some of the tangible costs associated with small fire events (e.g.: property damage, insurance claims, SAIDI and SAIFI impacts, cost of the fault response and repair, and fire penalty scheme costs, if applicable), it is much more challenging to identify and estimate the costs of major fire events, particularly intangible impacts (which include life, injuries, biodiversity, amenity, stress and anxiety, etc.). The challenge is made difficult given that major bushfire events are rare; however, it is widely acknowledged that it is a real risk to DNSPs. The Australian Energy Regulator also requires networks to make these considerations as part of their reset submissions for bushfire-related mitigation funding every 5 years.

Power transmission networks face a number of competing challenges, including the regulatory requirement to deliver a reliable, modernised system that can operate under a changing climate. It is therefore important that energy providers consider the impacts of natural events such as bushfires in their risk management planning, and importantly, how networks will adapt to increase the resilience of electricity networks in the context of major and cascading events.

To address some of these concerns, Project IGNIS developed a methodology to be applied consistently across the networks to better quantify the impacts of major bushfires caused by their network assets. This methodology, which was co-designed with a selection of networks, produced an industry-supported and credible reference for funding applications. It is envisaged that this would provide a stronger basis for bushfire mitigation related investment, and therefore greater risk reduction. Project IGNIS demonstrated the applicability of the methodology via the conduct of a few cases studies, none of which catered for northern Australia. Queensland was not included in the original Project IGNIS scope therefore this project has applied the IGNIS methodology to a Queensland case study site, selected by Powerlink and quantified the losses of the major interconnector during a major bushfire.

1.2. Aim

The aim of this project was to improve the scientific understanding of the risk posed by bushfires to the Queensland Powerlink transmission network. Specifically, this project aimed to advance knowledge to better understand impacts of major bushfires on network assets and communities in Queensland, taking into consideration tangible and intangible impacts. The project builds on the work of Project IGNIS (Parkins *et al.* 2020) and aims to provide insights into risks posed to and from the Powerlink network. The methodology used in this project provides a robust tool for providing relative assessments of risk and to guide future management or risk mitigation efforts. This methodology is largely consistent with many state agencies undertaking similar fire risk assessments (i.e., New South Wales Rural Fire Service) and has also been consistently applied across many other energy network providers around Australia.

The study aimed to quantify impact using two approaches. Firstly, the **Annualised Loss <u>from</u> the power transmission network** was defined as the potential impact that could result from an ignition originating from a structure. In this approach, areas of the network which pose the highest risk to human and environmental assets are identified. The impacts on various assets including houses, human lives, agriculture, environment, and infrastructure are also assessed.

Secondly, the **Annualised Loss <u>to</u> the power transmission network** was characterised as the likelihood of a bushfire occurring in the landscape surrounding the Powerlink network leading to damage or loss of the network. In this approach, areas of the network likely to experience the greatest impacts from bushfires were identified.

1.3. Study area

The study area included the extent of the current Powerlink transmission network, and two proposed transmission extension lines (GENEX and MACINTYRE) (Figure 1.1) The region is characterised by lower topography along the coastal regions, with higher elevation occurring in patches generally associated with the Great Australian Divide (Figure 2.3). The region has a varied fire history which is influenced by the transmission of forest, rangelands and agricultural zones.

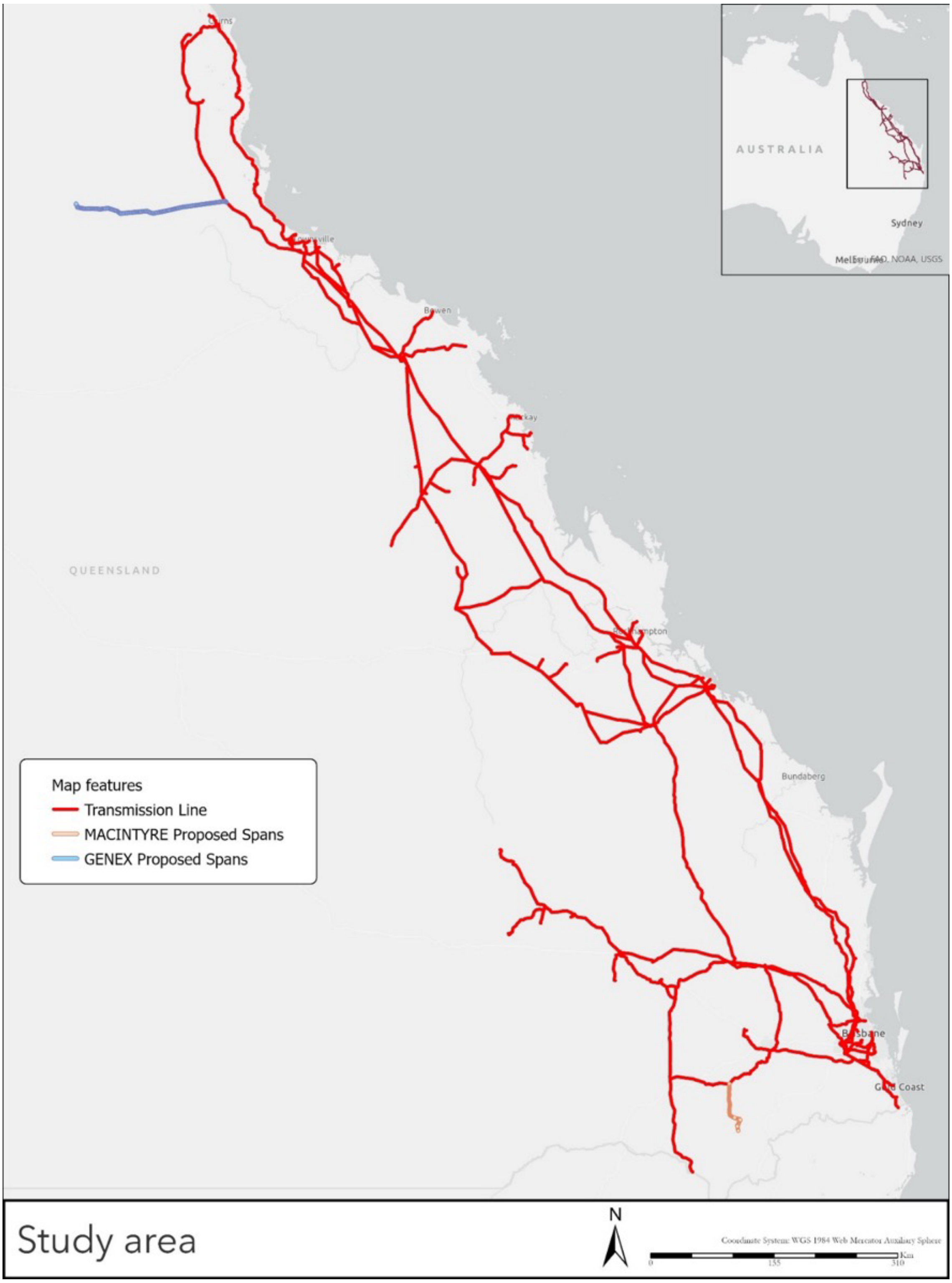

FIGURE 1.1 THE POWERLINK NETWORK ACROSS QUEENSLAND, AUSTRALIA (RED), INCLUDING TWO NEW SPANS, MACINTYRE (ORANGE) AND GENEX (BLUE).

2. Methodology

2.1 Approach

The overall approach used in this project is consistent with other fire risk modelling that has been undertaken by several other energy network providers since the completion of Project IGNIS. Overall, the approach involves four key stages (Figure 2.1). Firstly, the landscape context is set, where a broad range of data layers are collated for the greater study region (the most up-to-date layers are used, and are consistent with the layers being used by state agencies); secondly, a fire event simulator (PHOENIX RapidFire) is used to model fires in the study landscape; thirdly, these modelled fire outputs are combined with asset loss curves and economic data to determine potential impacts; and finally, all of the outputs are combined within a Bayesian Network framework, which accounts for the likelihood/ probability of fires occurring in the study region, with total losses and impacts (in terms of consequence and cost $) being the primary output. The resulting information can be used to identify the highest risk locations (i.e., the ignitions along the Powerlink network which would result in the greatest consequences, or ignitions in the landscape that will have the greatest impact to Powerlink assets), the conditions under which the impacts will be greatest (i.e., under bad fire weather conditions, or where fuel loads are greatest), and the potential associated economic costs associated with these ignitions.

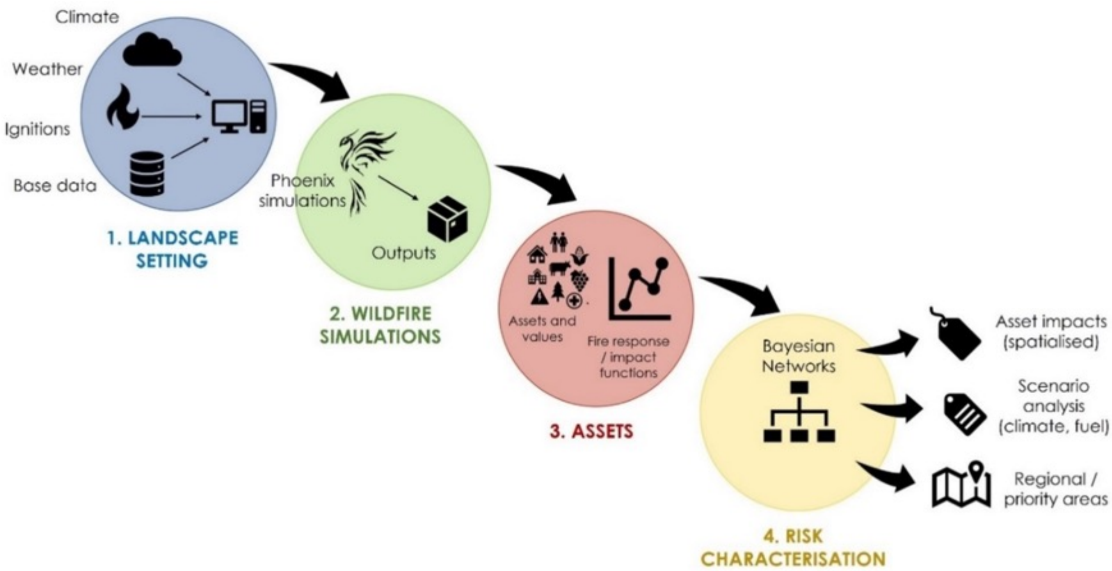

FIGURE 2.1 BUSHFIRE RISK ASSESSMENT CONCEPTUAL FRAMEWORK

Numerous studies have utilised the PHOENIX RapidFire Bushfire Simulator (hereafter PHOENIX) to examine the effects of weather, fuel management strategies, suppression, and fire behaviour (Duff, Chong & Tolhurst 2013; Penman et al. 2013; Collins et al. 2015). Inputs for PHOENIX include fuel, wind reduction factors, topography, assets, road proximity, fuel disruption, weather and suppression resources (Chong, Tolhurst & Duff 2013). One method for examining risk in the landscape is to compare burn probabilities under various scenarios (Brillinger, Autrey & Cattaneo 2009; Ager, Vaillant & Finney 2010; Parisien et al. 2010). Burn probabilities are estimated by creating a set of ignition points in the landscape and using PHOENIX to run each point individually under one or multiple weather scenarios. The burn probability is then calculated as the number of times the area is burnt, divided by the number of ignitions. Results are then weighted based on the probability of each FFDI occurring. Using this approach, we can also determine the impact of fire on a range of assets in the chosen landscape.

Risk-based decision-making aims to quantify the likelihood of an impact occurring, and the consequences of this impact to human and environmental systems, processes, or values. The approach for assessing bushfire risk in the landscape includes the following steps: landscape setting, bushfire simulations, assets (human and environmental) and risk characterisation. In the final step, risk characterisation is undertaken using Bayesian decision networks (Figure 2.2).

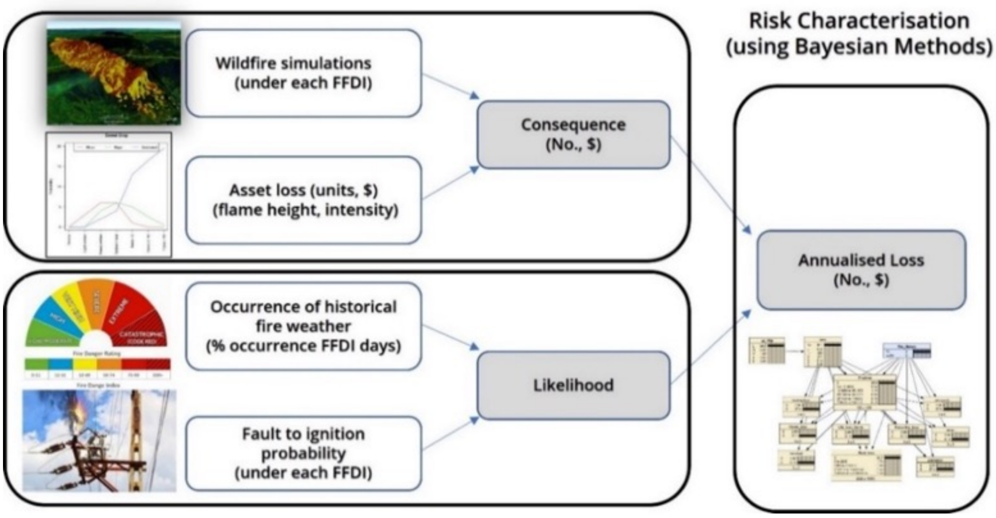

FIGURE 2.2 BUSHFIRE RISK ASSESSMENT CONCEPTUAL FRAMEWORK (ADAPTED FROM PARKINS ET AL. 2020)

2.2 Consequence assessment

2.2.1 Bushfire modelling and simulations

Fire behavior simulators apply models of fire behaviour to environmental determinants such as vegetation type and condition, terrain, and weather to estimate key fire properties such as intensity, rate of spread and flame height in a spatially explicit manner (Figure 2.3). Simulation fire properties can be used as inputs to estimate risk to assets and management values (Ager, Vaillant & Finney 2010; Thompson et al. 2011; Salis et al. 2016). The PHOENIX Simulator (Tolhurst, Shields & Chong 2008) uses two basic fire behaviour models: the CSIRO southern grassland fire spread model (Cheney, Gould & Catchpole 1998) and a modified McArthur Mk5 forest fire behaviour model (McArthur 1967; Noble, Gill & Bary 1980). All simulations were run using 180 m resolution grid cells to optimise model performance and follow the recommendations of Tolhurst, Shields, and Chong (2008). This approach uses historical data and provides a realistic fuel moisture estimate (wetter overnight and drying out during the day) and each individual fire is allowed to run for up to 12 hours which allows the model to capture the worst conditions of the day (in the afternoon).

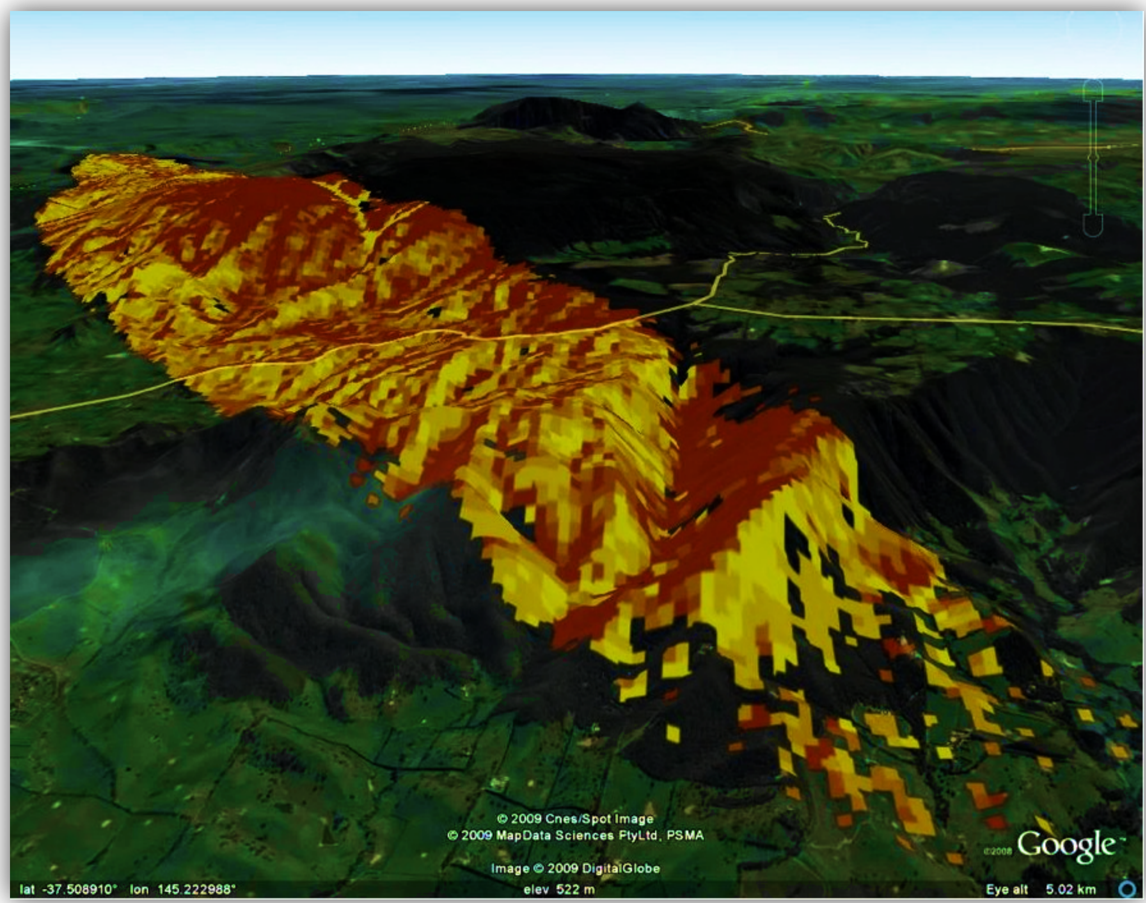

FIGURE 2.3 EXAMPLE OF A SINGLE BUSHFIRE SIMULATION GENERATED BY PHOENIX; COLOURED SQUARES INDICATE FLAME HEIGHT WITH DARKER RED COLOURS REPRESENTING HIGHER FLAME HEIGHTS AND LIGHTER YELLOWS REPRESENTING LOWER FLAME HEIGHTS.

2.2.2 Input data

Data layers were provided by the Queensland Fire and Emergency Services (QFES) or have been developed in-house by FLARE Wildfire Research. These include the current versions of the input variables of fuel, topography, and disruptions in the landscape (i.e., fire history, land use). The approach outlined below is consistent with procedures used by QFES as well as research elsewhere. **However, our research improves on the current processes used by including a greater diversity of weathers and ignition models**. Table 2. 1 summarises the bushfire simulation model data inputs. Graphical examples of the input variables are also provided below.

TABLE 2.1 BUSHFIRE SIMULATION SPATIAL AND DATA INPUTS

Input	Description
Topography	A 30 m resolution digital elevation model was included to allow PHOENIX to account for the influence of topography on fire behaviour (Figure 2-3). The Study region is characterised by lower topography along the coastal regions, with higher elevation occurring in patches in the south, northeast. And central parts of the study region (Figure 2-3). The region has a varied fire history; however, the northeast part of Queensland has been less affected in recent years by bushfire (Figure 2-4).
Fuel and Vegetation	Fuel accumulation models for major vegetation types of the case study landscape were provided by QFES. Disruptions to fuels through streams and roads were represented by the estimated width on a 30 m raster and were also provided by the relevant agencies. PHOENIX estimates fuel loads using separate fuel accumulation curves for surface (including near surface), elevated and bark fuels (Hines et al. 2010). These curves use a negative exponential growth function (Olson 1963) and vary between vegetation types. To capture the effect of varying fuel loads in the landscape, two fuel scenarios were generated: • **Current fuel setting** which considers fire history, current vegetation mapping and land use. This scenario captures the landscape under contemporary conditions. • **Maximum fuel setting** where the fuel load for each vegetation type is set to maximum. In creating this fuel layer, we assumed there had been no bushfires or prescribed burning activities. Fuel load in this capacity remains static.
Weather streams	The analysis of bushfire risk and its potential impact on the power transmission network requires a comprehensive assessment of the prevailing weather conditions, as well as the physical and environmental factors that may contribute to the spread of fires. To capture this information, Automatic Weather Station (AWS) records were utilised to select a series of weather-days based on the Forest Fire Danger Index (FFDI). Historical weather records were derived from the most representative station in proximity to the Powerlink network (Figure 2-7). FFDI is a composite measure that combines temperature, relative humidity, wind speed, and a long-term drying index to predict the difficulty of suppressing a potential fire. To capture the variability of weather conditions, three different weather types were selected based on the predominant FFDI driver (strong wind; strong wind with a significant directional change; and high air temperature). This allowed for a 24-hour weather stream to be generated, which was used to generate a stable and realistic fuel moisture estimate based on temperature and humidity.
Fire History	Fire history is used by PHOENIX to estimate the current fuel loads for each major vegetation type by combining time-since-fire with accumulation variables to separately predict surface, near surface, elevated and bark fuel hazard scores and to infer fuel loads. Accumulation variables were provided by QFES. The fire history was also sourced from QFES and was updated and released in 2022 (Figure 2-4).
Ignitions	Two ignition scenarios were considered: • Scenario 1: Impact from the network. Ignition locations were set at all transmission

Input	Description
	tower locations in Queensland at each structure location (Figure 2.6). In total, this resulted in 25,913 ignition points. • Scenario 2: Impact to the network. An ignition grid was generated using a 15km buffer of the power transmission network, with gridded ignition locations assigned every 2km (Figure 2.6). In total, this resulted in 39,309 ignition points. Ignitions were randomly assigned weather a single weather stream within each FFDI driver category. Each weather stream contains hourly data for air temperature, relative humidity, wind speed, wind direction, drought factor and curing. All weather streams covered a 24-hour period beginning at midnight to allow the model to generate stable and realistic fuel moisture estimate based on temperature and humidity. This also allows us to capture the worst conditions of the day, with meaningful fuel moisture estimates. The analysis undertaken assumes equal probability of ignition across the network. These values could be improved in the future if we had information regarding failure rates as well as finer scale data. It is noted that part of the Powerlink network extends south into NSW (27 towers); this part of the network was not included in the analysis due to the spatial input layers provided by QFES being clipped to the state boundary.

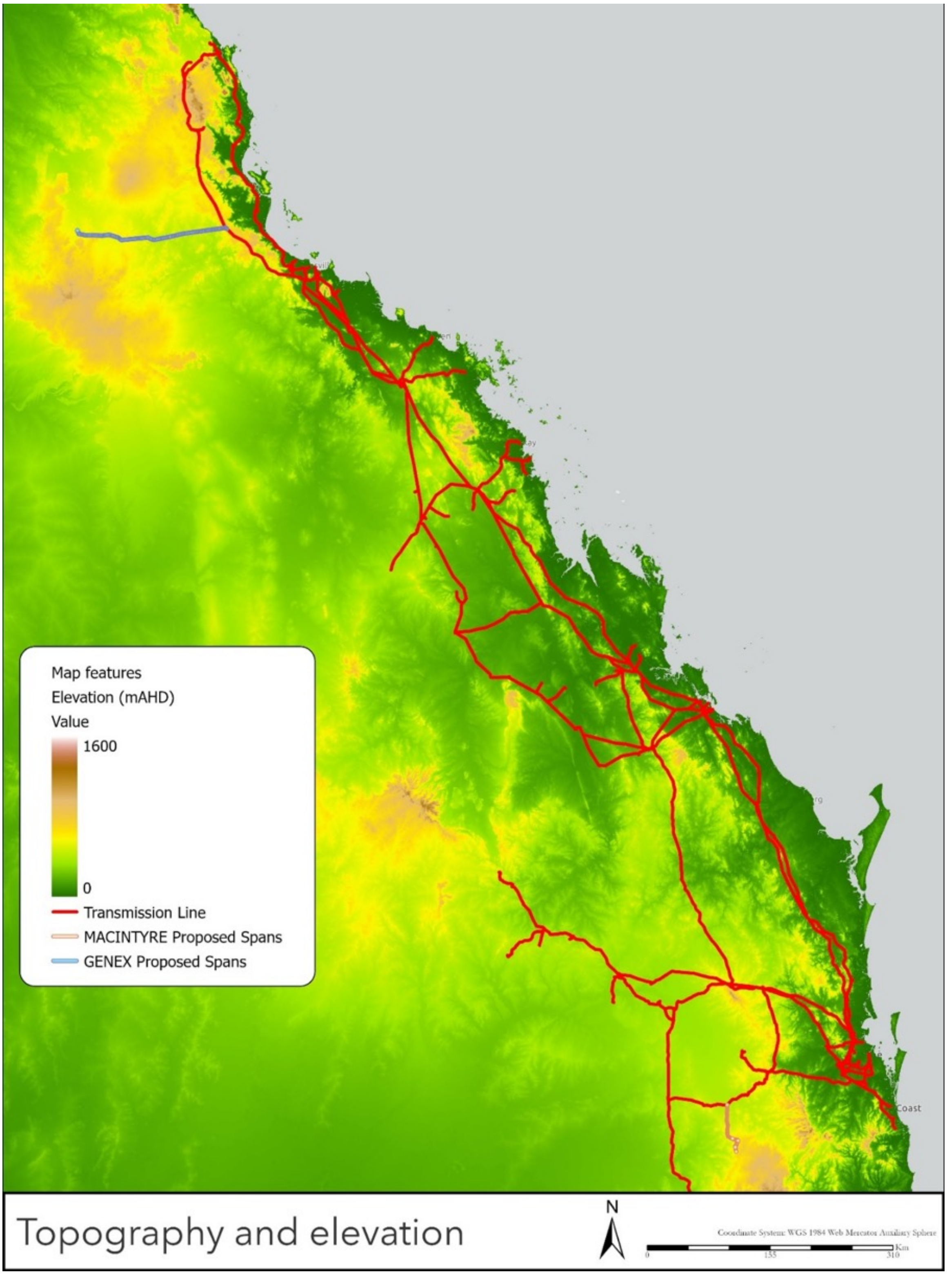

FIGURE 2.3 ELEVATION AND TOPOGRAPHY FOR THE STUDY AREA IN METERS ABOVE HEIGHT DATUM (AHD); THIS DATA LAYER IS USED AS AN INPUT IN THE PHOENIX SIMULATIONS.

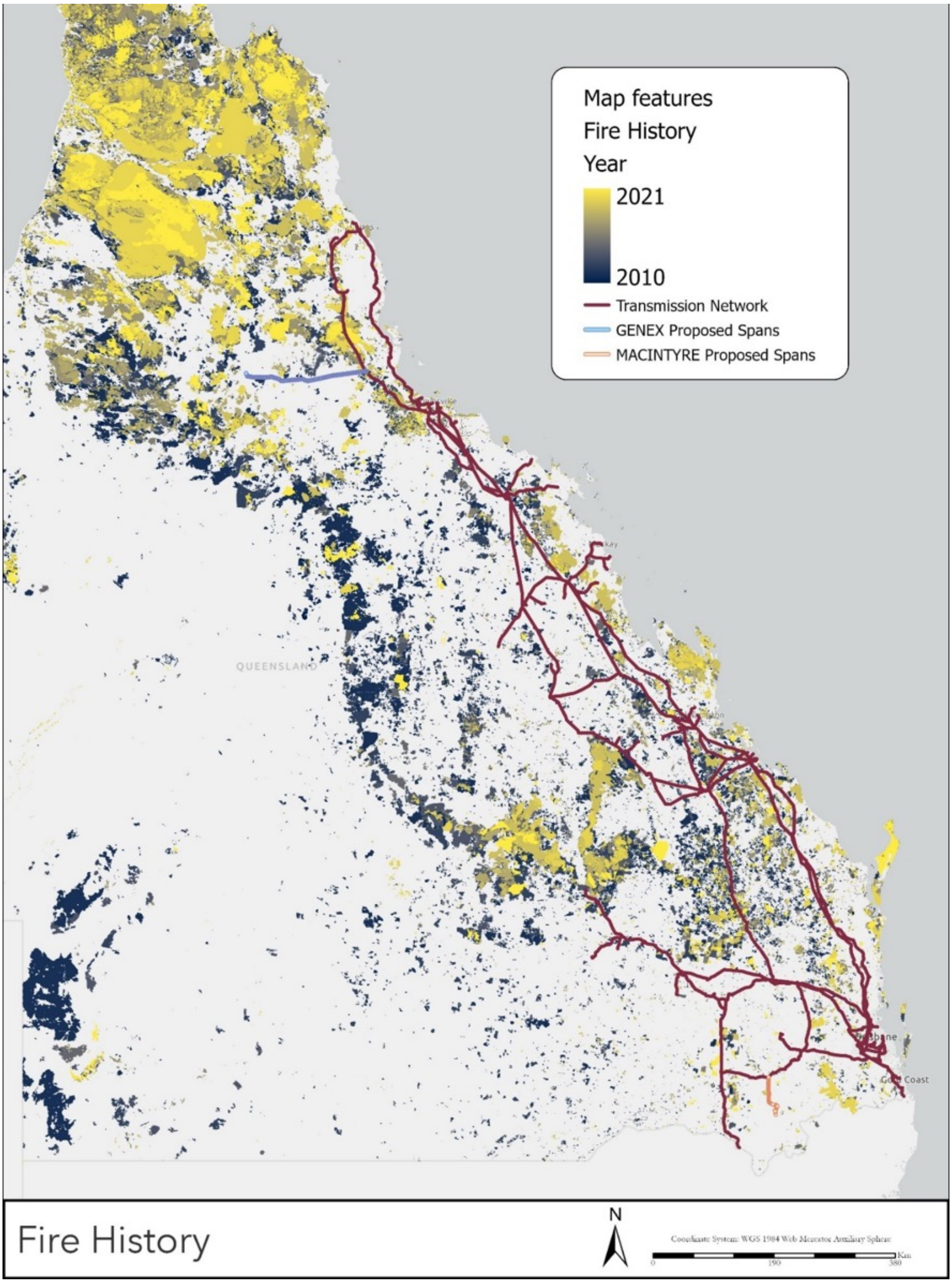

FIGURE 2.4 FIRE HISTORY ACROSS THE STUDY AREA; THIS DATA LAYER IS USED TO ADJUST THE FUEL LOADS IN THE PHOENIX SIMULATIONS BETWEEN THE CURRENT FUEL LOAD AND MAXIMUM FUEL LOAD SCENARIO. THE NORTHEAST PART OF QUEENSLAND HAS BEEN LESS AFFECTED IN RECENT YEARS BY BUSHFIRE.

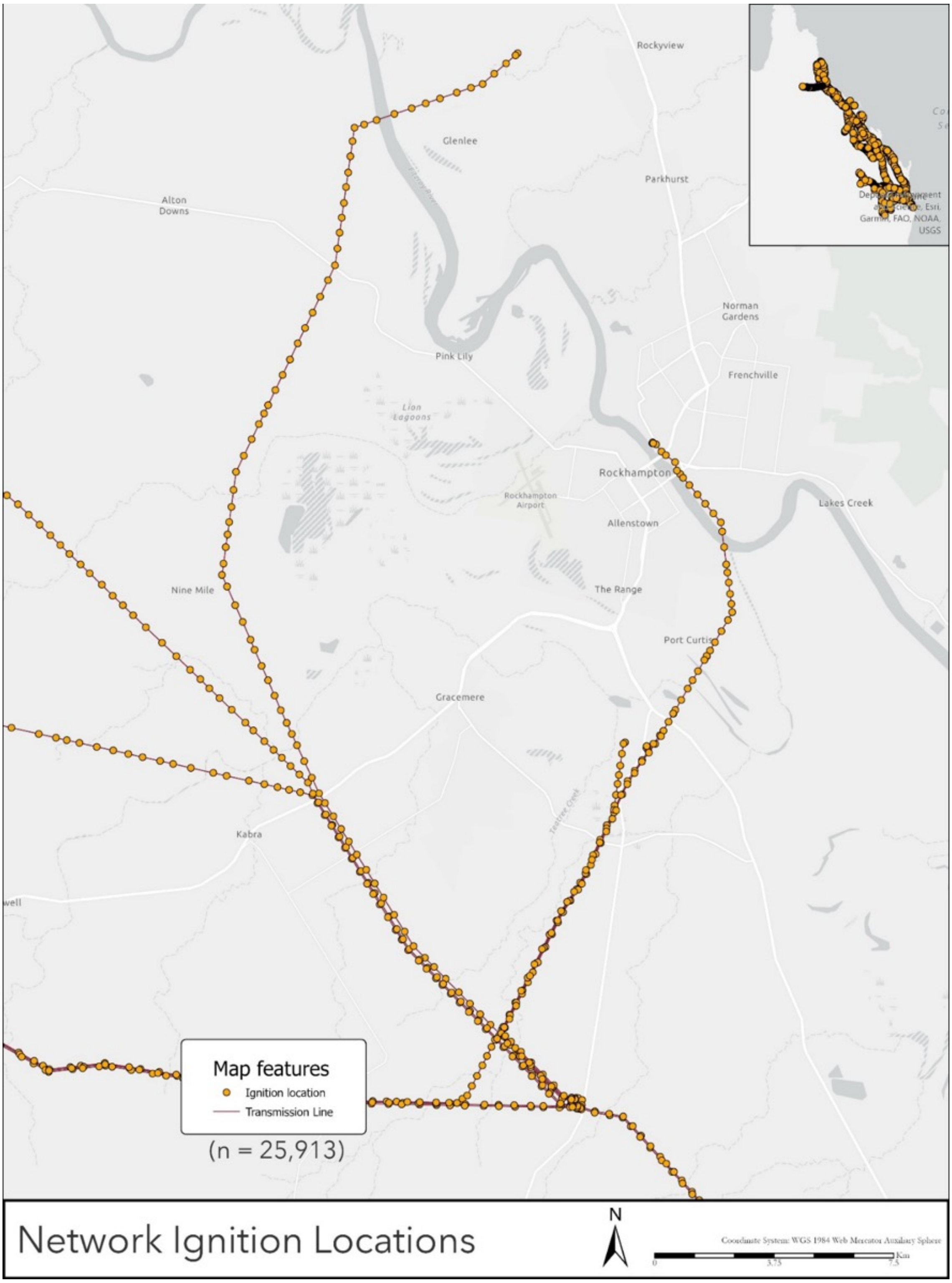

FIGURE 2.5 NETWORK IGNITION LOCATION LOCATIONS TO ASSESS IMPACT FROM THE POWER TRANSMISSION NETWORK; THIS DATA LAYER IS USED AS AN INPUT IN THE PHOENIX SIMULATIONS.

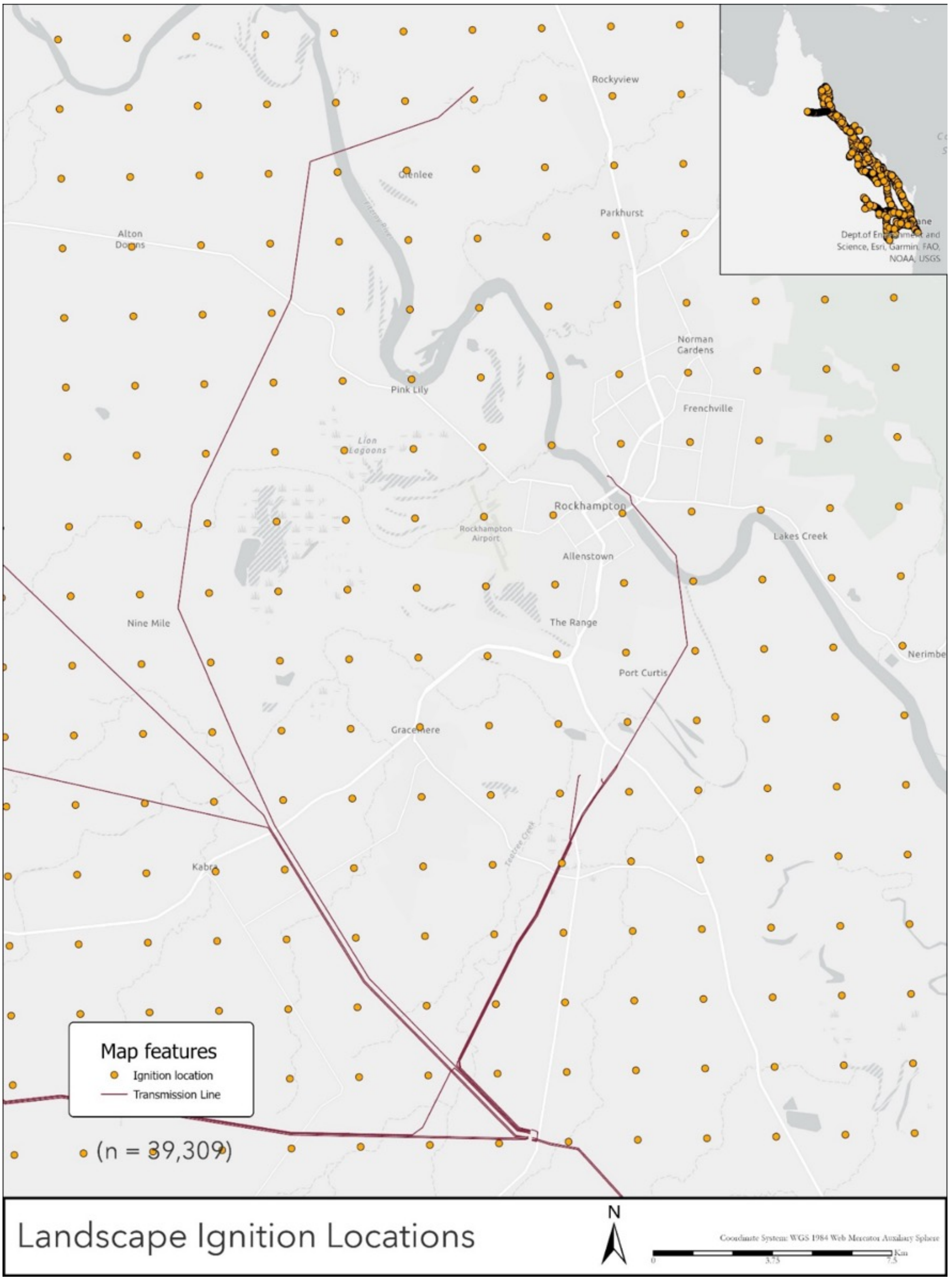

FIGURE 2.6 GRIDDED LANDSCAPE IGNITION LOCATIONS FOR ASSESSING IMPACT TO THE POWER TRANSMISSION NETWORK; IS USED AS AN INPUT IN THE IN THE PHOENIX SIMULATIONS.

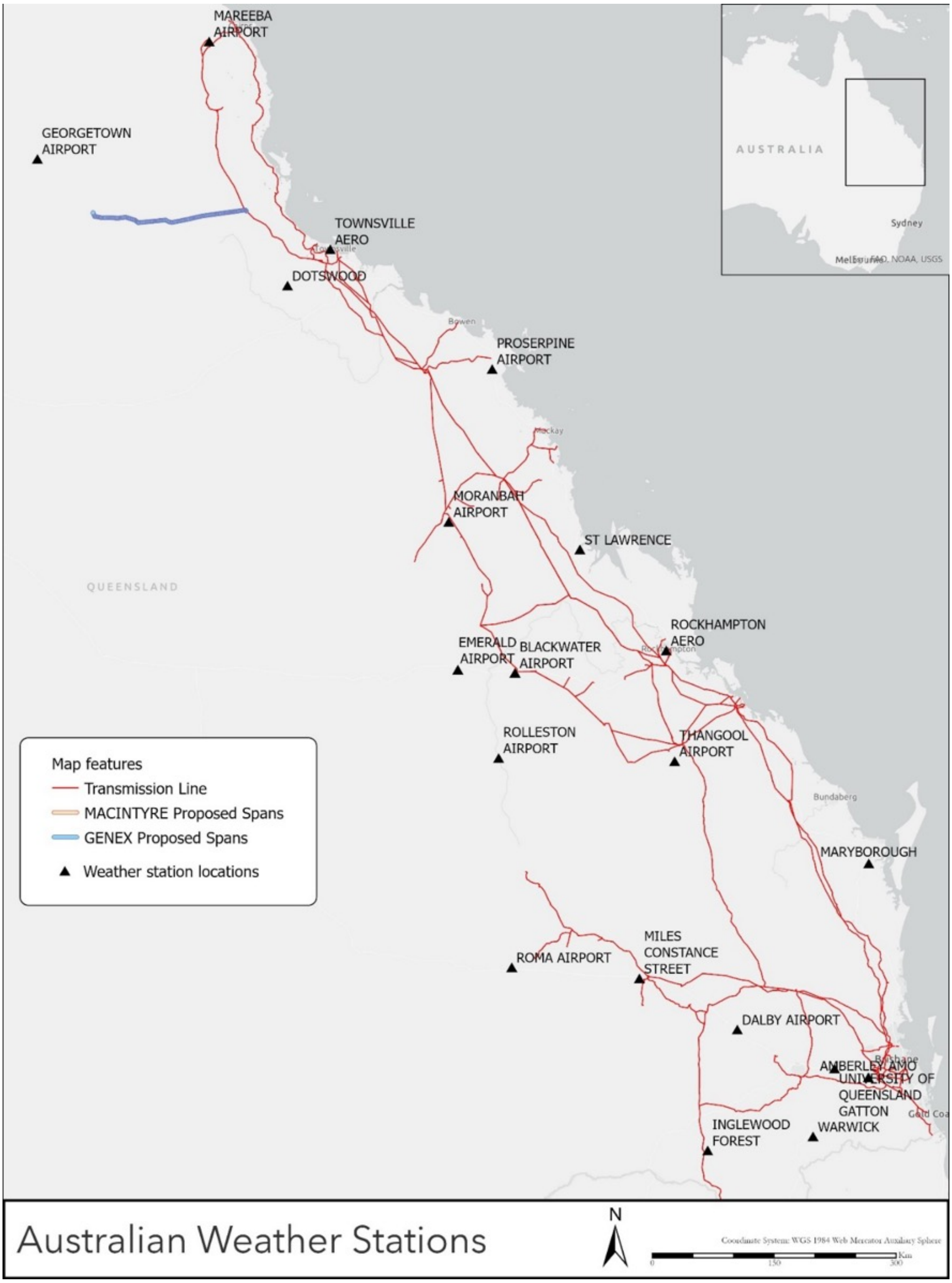

FIGURE 2.7 AUSTRALIAN WEATHER STATION LOCATIONS NEAR THE TRANSMISSION NETWORK USED TO SELECT WEATHER STREAMS AND SAMPLE FFDI TRANSMISSION FOR MODELLING.

2.2.3. Asset exposure and loss functions

The impact of bushfires on the energy network is expressed as an annualised loss, which takes into account the likelihood of ignition and the exposure of assets to fire. This loss is calculated using a Bayesian Network (see section 2.4.1 for more detail), which provides a systematic and probabilistic method of assessing the impact of bushfires on the network. The impact of simulated fire on assets of interest within the study landscape were estimated using 'loss functions'. For this study, we have used the loss functions previously developed in NSW. These loss functions were constructed for a range of different assets and developed in collaboration with the NSW Rural Fire Service. Expert elicitation workshops were conducted to gather information about how different assets are impacted by increasing levels of bushfire severity. These results were combined into loss /vulnerability functions (example provided in Figure 2 8). The loss functions are matched to some of the spatial outputs from the PHOENIX simulations to get the probability of damage.

IMPORTANT NOTE: The loss functions used in both Project IGNIS and this Queensland case study are the best available data we currently have for quantifying asset impacts. While it is acknowledged that these loss curves were developed primarily for NSW, they are expected to be fairly consistent between most states on the east coast of Australia, for most assets of interest. However, future research which seeks to quantify asset loss functions for the range of assets in different states such as Queensland would be important to assess. One area of particular importance is the powerline asset loss functions, which were developed for distribution network assets. Asset loss functions for transmission networks have not yet been developed. Additional research which quantifies how asset loss curves might differ between different energy network asset types is strongly encouraged as future work in this space. As transmission lines are generally elevated higher off the ground than distribution lines, it is likely that that the current loss curves for distribution assets may be over-estimating loss for transmission assets, however this has yet to be formally quantified.

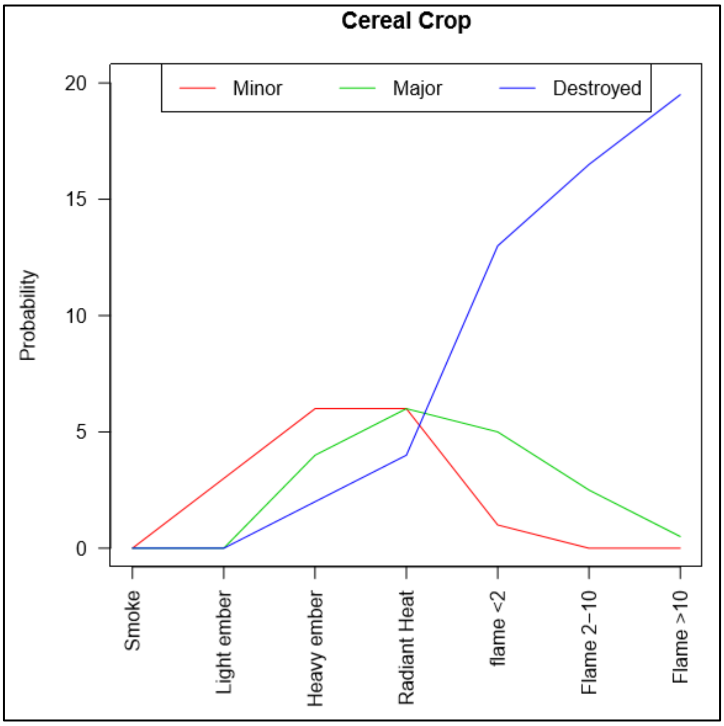

FIGURE 2.8 EXAMPLE ASSET LOSS RESPONSE PROBABILITIES TO SMOKE, HEAT, EMBER ATTACK AND FLAME LENGTH FOR CEREAL CROPS; SIMILAR LOSS CURVES HAVE BEEN DEVELOPED FOR ALL ASSETS.

Table 2.2 lists the assets considered in this study, including houses, lives, agriculture, environment, and infrastructure, and the associated measure of impact. This approach is flexible and can be easily expanded to include additional assets and new data in the future, making it a useful tool for risk-based decision making in bushfire planning.

TABLE 2.2 ASSETS EXPOSURE AND LOSS FUNCTIONS

Asset /Value	Description	Measure of impact
Crop loss/ Plantation loss/ Livestock loss/ Powerline loss	The impact of simulated fire on crops, plantations and vineyards was estimated using loss curves developed in collaboration with the NSW Rural Fire Service. Expert elicitation workshops were conducted to gather information about how different assets are impacted by increased levels of bushfire severity. These results were combined into loss curves and matched to the spatial fire simulation outputs to get the probability of damage. These results were combined into loss curves and matched to the spatial fire simulation outputs to get the probability of damage. We note at present there are no asset loss curves developed specifically for Queensland, and accordingly the curves for NSW have been adopted.	Area burnt (Ha) and Length (m)
House loss	The probability of house loss was calculated as a function of ember density, flame length and convection as presented in (Tolhurst and Chong 2011). House loss was calculated per 180 m cell and then multiplied by the number of houses in that cell to estimate the number of houses lost per fire. House locations were derived from authoritative national location data (PSMA 2016).	Houses (No.)
Life loss	Statistical loss of human life was based on house loss (using the house loss function), the number of houses exposed (using simulation output) and the number of people exposed to fire (Harris et al. 2012). Mesh block data from the Australian Bureau of Statistics was used to calculate the average number of people per household in each block. These data were then combined with the house location dataset to give the total number of people exposed to fire.	Lives (No.)
Road loss	Due to a lack of empirical data regarding the risk of damage to roads, we used a simple threshold of 10,000 kW/m to determine if roads within each 180 m cell were considered damaged by fire. The effects of fire are largely associated with infrastructure such as signs and road closures, rather than damage to the road surface itself.	Length (m)

2.3. Likelihood assessment/annualised risk

2.3.1. Bayesian Networks

Bayesian Network (BN) modelling is a useful and effective method for dealing with data gaps and uncertainties, and explicitly displaying the relationships between variables (Cheon et al. 2009; Hanea et al. 2010; Marcot & Penman 2019). BN structure is highly flexible, meaning this technique is appropriate for a diverse range of applications and disciplines. Bayesian Networks (BNs) are statistical tools that are ideal for risk analysis of complex environmental systems (Pollino et al. 2007; Johnson et al. 2010; Kelly et al. 2013), providing a useful tool for addressing uncertainties in environmental decision making. Outputs are expressed as probabilities, making them valuable in a risk management context (Marcot et al. 2001). Decision nodes in BNs represent discrete actions that can be assessed to compare outcomes and benefits of competing strategies.

Bayesian Networks (BNs) are increasingly being used in the context of complex environmental systems (Pollino et al. 2007; Johnson et al. 2010; Kelly et al. 2013). Several studies have also demonstrated their utility for fire management (Dlamini 2010; Papakosta & Straub 2011; Penman, Price & Bradstock 2011; Bashari et al. 2016; Hradsky et al. 2017), determining the potential impacts or proposed projects (Krüger & Lakes 2015), forecasting impacts from environmental disturbances such as fire (Dlamini 2010; Cirulis et al. 2019b), climate change (Sperotto et al. 2017), and providing a basis for environmental decision making (Barton et al. 2012). BNs are also used in a wide variety of other contexts (Marcot & Penman 2019), and since the completion of Project IGNIS (Quantifying catastrophic bushfire consequences, Parkins et al. 2020) BNs are now a key part of the methodology for quantifying fire risk for energy networks.

2.3.2. BN model design and parameterisation

For this part of the project we followed the Bayesian Network modelling methods of Marcot et al. (2006) and Chen and Pollino (2012). The primary steps were to construct a conceptual model of the problem; develop influence diagrams to depict the relationships of variables within the conceptual model; populate all the conditional probability tables within the model and specify values.

A separate BN model for each ignition point was created (Figure 2 11). Data for the conditional probability tables (CPTs) in the BN was derived from the simulation study (PHOENIX) and measured data for the study region. Data generated in the fire simulations was used to estimate the probability transmissions in the CPTs for each of the output nodes: fire area, houses, lives, powerlines, crops, plantations, and horticulture.

One approach to BN modelling is to use weighted cases, a method that assigns different weights to each data point in the analysis. This allows for a greater emphasis to be placed on certain data points that are considered to be more important or relevant to the decision being made. Additionally, Bayesian spatial smoothing can provide more accurate estimates by weighting the influence of outliers or other extreme values in the data. This method has been successfully applied to a variety of applications, including predicting land cover changes, analysing the transmission of species, and mapping environmental variables. The use of weighted cases in Bayesian learning can help to improve the accuracy of predictions and better inform decision-making in complex risk scenarios. In this project, we used these methods to capture greater variability in the ignition node of the BN. We gathered data from the ignition point of interest, but also included additional data from surrounding points (see Figure 2 9).

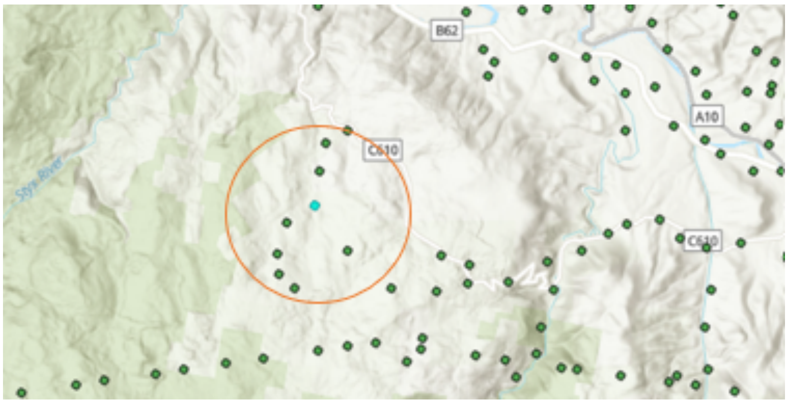

FIGURE 2.9 EXAMPLE OF HOW DATA FROM MULTIPLE IGNITION POINTS FROM A SIMILAR SPATIAL LOCATION ARE CAPTURED (ORANGE CIRCLE), TO INFORM THE POINT OF INTEREST (BLUE POINT).

2.3.3. Fire weather occurrence (historical)

Fire weather occurrence is based on the frequency of occurrence of days in each FFDI category using historical weather data. The FFDI transmission for each AWS was determined during the Queensland fire season (August to December) for records since the year 2000. To calculate the fire weather occurrence in a specific area, the number of days in each FFDI category is counted and divided by the total number of days the fire season period (August to December), providing an estimate of the probability of a bushfire occurring in each FFDI category. This was then used to populate the ignition chance node (called "all FFDI" in Figure 2 11 below).

Figure 2 10 below show for the fire season in Queensland (August to December) for AWS stations used in this study (see Figure 2 7). In general, the study area is dominated by low, medium, and very high ratings. Extreme and catastrophic fire weather conditions have been observed in southeast Queensland, however, have not been observed in more coastal weather stations and stations further north (e.g. around Cairns). The transmission and occurring of fire weather days is important in the calculation of annualised loss and has been factored it the overall assessment of risk at each ignition location using the Bayesian modelling approach discussed in Section 2.3.1.

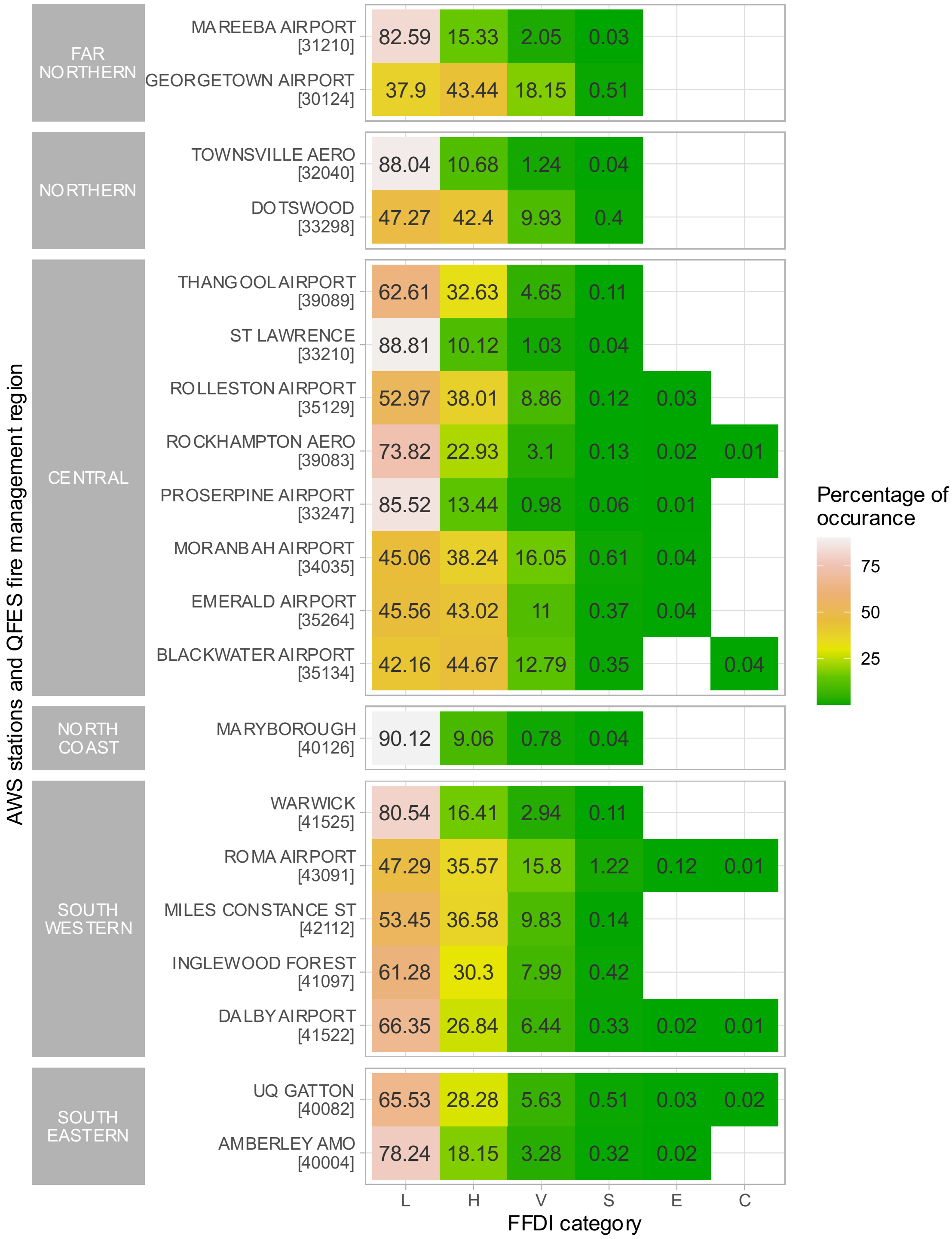

FIGURE 2.10 FFDI FREQUENCY FOR AWS STATIONS USED IN THIS STUDY ACROSS QUEENSLAND, ARRANGED FROM NORTH TO SOUTH USING THE QFES FIRE MANAGEMENT REGIONS. BLANK CELLS INDICATE NO RECORDED OBSERVATIONS FOR THAT PARTICULAR FFDI CATEGORY AT THAT STATION. THE PERCENTAGE OF OCCURRENCE IS SHOWN BOTH VISUALLY USING THE COLOUR GRADIENT AND TEXT VALUE.

2.4. Economic data and modelling

Queensland was not included in the original Project IGNIS scope. As such, to calculate annualised cost additional economic modelling for Queensland was required. This was undertaken by Dr Veronique Florec, who also undertook the original economic modelling as part of Project IGNIS. The approach used here is consistent with the methodology developed through Project IGNIS, however the level of detail is much higher for this region due to greater availability of data and additional time to derive/collate these values.

The overall approach is detailed briefly below, however the details of this part of the project have been provided as a separate report prepared by Dr Florec. This can be found in Appendix C.

2.4.1. Approach

Economic valuation as part of the bushfire risk quantification methodology involves the integration of individual asset information (i.e., spatial location), impact assessments under different weather streams (from loss functions and simulation outputs), and key economic information (direct/indirect costs and tangible/intangible impacts).

When a bushfire occurs, we assess what has been damaged and how severe the damage is to estimate bushfire impacts. Economists estimate impacts using the reconstruction costs of an asset, by measuring the total cost to reinstate the asset to its former state, before it was damaged or destroyed by bushfire. This can sometimes be different to the market value of an asset. For instance, the market value of a house (what it can be sold for) is different to its reconstruction costs. The market value of a house depends on how the real estate market is performing at any given point, which includes the price of the land where the house is located. However, when a house is damaged by a bushfire, the land is not damaged per se. Thus, we measure the impacts on the house by measuring it reconstruction costs, i.e., what it would cost to replace the structure and the contents of the house to how it was before it was destroyed by the fire.

In simulation studies, we apply the same economic principle and use reconstruction costs to estimate economic impacts. The only difference is that instead of knowing where the fire has been, a simulator tells us where fires are likely to go and the potential damage they are likely to cause to different assets.

We have collected data to estimate the dollar values of different tangible and intangible assets. This process is explained in more detail for each asset type (see Appendix C). In the case of intangible assets, it is better to assign an approximate value than to assign no value at all (Pannell and Gibson 2016). If we do not allocate a dollar value to an intangible asset, we are in effect assuming that its value is equal to zero or that it has little to no importance and its value is negligeable. However, we know that neither of these assumptions is true and intangible impacts from natural hazards are substantial and can sometimes be greater than tangible impacts (Deloitte Access Economics 2016).

For this study, economic data was provided at two scales:

1. Local Government Area - included values such as houses, commercial and industrial buildings.
2. State-based values - included values such as human life, power network infrastructure and agricultural infrastructure such as farm sheds, provided as a single value with no spatial variability.

3. Results - Annualised risk from the network

Understanding the potential for ignitions from energy network assets is essential for the development of strategies and initiatives aimed at building and sustaining resilience to the power management sector. Here we examine the impacts from fires starting from the Powerlink network (i.e., from pole ignition sources). Results have been presented as spatial outputs for impacts to the power network (expressed as annualised risk).

Maps and summary statistics for annualised risk to individual assets which originate from each ignition location are in Appendix A. Appendix A provides figures which provide a zoomed in comparison of results between three case study regions: Brisbane, Gladstone and Townsville. The full spatial dataset can be interrogated using the accompanying spatial database and webapp.

3.1. Annualised loss from ignitions originating from the power network

Figure 3 1 below shows the total area burnt from ignitions originating on the network. These data indicate the ignition locations (along the network) likely to cause the largest area burnt should a fire occur. The results are presented as total annualised risk for the potential for impact from all ignition locations under the full range of FFDI categories. Area burnt was a direct output from the fire behaviour simulations; other metrics were calculated based on the spatial intersection with individual fires and the total length or area intersected by fires.

These maps indicate where high impact ignitions may originate and can be used to inform risk management and mitigation activities from the power network. For example, ignition origin points for multiple assets can be identified for mitigation activities which result in the highest overall benefit to a range of assets. Risk profiles for each asset vary due to geographic variation in the transmission of assets across the landscape and proximity of assets to each ignition location. For example, crop and livestock loss is more likely to occur in farmland; plantation loss is more likely to occur in forested areas.

Spatial outputs from line ignitions can be used to identify sections of the Powerlink network with the highest risk, and therefore identify areas where additional management could occur to give the greatest reduction in the potential loss from bushfire risk. However, the current analysis does not consider the cost of the actions nor the ability of those actions to reduce fire risk. Such an analysis would need to consider the role of independent and additive actions of changing the risk to ignition and fire spread.

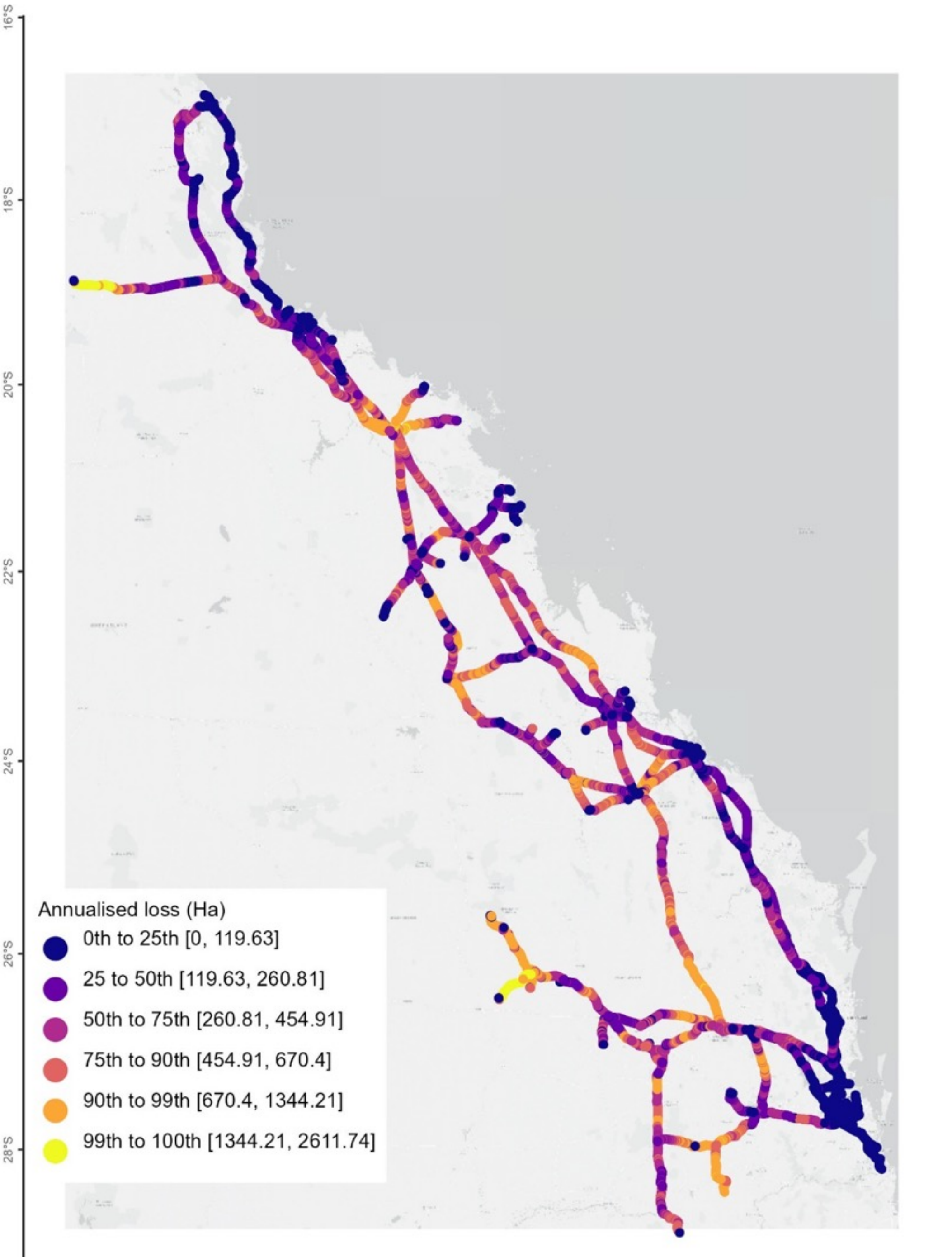

FIGURE 3.1 ASSET LOSS BY LINE IGNITION LOCATION- AREA BURNT. RESULTS ARE PROVIDED AS ANNUALISED LOSS (HECTARES), WITH LIGHTER COLOURS INDICATING THE HIGHER RISK LOCATIONS.

3.2. Annualised cost for ignitions originating from the power network

Figure 3 2 below shows the total annualised cost for all assets, combined for each ignition location along the power network. This indicates where the greatest economic impact (in terms of dollar value) has the potential to occur in terms of total annualised cost. The results are presented as total annualised cost for all ignition locations under the full range of FFDI categories.

Maps and summary statistics for annualised risk to individual assets which originate from each ignition location are in Appendix B. Appendix B provides figures between which provide a zoomed in comparison of results between three case study regions: Brisbane, Gladstone and Townsville. The full spatial dataset can be interrogated using the accompanying spatial database and webapp.

It is important to note that there is large uncertainty in the contributions of statistical house and life loss. This is driven by some of the limitations around calculating lives lost and the ability of these calculations to adequately capture human behaviour. For example, human choice and evacuations are currently not captured in these calculations, and so the values are expected to be lower (due to people leaving early, and less people staying to defend properties) as a result of better education pre-fire and better messaging systems on days of high fire danger.

Interestingly, the ignitions causing the greatest area burnt (Figure 3 1) do not always correlate with the areas of highest annualised cost (Figure 3 2). In general, ignitions near population centers result in fires with higher annualised cost, which is not surprising as the cost of housing and human lives dominated the calculation of annualised cost. This is most likely driven by the different land uses between regional and urban centers, in particular with housing distributed across the urban-wildland interface.

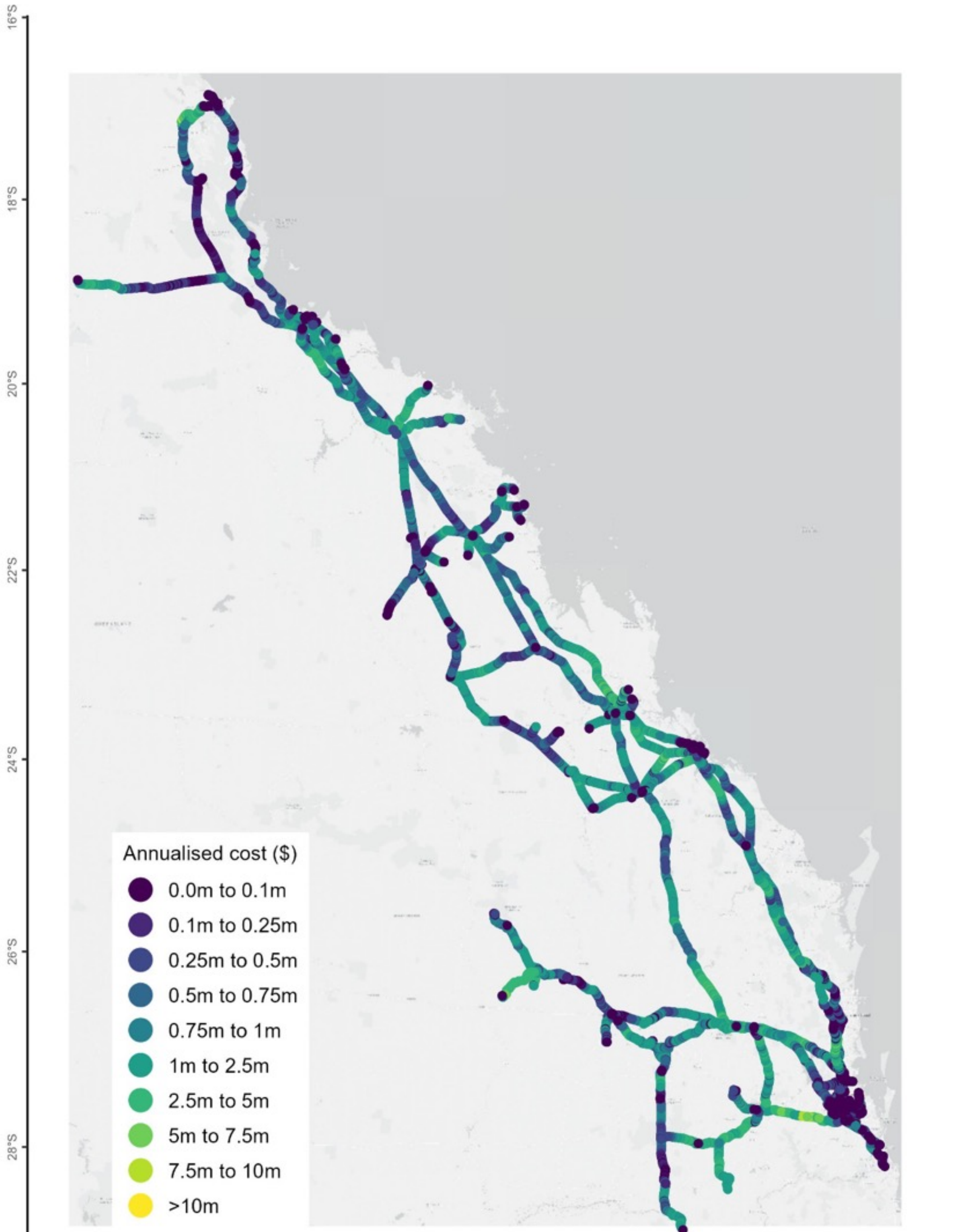

FIGURE 3.2 TOTAL ANNUALISED COST ($) EXPRESSED AS PERCENTILE CLASSES, DARKER COLOURS REPRESENT LESS COST, LIGHTER COLOURS REPRESENT HIGHER COSTS.

3.3. Change in risk between the current and maximum fuel load scenarios.

Recent fires in the landscape reduce fuel loads and therefore fire risk. As vegetation communities mature, they reach a maximum fuel load if subsequent fires or fuel management does not occur. By comparing the current fuel loads in the landscape using current fire history against fuel loads without fire history (maximum fuel scenario), we can examine how risk-profiles may change as fuel loads mature.

Results are expressed as a factor of change, indicating the direction and magnitude of change in risk profiles as vegetation communities mature. Depending on fire history, the risk profiles across the landscape have the potential to increase as fuel loads reach their maximal state in mature vegetation. In many areas the risk profile between the two scenarios is similar, meaning that overall - the risk profile is unlikely to change as the vegetation communities mature (Figure 3 3). However, we also identified several areas across the network where current risk is reduced due to recent fire seasons (Figure 2 4).

Change in risk has been expressed as the relative percent difference (RPD) at each pole. **The results indicate that for the majority of Queensland, risk profiles will not change (shown in grey) across the network in the absence of future fire in the landscape.** Parts of the network have the potential to see an increase in risk (shown in orange). Many of these areas are associated with recently burnt areas (Figure 2 4) and fuel loads are regenerating following fire. Areas where risk may decrease (shown in blue) are likely the result of the complex interactions between weather and fuel which may result in a localised decrease in fire risk. This information may assist in targeting key regions where increased fuel management may help to mitigate the increased fire risk into the future.

Results for individual assets are provided in Appendix A (see Figure 1 and Table 1). Interestingly, very little difference was observed between the current and maximum fuel scenarios (Appendix A, Figure 1). This may be explained in part by the relatively small number/extent of bushfires in this region, when compared to other parts of south-eastern Australia. The study region currently has fewer bushfires (and undertakes less prescribed burning compared to New South Wales and Victoria), suggesting that the fuel loads in this region are less dynamic and therefore little variability between what the fuel loads currently are and what they would be if no additional fuel management or fires were to occur (maximum fuels). Much of the study region is also dominated by grassland systems. Densely vegetated forested regions are characterised by much higher fuel loads, and bigger changes in fuel over time. Grassland systems reach maximum fuel loads much more rapidly and are often characterised by smaller changes in fuel loads over time.

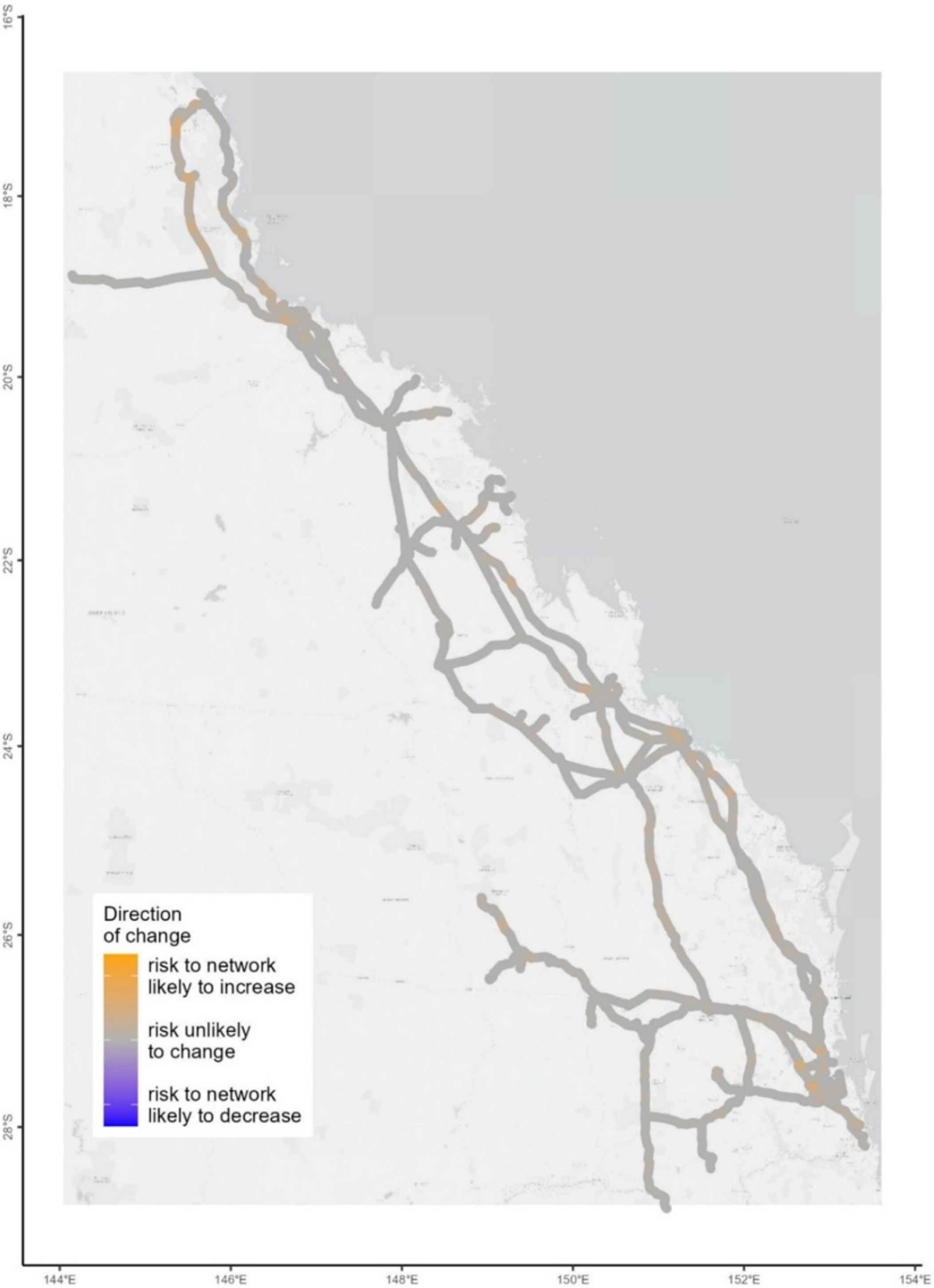

FIGURE 3.3 DIRECTION OF CHANGE THE RISK PROFILE CAN TAKE FOR AREA BURNT BY IGNITIONS WHICH ORIGINALTE FROM STRUCTURES AS FUEL LOADS MATURE ACROSS THE LANDSCAPE BASED ON THE CURRENT FIRE HISTORY LAYER. GREY AREAS INDICATE LITTLE OR NO CHANGE, ORANGE AREAS INDICATE PARTS OF THE NETWORK WHERE RISK TO THE NETWOR IS EXPECTED TO INCREASE WITHOUT FUEL MODIFICATION, AND BLUE AREAS INDICATE PARTS OF THE NETWORK WHERE RISK IS LIKELY TO DECREASE. THIS DATA CAN BE FURTHER INTERROGATED AND DIRECTION OF CHANGE VIEWED IN MORE DETAIL USING THE WEBTOOL OR SPATIAL DATASET ACCOMPANYING THIS MAP.

4. Annualised risk to the network

Understanding landscape risk profiles for bushfires is essential for the development of strategies and initiatives aimed at building and sustaining resilience to the power management sector. Here we examine the impacts to the network from fires which begin in the landscape (i.e., from an ignition source not related to the power transmission network). Results have been presented as spatial outputs for impacts to the power network (expressed as annualised risk).

The ability to determine annualised risk (expressed as a unit loss for an asset) is important as it quantifies losses from fire and can be used to identify ignition areas of greatest risk to the network. This analysis can assist in the development of regional-based fire management plans and risk mitigation activities to support the protection of the power network from landscape bushfires. In addition, this information may be important for determining where future investments and networks upgrades are targeted to reduce network disruption caused by bushfires. Areas currently characterised by high impact may require further consideration in network management and maintenance (i.e., additional fuel management along network corridors, planning for suppression resources at critical locations, or consideration of regular fuel treatments in adjacent areas, for example).

4.1. Annualised loss to the network from landscape fires

Figure 4 1 shows the annualised risk to the power network based on the current fire history, where risk has been categorised as percentiles for probability of loss across the network. Risk is shown by aggregating the results into 5km hexgrid cells and taking the mean value of impact to the network within each cell.

These results indicate the highest probability of loss (to the Powerlink network) from fires starting in the landscape occur around the coastal (to the north of the study region) and highly urbanised regions (i.e., around Brisbane and Rockhampton). These areas of higher risk may, in part, be explained by the presence of forested regions to the west of both of these regions.

While the risk is higher in the more urbanised areas, it is important to note that ignitions which occur in more densely vegetated areas commonly result in larger, more severe fires due to the higher fuel loads, topographical variation and less rapid suppression. In comparison, ignitions which occur at the Wildland Urban Interface or in more populated areas are generally identified more rapidly, resulting in faster and more effective suppression, and less impact to values such as energy network assets. **While Powerlink have little ability to change the likelihood of landscape ignitions resulting in bushfires that may impact on their network, these results help to identify the areas of highest risk to the network, potentially guiding where additional fire mitigation measures should be directed in the lead up to fire seasons.**

It is important to note that the asset loss curves used to estimate impacts to powerline assets are based on low voltage and high voltage powerlines and poles. **We currently do not have asset loss functions specifically developed for transmission towers.** Transmission towers are generally larger, with key components located higher off the ground and usually made from different construction materials (compared to other parts of the network). Given we don't currently have asset loss curves for transmission towers, in this study we have used the loss functions available for powerlines. **An important future improvement to the methodology would be the development of a transmission tower specific loss function, which would facilitate more accurate estimates of loss across a broader range of power transmission asset classes and infrastructure.**

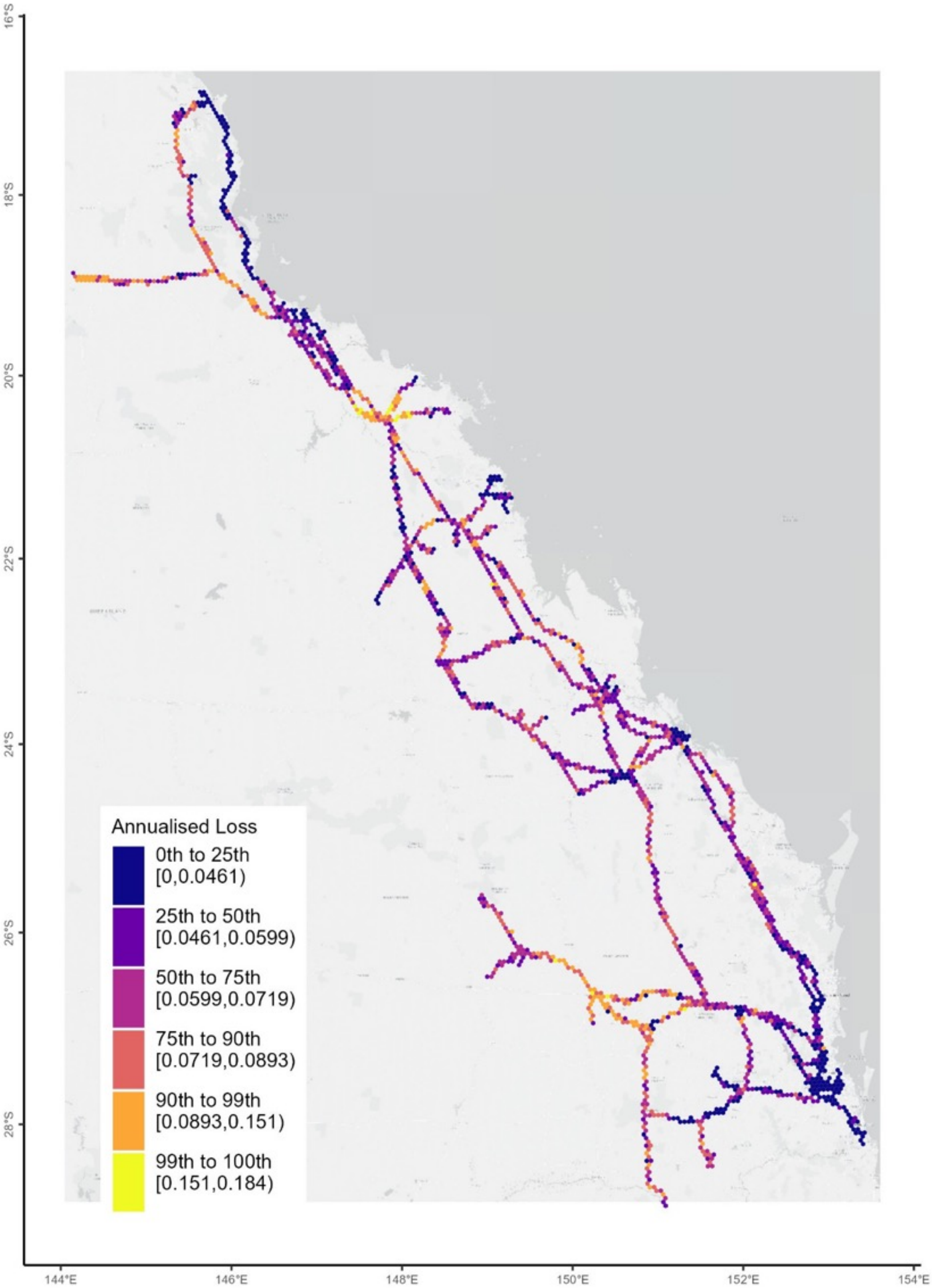

FIGURE 4 1 ANNUALISED LOSS OF THE NETWORK BASED ON THE MAXIMUM FIRE HISTORY. LIGHTER AREAS (YELLOWS) INDICATE HIGHER RISK TO THE POWERLINK NETWORK FROM FIRES STARTING IN THE LANDSCAPE, DARKER AREAS (BLUES) INDICATE LOWER RISK.

5. Using the research to inform the future

Natural Hazards Research Australia (the Centre) has a focus and commitment to supporting the end users of its research to best use the knowledge, data and insights from research projects and other activities to improve the capacity and capability of all Australians to be more resilient to shocks and stressors caused by an increasing exposure to natural events. It is important to Powerlink that their business is empowered to best use the understanding of impacts of significant fires, either by natural causes or caused by assets, to inform engagement and education opportunities around risk, maintenance priorities, future mitigation options and broader investment decisions. The section below offers some possible pathways by which Powerlink could use the results of this study to inform strategic and operational imperatives.

Engagement- better understanding the risk (s)

It is acknowledged that bushfire risk is variable across the entire Powerlink network and as a result, employs a number of engagement activities to help various stakeholders and communities to understand risks and impacts caused by bushfire fuelled disruptions to the network. In saying that, Powerlink are keen to use the scientific and economic quantification of risks and impacts highlighted in this study to continue/augment a strategic approach to risk management, avoiding piecemeal risk mitigation activities that may have limited effect on current and future stakeholder they are trying to influence.

It is acknowledged that Powerlink are part of a complex ecosystem of stakeholders, including communities that play a critical role in reducing risks and impact of bushfires and thereby supporting the resilience of Queenslanders. If a risk isn't being owned, it isn't being managed. This research can aid Powerlink having discussions with different stakeholders about both ownership and management options, specifically:

- better explaining the context of risks
- clarifying who has responsibility to manage certain risks
- available treatment options and the potential effectiveness of different strategies.

It is envisaged this work could inform future engagement activities on the above specifically with the Queensland Reconstruction Authority, HQ Plantations, councils, county mitigation groups, national parks and 3rd party burning contractors.

Powerlink is also keen to consider the development of some tangible research informed products that can support discussions on risk with stakeholders such as a flyer of ignition risk summary to be used in the field.

This work could also inform discussions with brownfield and greenfield landholders that have high voltage networks planned or existing, so that fire risks can be managed as part of property, catchment and landscape fire mitigation.

First Nations engagement

Powerlink is bolstering its internal first national capability and are actively considering new and improved ways to engage with first nations knowledge and expertise into mitigation and treatment options related to fires in the landscape. Whilst there is a suite of new/projected activities planned, such as cultural cool burns, there are opportunities to pivot the use of existing resources in engaging with First Nations communities around bushfire resilience.

Maps using the outcomes of this research which highlight areas along the network that are less resilient to significant bushfires and likely therefore see impacts, could be a useful tool to engage with traditional owner groups. For example, maps of potential high-risk locations can be overlayed with cultural asset locations to ensure adequate management for these regions. In addition, the AIATSIS map can be used to springboard discussions (and inform the timing of those discussions) around cultural burns in areas along the network that have been modelled to have the highest risk and highest projected impacts related to significant bushfires.

Education and training

Maintaining strong collaboration over time with Queensland Fire and Emergency Services for the development and delivery of timely and accurate advice regarding bushfire risk and impacts to assets and communities has been vital to Powerlink, however there is an acknowledgement that further work can be undertaken to inform a broader capability lift between both entities on quantifying bushfire risks and impacts. Specifically, there may be opportunities for Powerlink, QFES and the Centre to build on current knowledge and further extend knowledge and expertise on fire simulations and how risk plays out across the landscape by way of some formal training opportunities.

In addition, we know that the renewable energy sector in Queensland is growing,currently representing 26% of all electricity use in Queensland. The significant presence of renewable energy technologies and assets across Queensland also affects bushfire related risks and impacts caused by those fires on the community. The outcomes of this work could involve some targeted and tailored outreach activities with the renewable energy sector on current bushfire risk and potential impacts to assets and communities.

Network maintenance and mitigation

Essential to any transmission business is not only the appropriate planning and placement of assets but also maintenance activities across the network, especially in preparing for significant weather driven events such as bushfires, storms and floods. In light of this, outcomes of this work can be used to assist Powerlink in prioritising where maintenance needs to occur across the network,such as targeting insulator replacements, in line with the modelled risks and impacts to assets and communities.

Vegetation management on easements is part of Powerlink's remit however prescribed burning is not. Whilst the entity works with landholders to mitigate fire risk through bushfire planning and engagement, they still play an important role in influencing understanding and attitudes regarding bushfire risk and impacts across its network. The outcomes of this work can inform Powerlink's advice regarding the selection of corridors for planned burns.

Other tangible opportunities for this work to inform operational imperatives is providing Powerlink staff with an identification of the priority feeders on the network and managing related risks between feeder sections. For example, the modelling from this project can allow Powerlink to pinpoint 20 or 30 feeders that have the highest exposure to significant bushfire which the organisation can then use to articulate an integrated management plan for each.

Investment decisions- easements and network

For organisations such as Powerlink, the approach to easement management is vital for operations and long-term strategic planning around asset placement that best service communities. Through understanding regions with the highest exposure to bushfire risk and an understanding of the suite of impacts to the network and surrounding communities, the outcomes of this work can inform business decision making on easement acquisition/ purchasing, corridor selection and help to inform prioritisation of maintenance activities along the network.

Understanding bushfire risks can also inform network investment decisions. This can include possible alterations to the route, planning, design, maintenance and operation of the network. Fire risks from these research outcomes will be evaluated to determine how it can best be integrated into engineering and risk-based investments.

Conclusion

The world is increasingly interconnected, and the changing climate is increasing the frequency and intensity of natural hazards, including bushfires. It is in this context that the ability of organisations like Powerlink to better understand and address risks is vital. There are significant opportunities for innovative business decision making on operational and strategic imperatives regarding bushfire risks to reduce impacts on communities. This research can be used as tool/part of the toolbox that Powerlink has to enable a broader view of bushfire risks and help improve two-way engagement with many across Queensland about bushfire risks and impacts which we can expect to see beyond experience and imagination in the future.

It has assisted in identifying areas for further research and improvements in modelling to better quantify the risks associated with fires and transmission networks.

6. Summary and key findings

Understanding the potential consequences of ignitions starting from energy network assets is a key concern for the energy industry and fire management agencies alike, especially as the climate changes and we see increases in fire occurrence, severity and frequency. Transmission networks are the high-voltage components of energy distribution systems, carrying electricity over vast distances to meet the increasing demands of an expanding society. Transmission networks are essential for ensuring a reliable power supply; however they also traverse diverse natural and human-modified landscapes, often passing through remote and fire-prone areas. As such, there is an urgent need to comprehensively assess and manage the risks associated with energy networks to safeguard lives, property, and the environment. A better understanding of future fire risk from energy networks, including where in the landscape ignition risk is highest and under what conditions the consequences will be greatest, is critical for ensuring effective and timely management for bushfire prevention.

The aim of this project was to develop a bushfire consequence model to quantify the range of likely bushfire outcomes for a range of assets across the Powerlink network. Fire risk modelling methods were used to help assess the potential impacts both from and to the Powerlink network.

PHOENIX RapidFire was used to determine predominant landscape-scale fire risk from and to the entire Powerlink transmission network across Queensland. This was achieved by simulating two different ignition scenarios: powerline ignitions (1km spacing along the Powerlink powerline network), and landscape scale ignitions (2km gridded ignitions within a 15km buffer of the network). A series of weather-days were selected from Automatic Weather Station (AWS) records based on the Forest Fire Danger Index (FFDI) to capture variation in weather and associated effects on fire behaviour.

Results from this project will support Powerlink business operations, justifying ongoing commitment and investment to bushfire risk mitigation activities. The ability to predict where the highest risks are to (and from) the network and surrounding assets is important for determining where management actions can be implemented in an attempt to reduce those vulnerabilities.

One of the objectives of this project was the ability to determine the areas of the greatest consequence from ignitions along the Powerlink network, including the ability to identify where the greatest risk originates from (i.e., where an ignition is likely to cause the greatest impact). This is an important piece of information, as it may help to guide future fire mitigation efforts to achieve the greatest reduction in risk and may help guide future investments. However, it is important to note that this has not been designed to be used for insurance purposes.

Key findings and implications:

Overall, annual area burnt from ignitions starting on the Powerlink transmission network was found to be greater around Townsville and Gladstone compared to the greater Brisbane region. These regions correlate with areas of urban settlements and higher housing density (and hence powerline density). **The higher risk areas occur where a complex urban interface exists in a topographically diverse landscape covered with fire prone vegetation.** Higher risk locations were also present in the far west of the network (north-west of Brisbane, and north-west of Rockhampton).

Ignitions that resulted in the greatest annual area burnt did not often correlate with the areas of highest annualised cost. In general, ignitions near population centers result in fires with higher annualised cost, as the cost of assets such as housing and human lives significantly increase the calculation of annualised cost.

In terms of annualised risk to the Powerlink network from fires starting elsewhere in the landscape, **the highest probability of loss of the network was found to occur in the coastal and highly urbanised regions** (i.e., around Brisbane and Rockhampton). These areas of higher risk may be explained by the presence of forested regions to the west of both locations. Ignitions occurring in these more forested parts of the landscape may result in larger fires that could rapidly impact the network. This information will be useful for guiding future fire risk mitigation efforts along the Powerlink network.

The outputs from this study indicate potentially high-risk ignition locations, as well as areas with the highest consequences should an ignition occur. This information can be used to inform strategic management, such as potential fuel treatment actions to reduce the risk of an ignition becoming active and spreading. Ignitions which occur in areas which have recently (i.e., in the last 1-5 years) been treated through prescribed burning, mulching, slashing, thinning or pruning have been shown to spread slowly, occur at lower intensities and have a higher likelihood of self-extinguishment compared to areas which have not undergone recent fuel management (Prestemon and Butry 2008; Syphard *et al.* 2008; Plucinski *et al.* 2014; Collins *et al.* 2015; Zhang *et al.* 2016; Clarke *et al.* 2019). In addition, this spatial information can be used to inform potential placement of suppression resources in the landscape, in order to protect key assets.

5.2. Limitations and future improvements

- Environmental factors such as weather and vegetation under powerlines may affect the probability of ignition. Similarly, structural features of the powerline such as age, maintenance level and construction materials will also influence ignition likelihood. **However, no models currently exist to predict the likelihood of ignition under these variables.** Results of this study should be used as a guide of which areas of the power transmission network have the greatest potential to cause damage to people and property, with this data potentially guiding future risk mitigation strategies (i.e., additional fuel management, increased resilience through pole replacement).
- The development of annually updated spatial layers for Queensland would be useful in ensuring the latest information is available for modelling. This could include the generation of additional asset layers (or sub-categories). We note the asset probability loss curves were developed for RFS in NSW and may be over or underestimating the risk to Queensland conditions. **In addition, the development of additional loss functions for other assets classes (i.e., transmission towers) would improve the impact estimations for energy network assets.**
- Currently the modelling uses historical weather data to capture a range of conditions and a range of FFDIs. **Gridded weather for the region would provide an important advancement to the current modelling**, and this is something that will be integrated into the methodology as soon as the data is available. This should result in more accurate weather data for the region both temporally and spatially.
- This modelling has utilised the old FFDI ratings, however **in the near future the modelling process will move to include the new National Fire Danger Ratings (FDR)**. However, this requires some detailed hindcasting of weather and other conditions, and is not yet ready for integration into the risk modelling framework. Many energy network providers are moving towards an annual refresh of their fire risk modelling. Annual refreshers of these profiles ensure the dynamic nature of changing fuel loads and recent fires (both planned and unplanned) are captured in the modelling process, especially considering the extremely widespread fires south-eastern Australia experienced during the 2019/2020 Black Summer season. The sheer extent of the Black Summer bushfires means that fuel loads across very large parts of eastern Australia are in flux, with dynamic changes to fuel load and structure likely to occur for many years. It will be important to capture this variability and associated impacts for fire risk over the next few years. Annual updates of the fire risk modelling will also enable the new FDR system and gridded weather to be integrated as soon as possible.
- In the current methodology, we have only explored the difference between current and maximum fuels. **The inclusion of additional management strategies could be easily integrated into the modelling to explore how risk changes depending on the type/scale/frequency of management** that could

potentially occur both in the landscape and at Powerlink assets. This is something that could be explored further in the future, as we now have a baseline of fire risk both to and from the network.

- Commercial and industrial assets are potentially overestimated due to a range of factors. As part of Project IGNIS, commercial and industrial assets were not included, due to a lack of spatial mapping and economic data at the time. **In addition, there are currently no asset loss curves for industrial or commercial buildings; and as such the loss impacts for these asset types are based on the current asset loss curves for houses**. This may not capture the full range of potential impacts from fire due to the diversity of building types and designs (e.g., farm shed vs. aircraft hangar), and asset classes in different land use settings (e.g. urban, rural and agricultural settings). In addition, there is currently a mismatch between the scale of the economic data available for these asset types, and the ability to spatially locate individual commercial or industrial buildings. Using the current approach, it is very hard to distinguish between a farm shed and a commercial building. Better spatial mapping of these assets will considerably increase the accuracy of the loss/cost estimates, and this is something that should be considered in the future. An average cost for these assets has been provided across a local government area (which captures a very large range of potential costs). Improving the spatial accuracy of these assets will enable more accurate values to be assigned to different commercial and industrial assets will be an important area for future research.
- Finally, the climate for southeastern Australia is predicted to increase under current climate change projections, with more frequent and more severe bushfires predicted for much of Australia. However, our current modelling approach does not account for future climates or associated changes to vegetation communities. The FLARE Wildfire Research group have developed FROST- Fire Regime Operations and Simulations Tool, which is able to model fire regimes under current and future climates. Where PHOENIX simulates individual fire events, FROST is able to simulate changes in the fire regime over decades to centuries. FROST is an innovative model that uses available environmental data to spatially and temporally predict current and future trends in fire regimes (Penman et al. 2015). **An important area for future research will be to quantify how different projections of climate change may change the risk both to and from energy networks, and also how management effectiveness may change under different conditions.**

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Appendix A: Annualised loss from the network (FLARE)

Powerlink Bushfire Risk Assessment 2023

How we present the geospatial results for the Annualised Loss for each asset by ignition location.

The results have been plotted from **annualised loss pole ignition data set**, with the results shown as categories based on the percentile transmission of data points within each range; the range of absolute values within each category has been included in the legend.

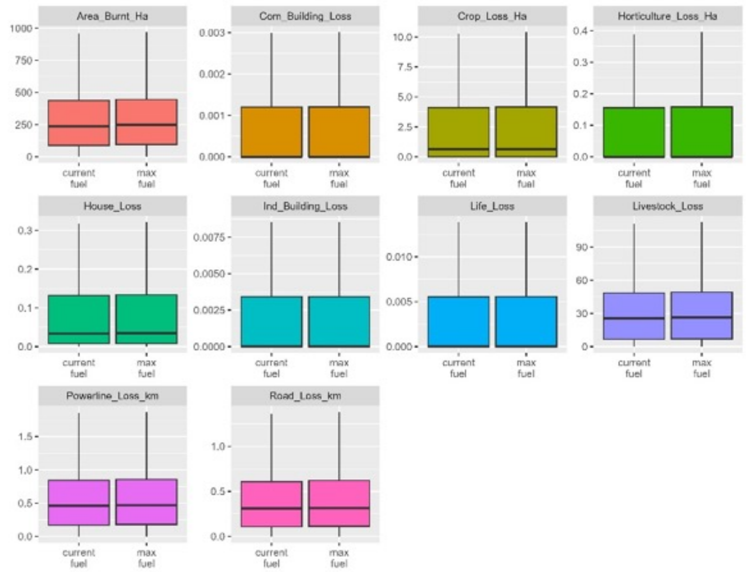

FIGURE 1 ANNUALISED RISK COMPARING CURRENT AND MAXIMUM LANDSCAPE FUEL LOADS

TABLE 1 ANNUALISED LOSS SUMMARY STATISTICS FOR QUEENSLAND

scenario_fuel	FFDI	metric	min	max	median	mean	sd
current fuel	ALL	Area_Burnt_Ha	0	2611.736	237.942	299.718	282.822
current fuel	ALL	Com_Building_Loss	0	0.078	0.000	0.002	0.004
current fuel	ALL	Crop_Loss_Ha	0	122.982	0.641	4.789	11.121
current fuel	ALL	Horticulture_Loss_Ha	0	19.444	0.000	0.323	1.196
current fuel	ALL	House_Loss	0	3.038	0.034	0.113	0.202
current fuel	ALL	Ind_Building_Loss	0	0.105	0.000	0.003	0.007
current fuel	ALL	Life_Loss	0	0.180	0.000	0.005	0.011
current fuel	ALL	Livestock_Loss	0	539.462	25.550	34.796	38.070
current fuel	ALL	Plantation_Loss_Ha	0	240.443	0.000	0.882	6.440
current fuel	ALL	Powerline_Loss_km	0	5.579	0.458	0.586	0.550
current fuel	ALL	Road_Loss_km	0	10.892	0.308	0.477	0.608
max fuel	ALL	Area_Burnt_Ha	0	2611.736	247.439	307.261	284.967
max fuel	ALL	Com_Building_Loss	0	0.078	0.000	0.002	0.004
max fuel	ALL	Crop_Loss_Ha	0	123.042	0.651	4.820	11.174
max fuel	ALL	Horticulture_Loss_Ha	0	19.444	0.000	0.326	1.203
max fuel	ALL	House_Loss	0	3.037	0.034	0.114	0.203
max fuel	ALL	Ind_Building_Loss	0	0.106	0.000	0.003	0.007
max fuel	ALL	Life_Loss	0	0.180	0.000	0.005	0.011
max fuel	ALL	Livestock_Loss	0	539.462	26.299	35.395	38.406
max fuel	ALL	Plantation_Loss_Ha	0	243.595	0.000	0.900	6.510
max fuel	ALL	Powerline_Loss_km	0	5.580	0.467	0.595	0.553
max fuel	ALL	Road_Loss_km	0	11.038	0.316	0.486	0.614

Metric: Area_Burnt

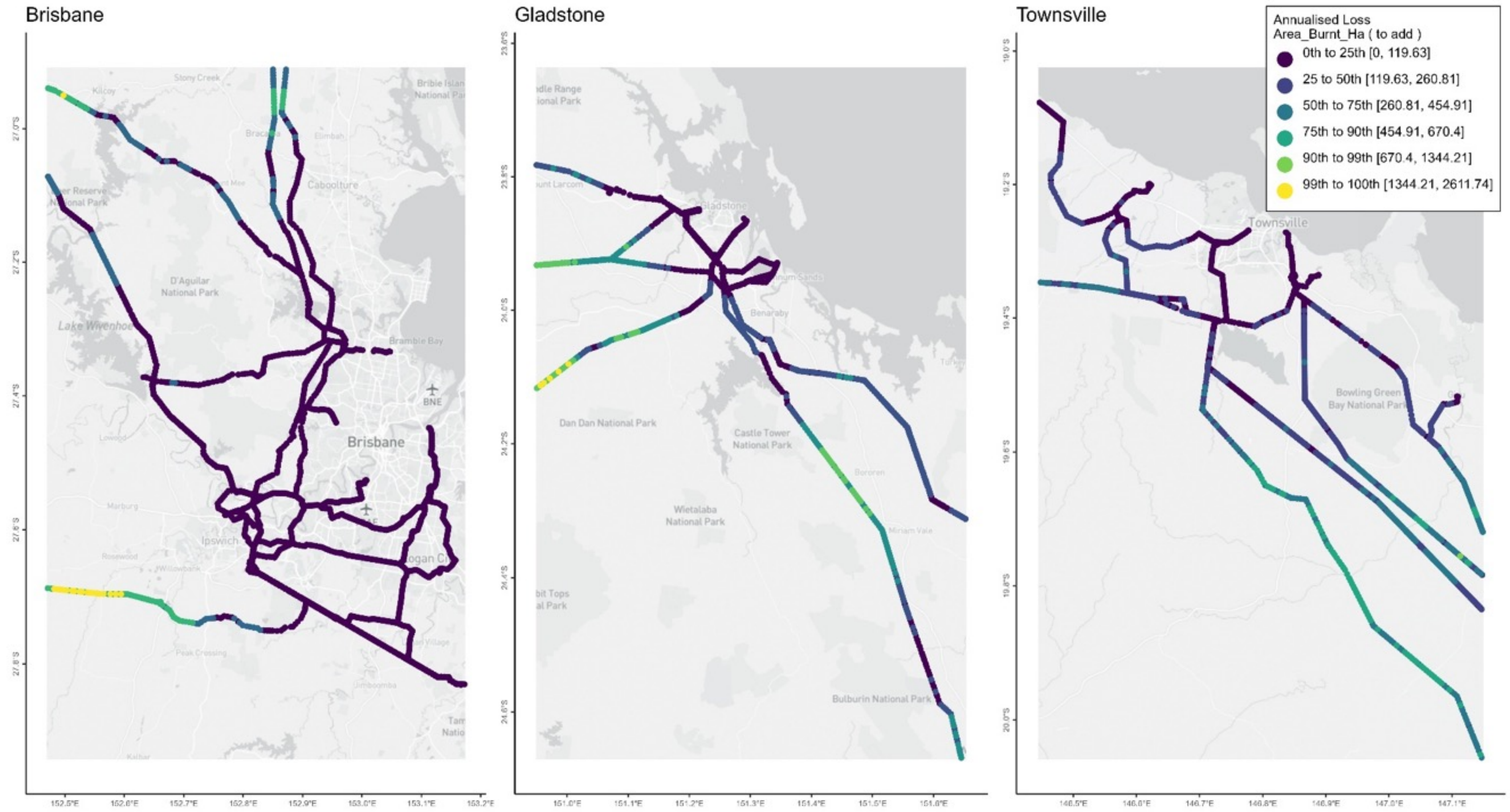

FIGURE 2 ANNUALISED LOSS FROM THE POWER NETWORK - AREA_BURNT

Metric: Com_Loss

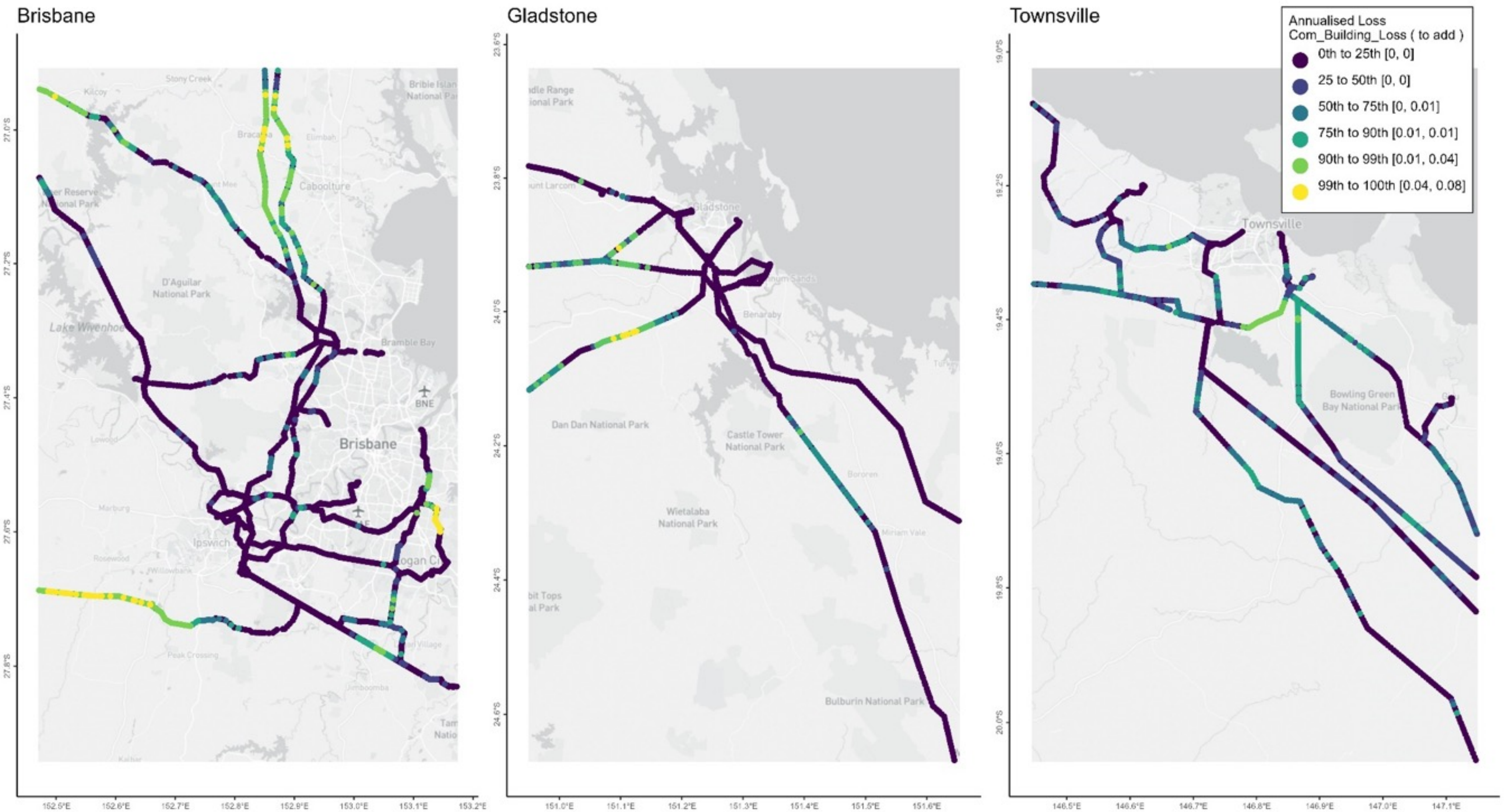

FIGURE 3 ANNUALISED LOSS FROM THE POWER NETWORK - COM_LOSS

Metric: Crop_Loss

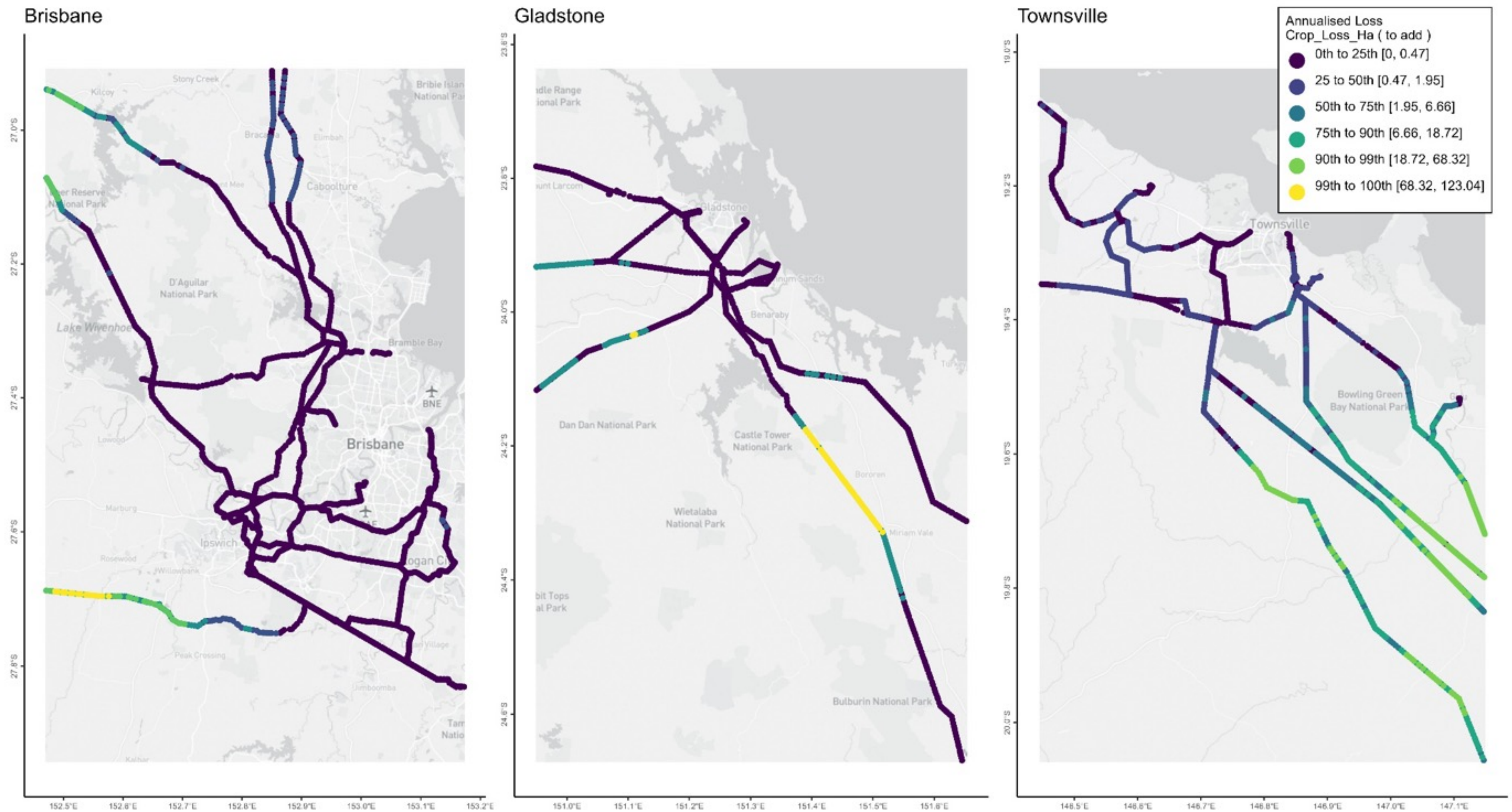

FIGURE 4 ANNUALISED LOSS FROM THE POWER NETWORK - CROP_LOSS

Metric: Horticulture_Loss

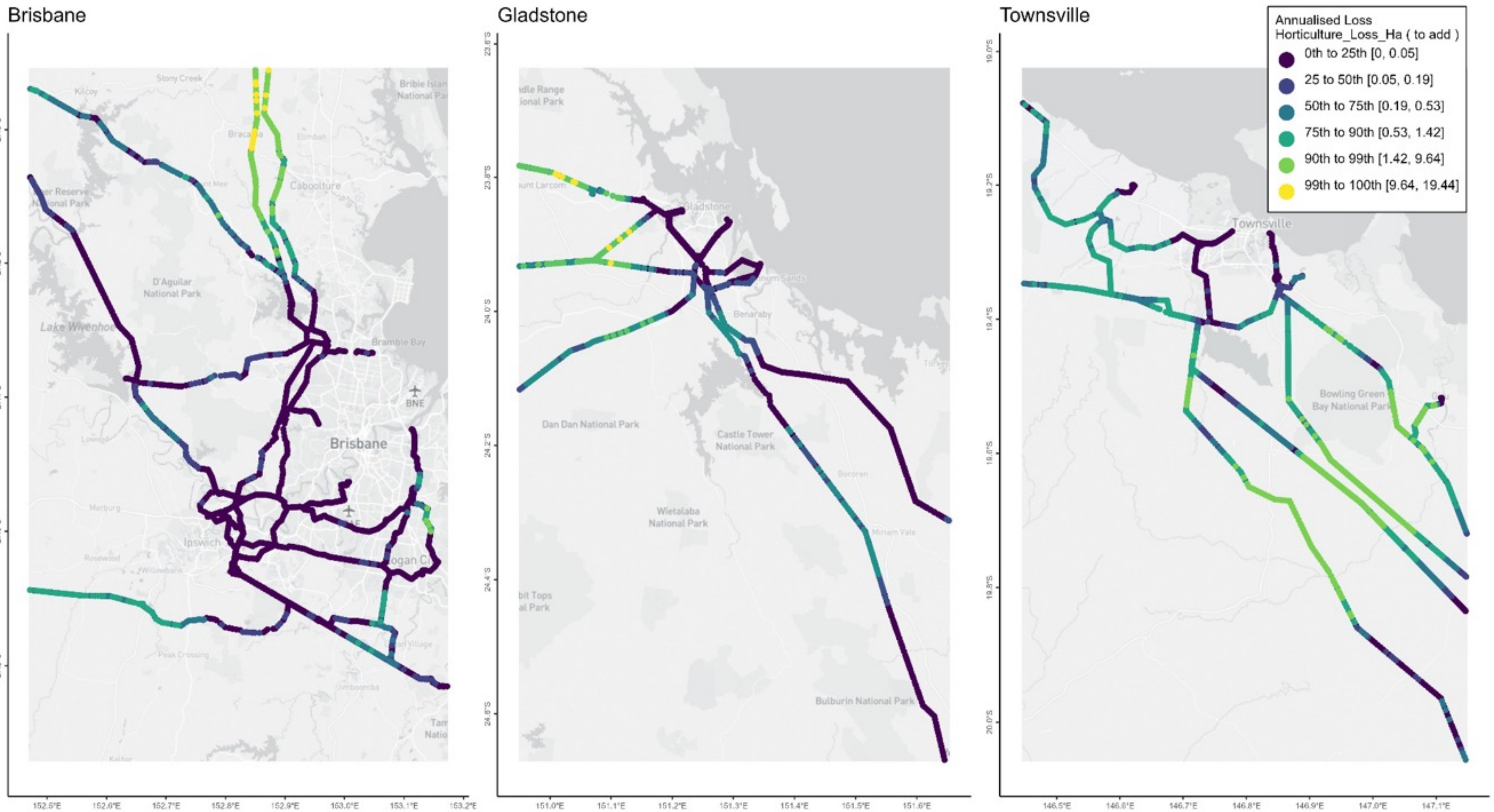

FIGURE 5 ANNUALISED LOSS FROM THE POWER NETWORK - HORTICULTURE_LOSS

Metric: House_Loss

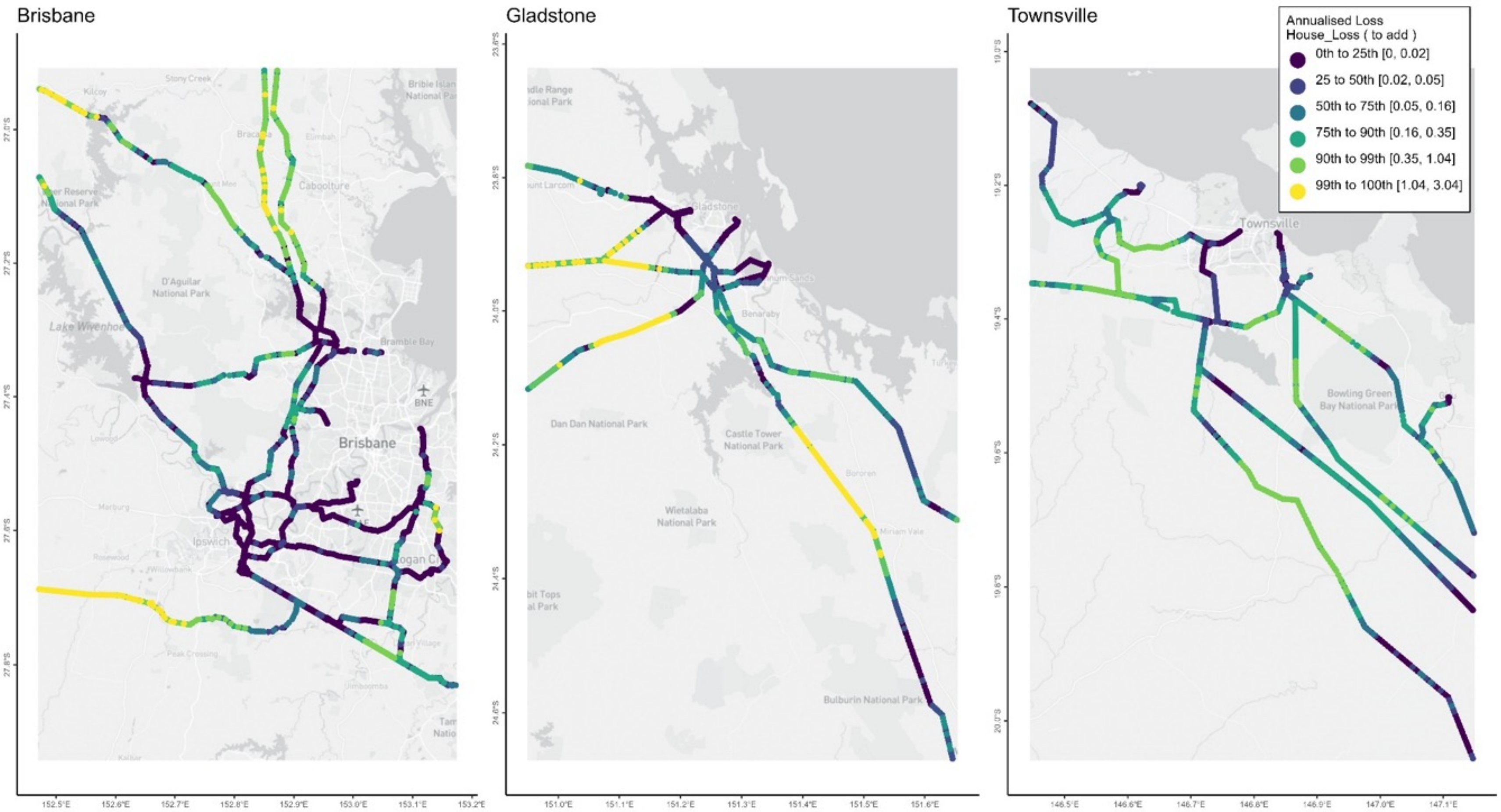

FIGURE 6 ANNUALISED LOSS FROM THE POWER NETWORK - HOUSE_LOSS

Metric: Ind_Loss

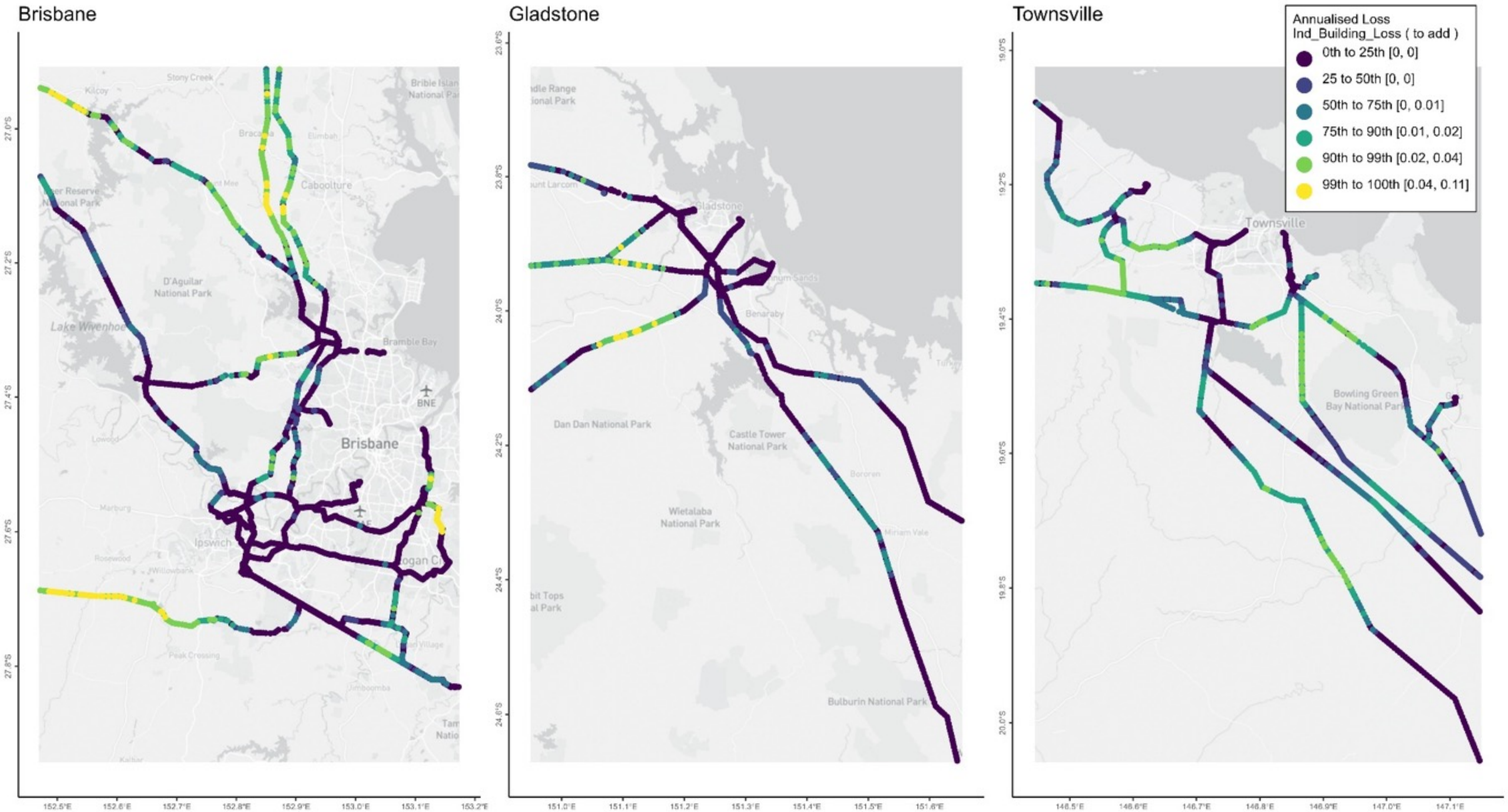

FIGURE 7 ANNUALISED LOSS FROM THE POWER NETWORK - IND_LOSS

Metric: Life_Loss

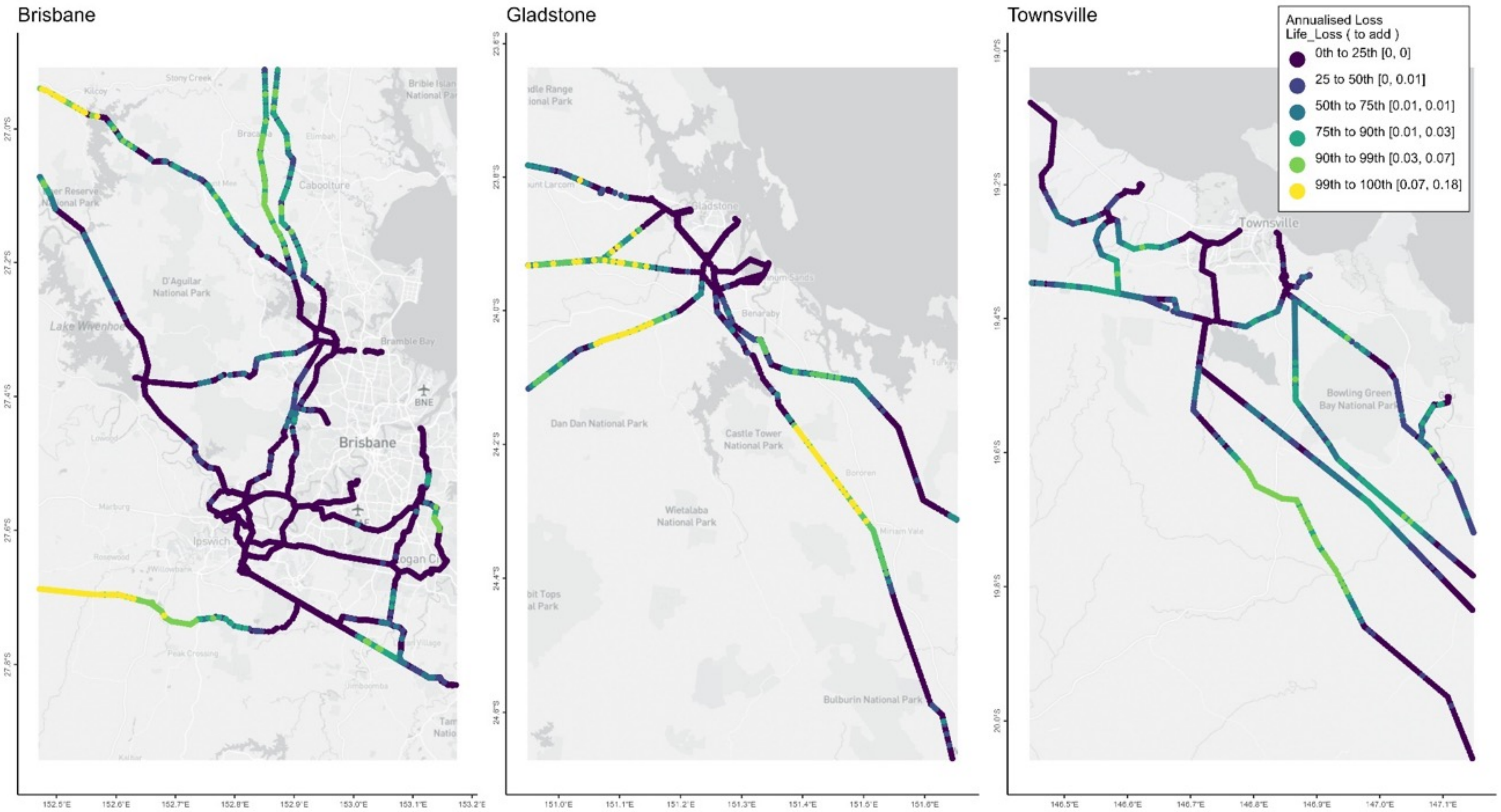

FIGURE 8 ANNUALISED LOSS FROM THE POWER NETWORK - LIFE_LOSS

Metric: Livestock_Loss

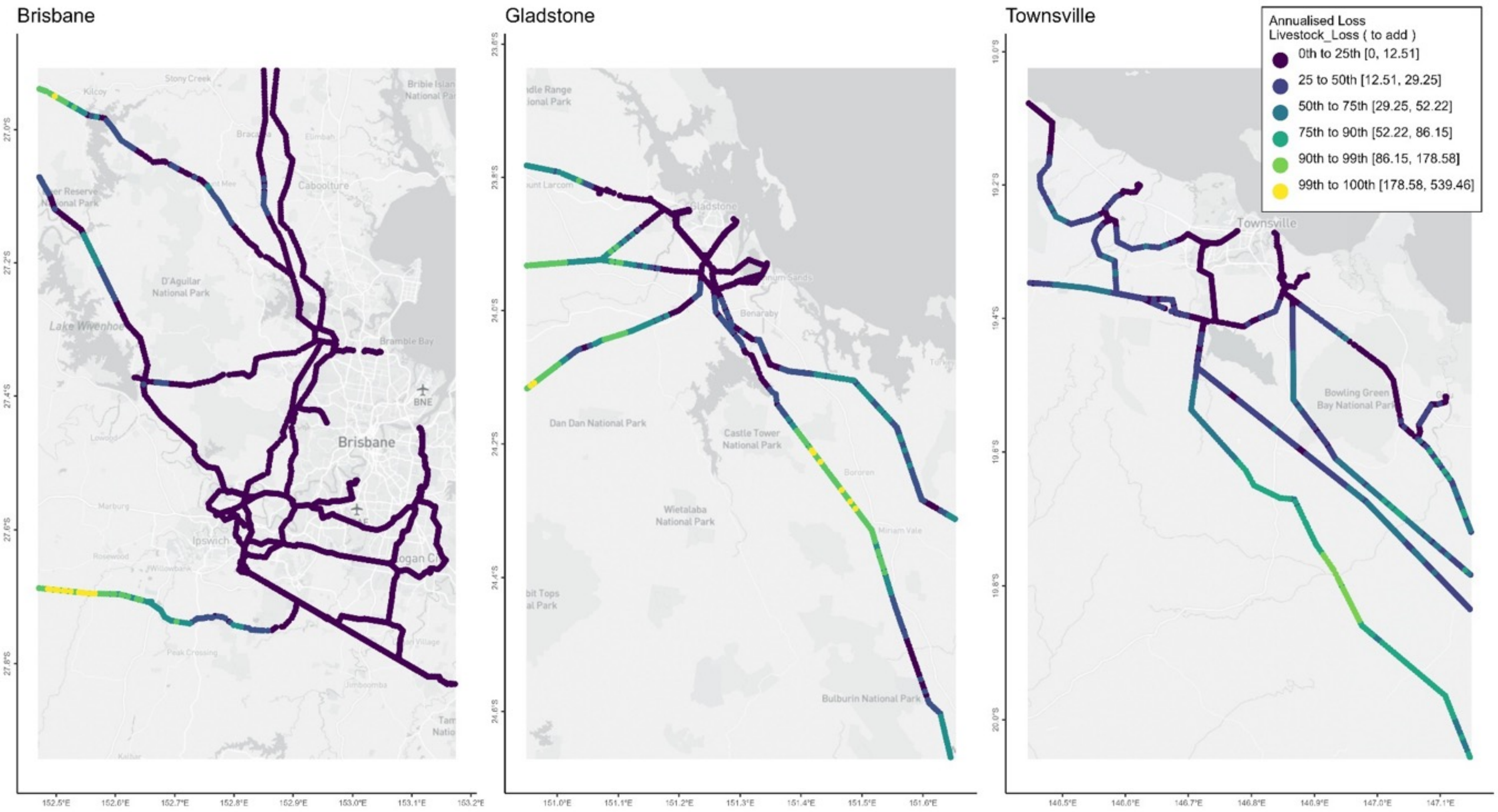

FIGURE 9 ANNUALISED LOSS FROM THE POWER NETWORK - LIVESTOCK_LOSS

Metric: Plantation_Loss

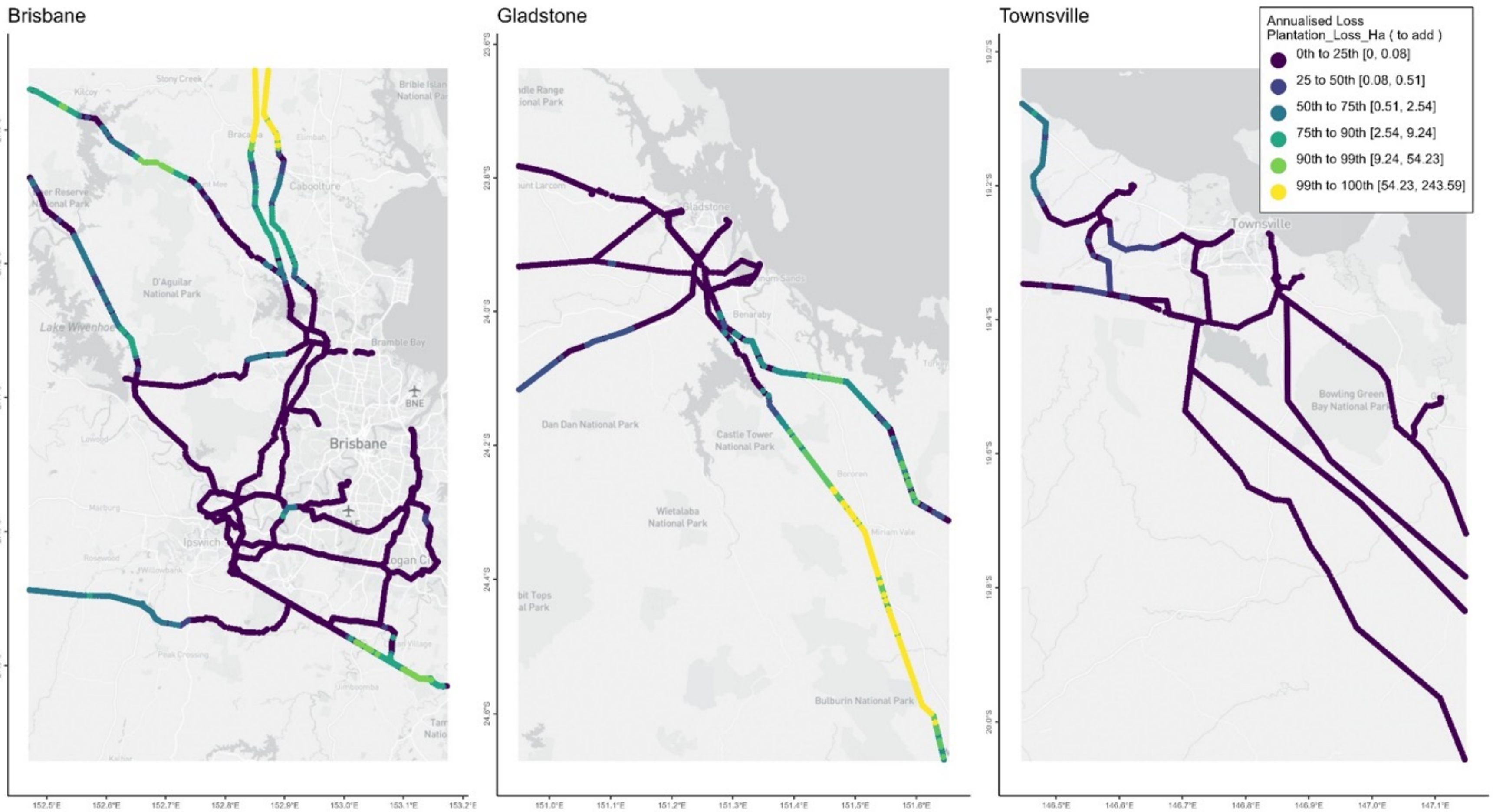

FIGURE 10 ANNUALISED LOSS FROM THE POWER NETWORK - PLANTATION_LOSS

Metric: Powerline_Loss

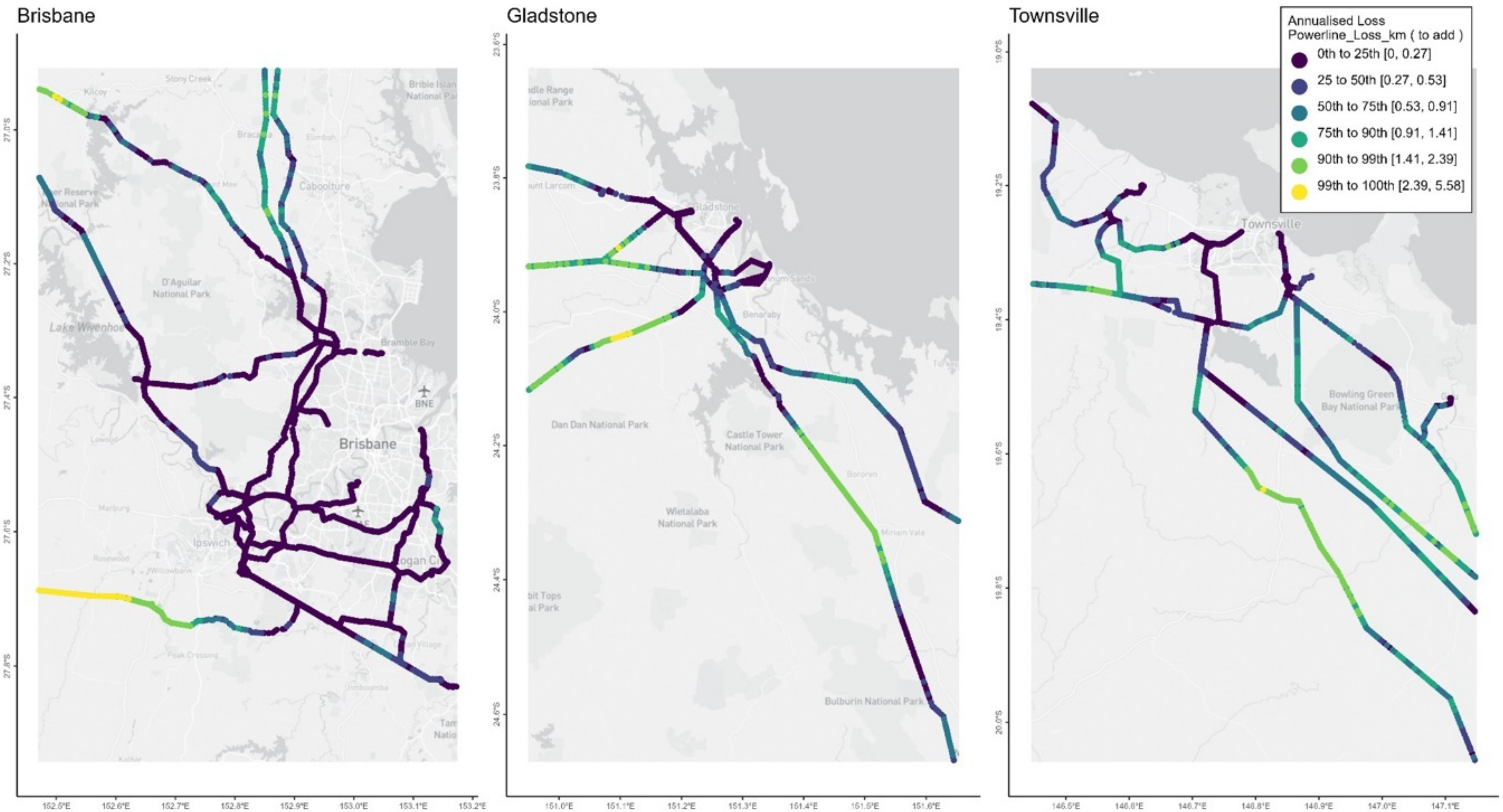

FIGURE 11 ANNUALISED LOSS FROM THE POWER NETWORK - POWERLINE_LOSS

Metric: Road_Loss

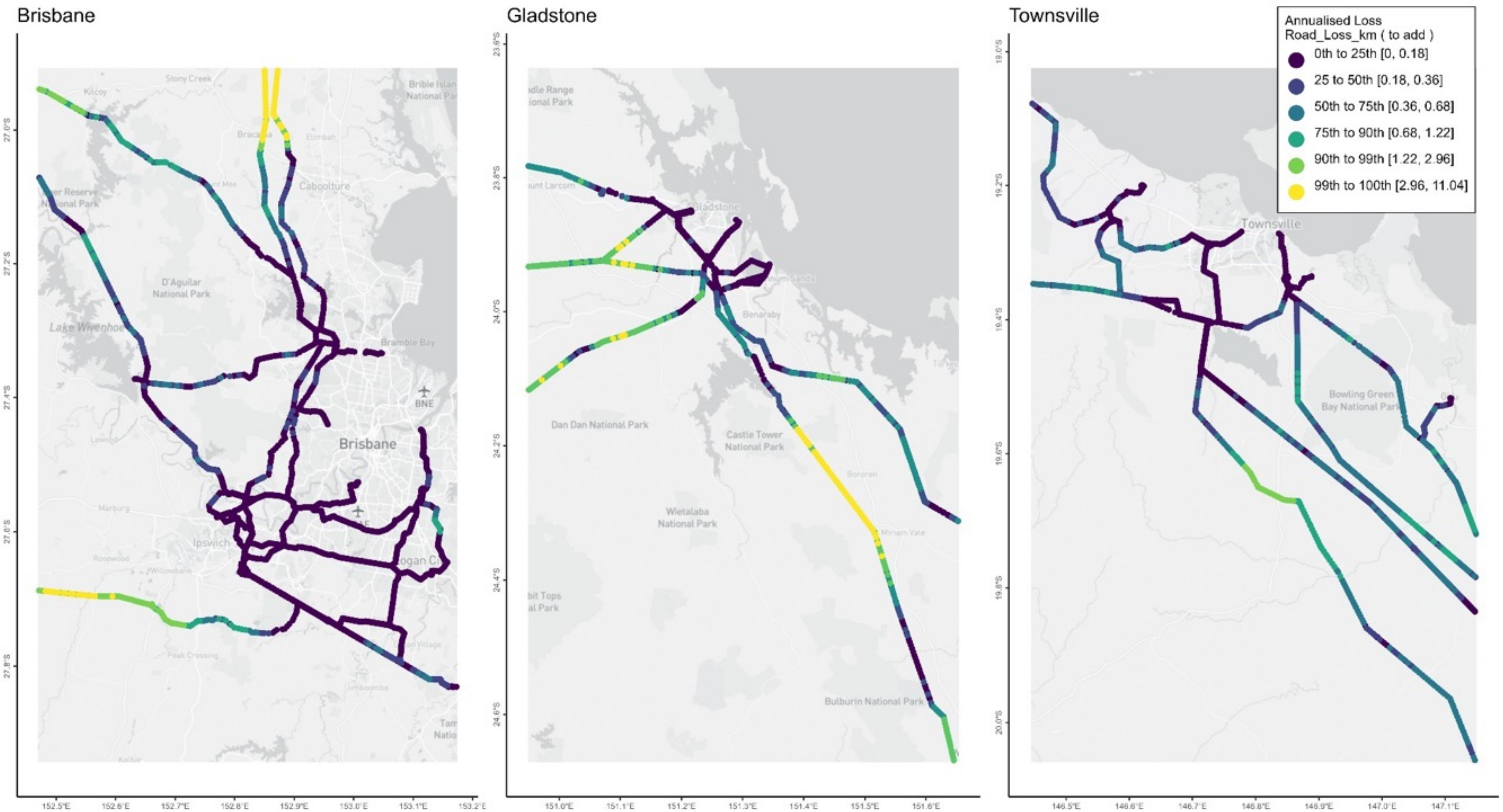

FIGURE 12 ANNUALISED LOSS FROM THE POWER NETWORK - ROAD_LOSS

Appendix B: Annualised cost from the network (FLARE)

Powerlink Bushfire Risk Assessment 2023

How we present the geospatial results for the Annualised Cost for each asset by ignition location.

The results have been plotted from **annualised risk pole ignition data set**, with the results shown as categories based on the percentile transmission of data points within each range; the range of absolute values within each category has been included in the legend.

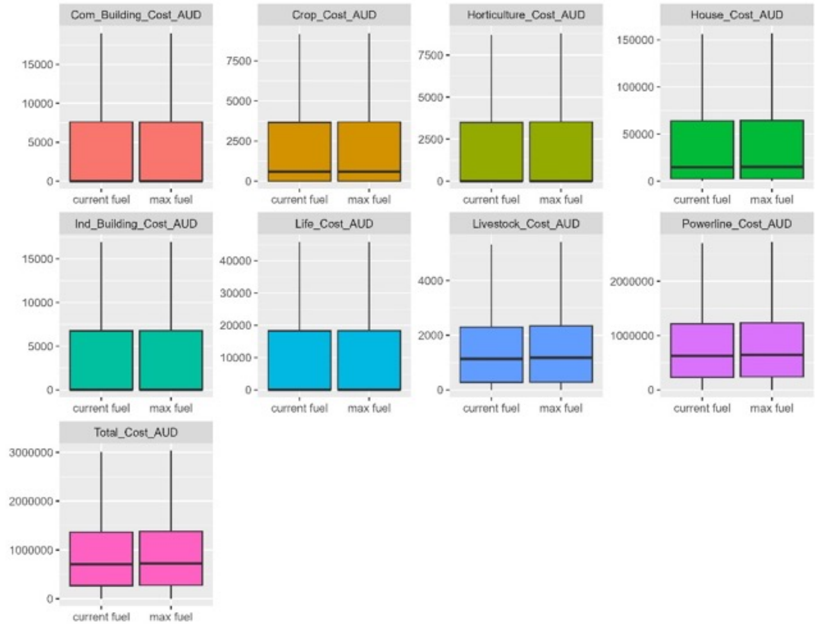

FIGURE 1 ANNUALISED RISK COMPARING CURRENT AND MAXIMUM LANDSCAPE FUEL LOADS

TABLE 1 ANNUALISED COST SUMMARY STATISTICS FOR QUEENSLAND

scenario_fuel	FFDI	metric	min	max	median	mean	total	prop
current fuel	ALL	Com_Building_Cost_AUD	0	1617420	0	16269	418041858	0.4119777
current fuel	ALL	Crop_Cost_AUD	0	294349	582	5097	130954821	0.1290552
current fuel	ALL	Horticulture_Cost_AUD	0	2259832	0	11276	289742714	0.2855397
current fuel	ALL	House_Cost_AUD	0	2232166	14907	55935	1437255198	1.4164063
current fuel	ALL	Ind_Building_Cost_AUD	0	360696	0	6991	179639804	0.1770339
current fuel	ALL	Life_Cost_AUD	0	892959	0	19177	492763099	0.4856150
current fuel	ALL	Livestock_Cost_AUD	0	45090	1136	1648	42352805	0.0417384
current fuel	ALL	Plantation_Cost_AUD	0	1935217	0	6595	169462761	0.1670045
current fuel	ALL	Powerline_Cost_AUD	0	9226822	632235	857229	22026490150	21.7069725
current fuel	ALL	Total_Cost_AUD	0	13396367	702941	980218	25186703211	24.8213433
max fuel	ALL	Com_Building_Cost_AUD	0	1617748	0	16296	418731166	0.4126570
max fuel	ALL	Crop_Cost_AUD	0	294382	591	5133	131898161	0.1299848
max fuel	ALL	Horticulture_Cost_AUD	0	2259832	0	11339	291360790	0.2871343
max fuel	ALL	House_Cost_AUD	0	2232166	15137	56407	1449371448	1.4283468
max fuel	ALL	Ind_Building_Cost_AUD	0	360887	0	7006	180019610	0.1774082
max fuel	ALL	Life_Cost_AUD	0	892838	0	19224	493959946	0.4867945
max fuel	ALL	Livestock_Cost_AUD	0	45090	1174	1681	43181596	0.0425552
max fuel	ALL	Plantation_Cost_AUD	0	1986685	0	6737	173100541	0.1705895
max fuel	ALL	Powerline_Cost_AUD	0	9277344	647124	870506	22367652807	22.0431862
max fuel	ALL	Total_Cost_AUD	0	13474153	719337	994329	25549276066	25.1786567

Metric: Total_Cost

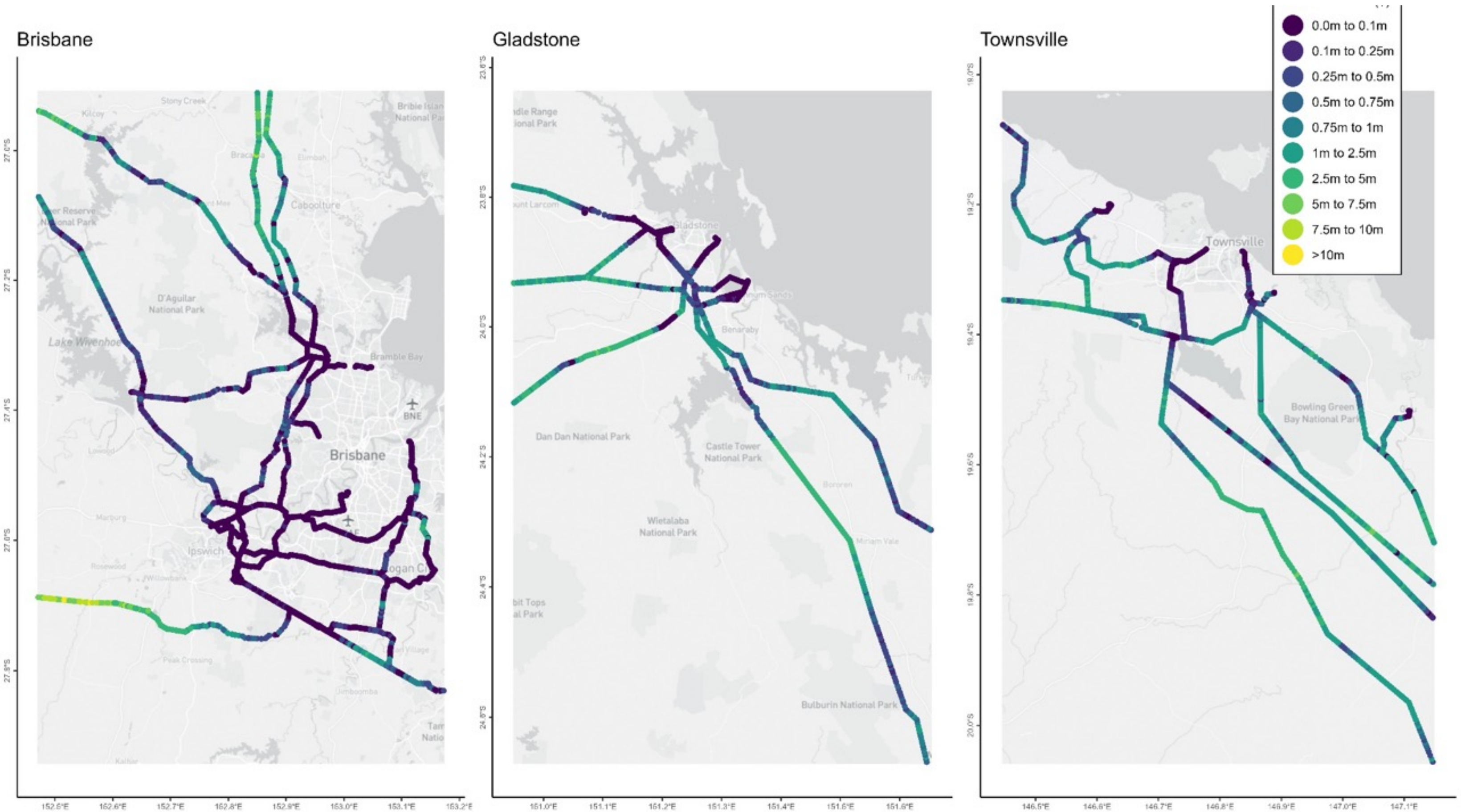

FIGURE 2 ANNUALISED COST FROM THE POWER NETWORK - TOTAL_COST

Metric: Com_Cost

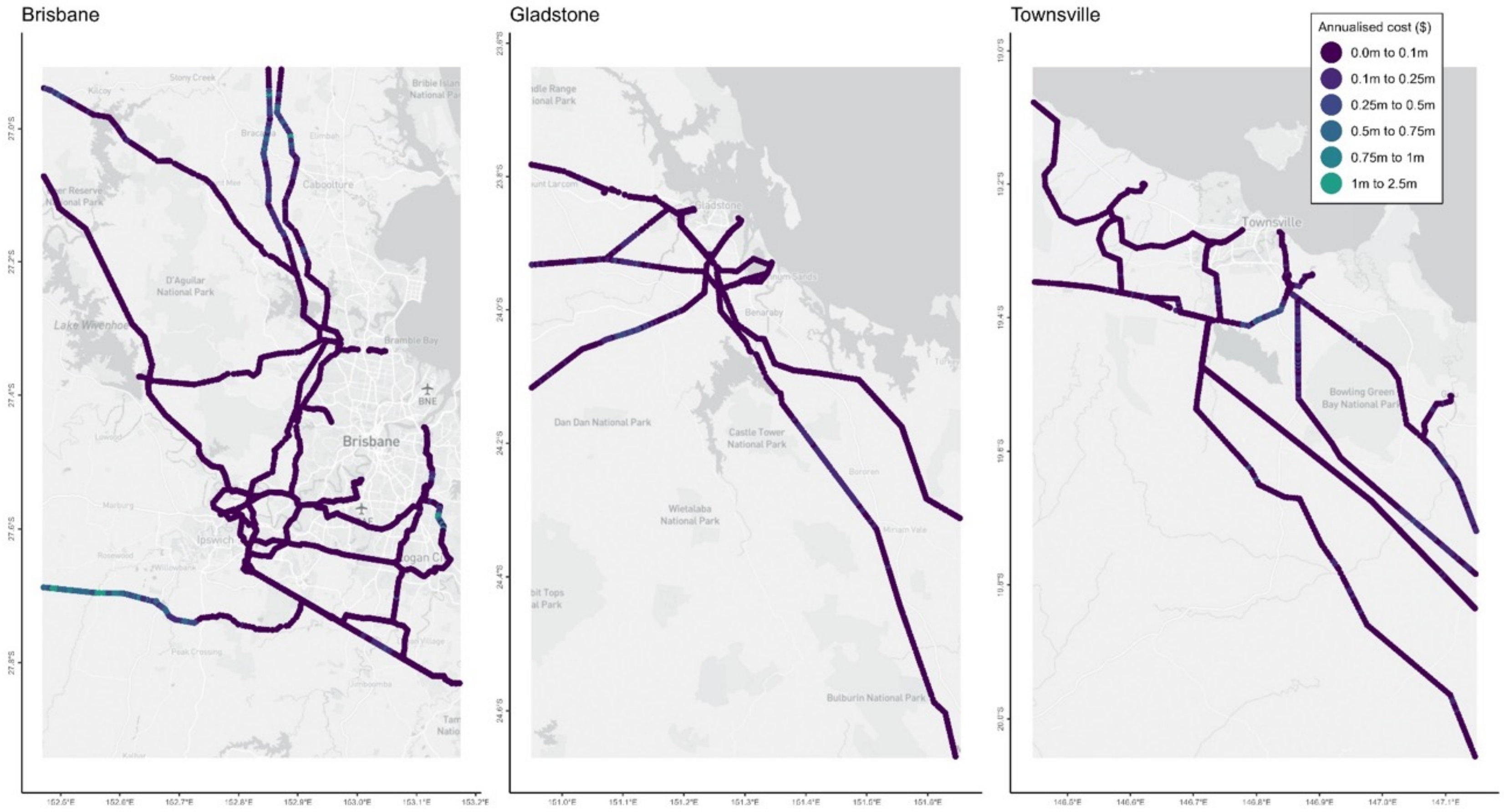

FIGURE 3 ANNUALISED COST FROM THE POWER NETWORK - COM_COST

Metric: Crop_Cost

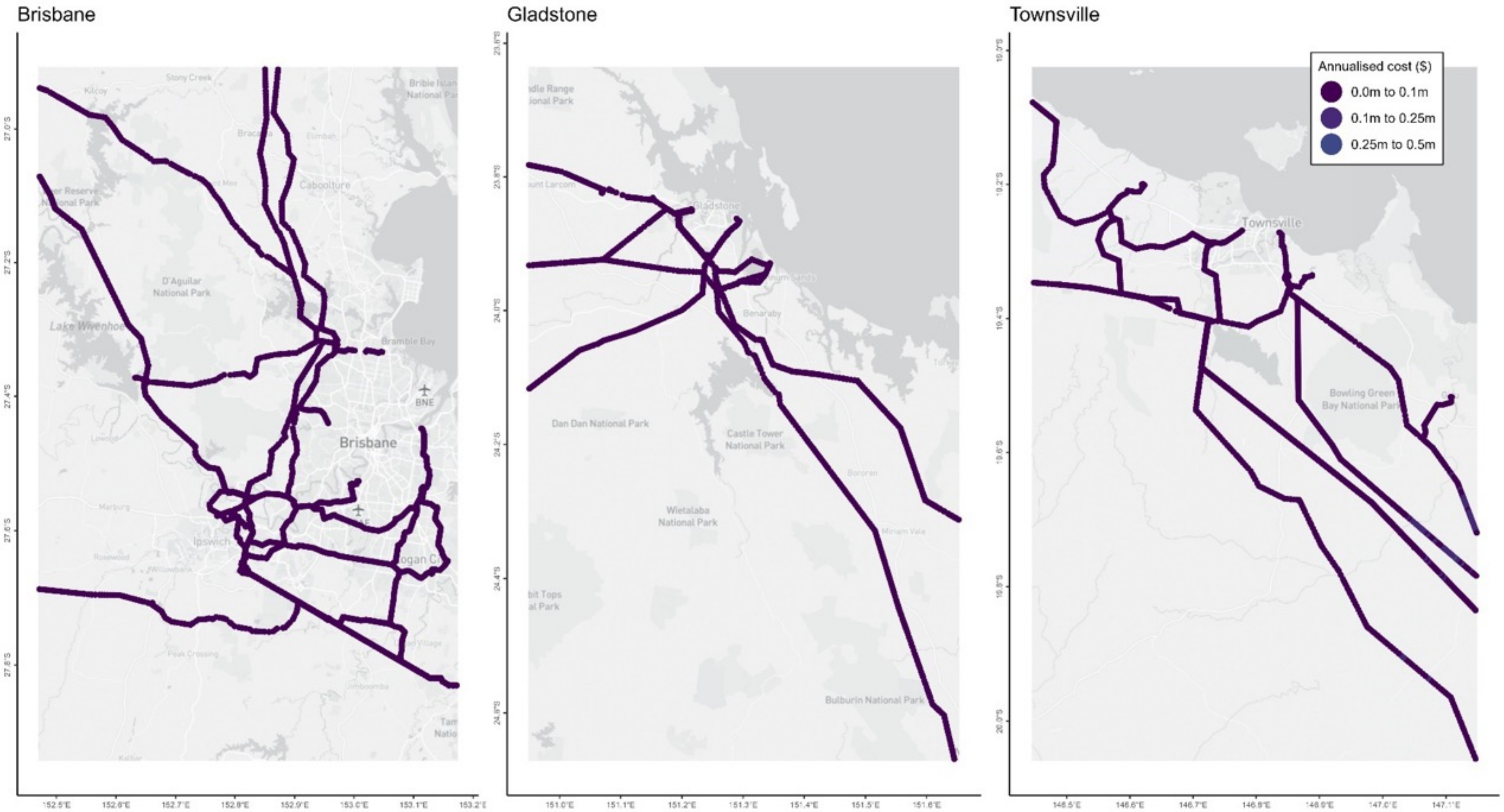

FIGURE 4 ANNUALISED COST FROM THE POWER NETWORK -CROP _COST

Metric: Horticulture_Cost

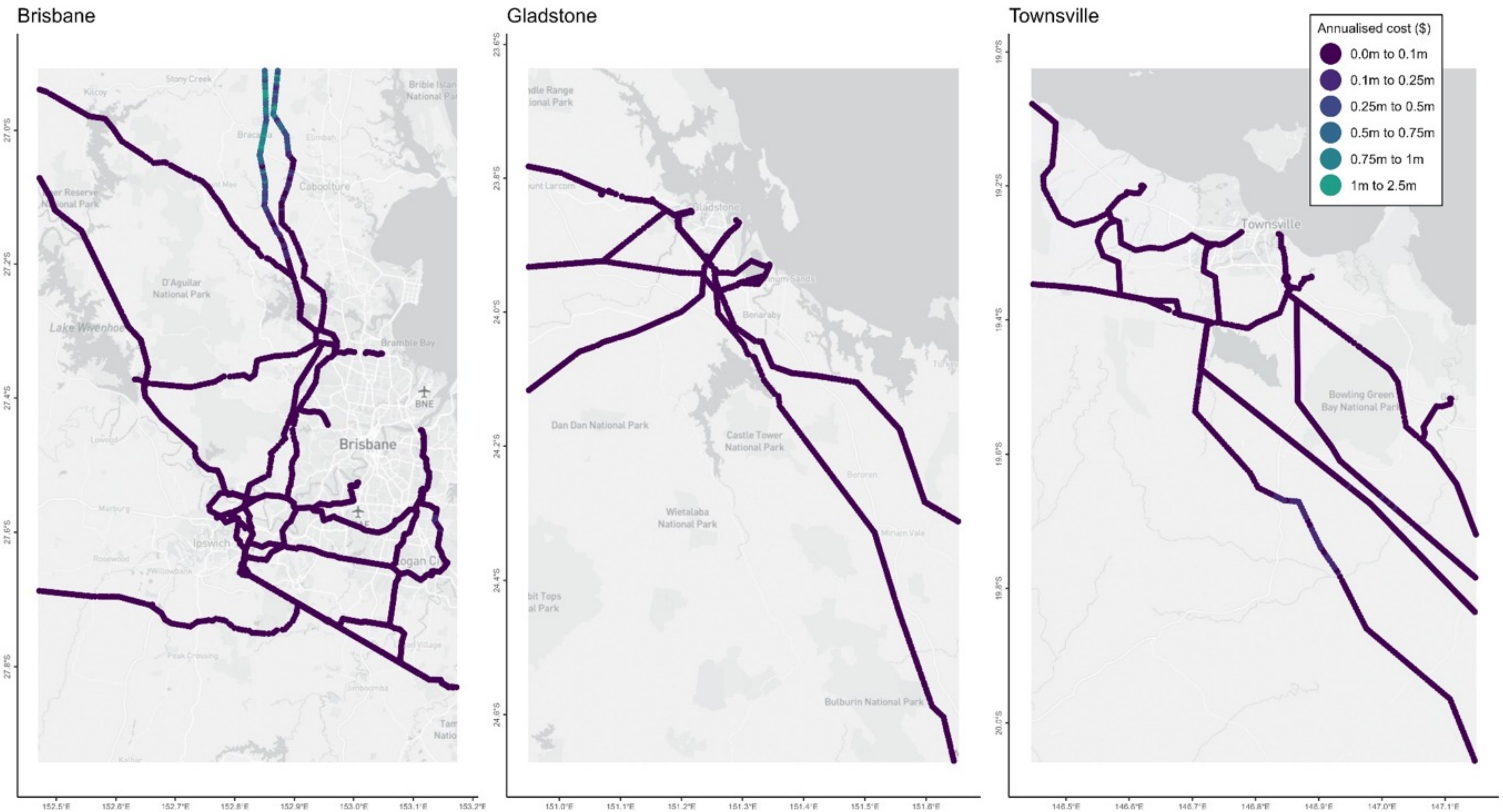

FIGURE 5 ANNUALISED COST FROM THE POWER NETWORK -HORTICULTURE _COST

Metric: House_Cost

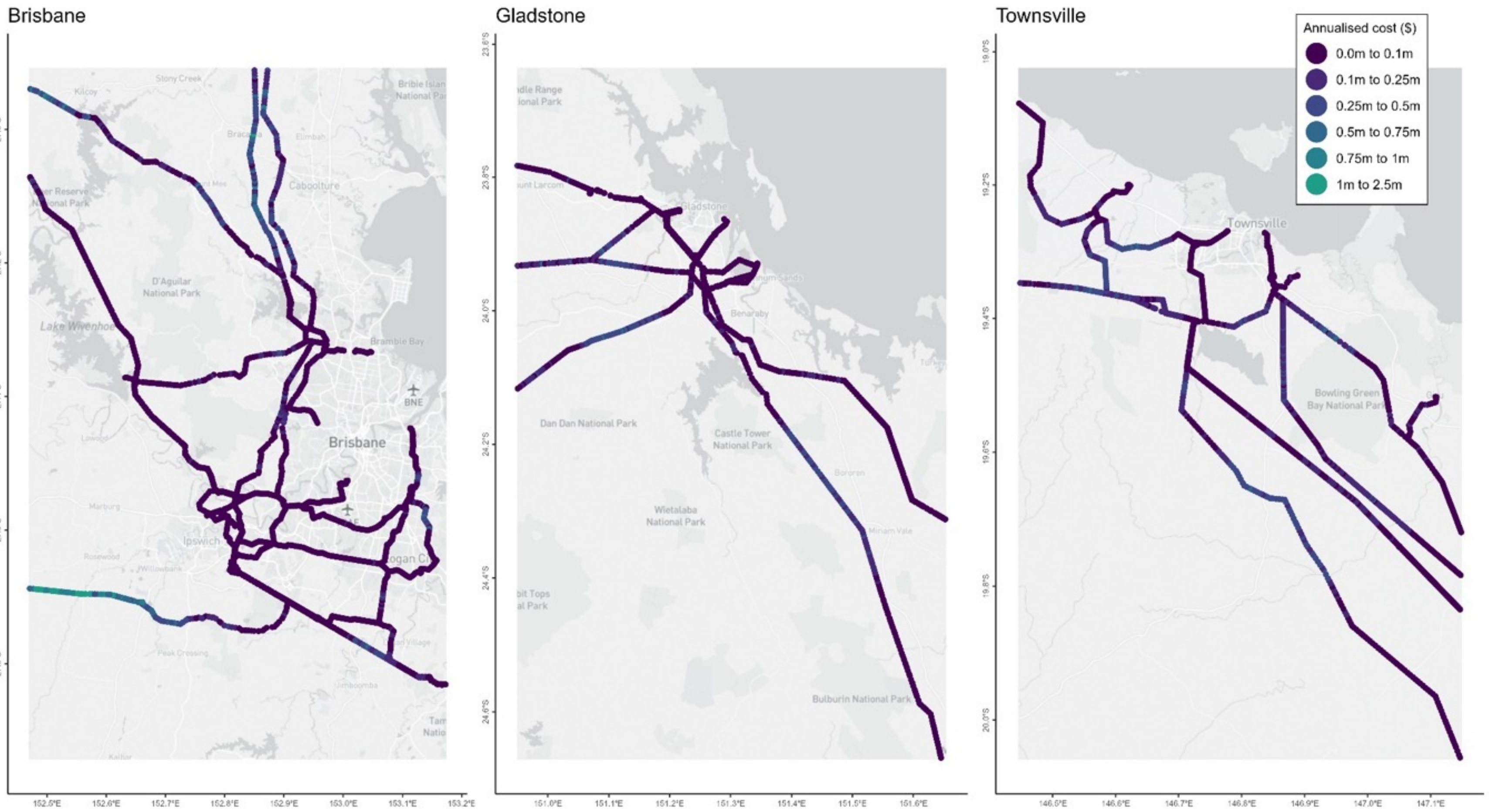

FIGURE 6 ANNUALISED COST FROM THE POWER NETWORK - HOUSE_COST

Metric: Ind_Cost

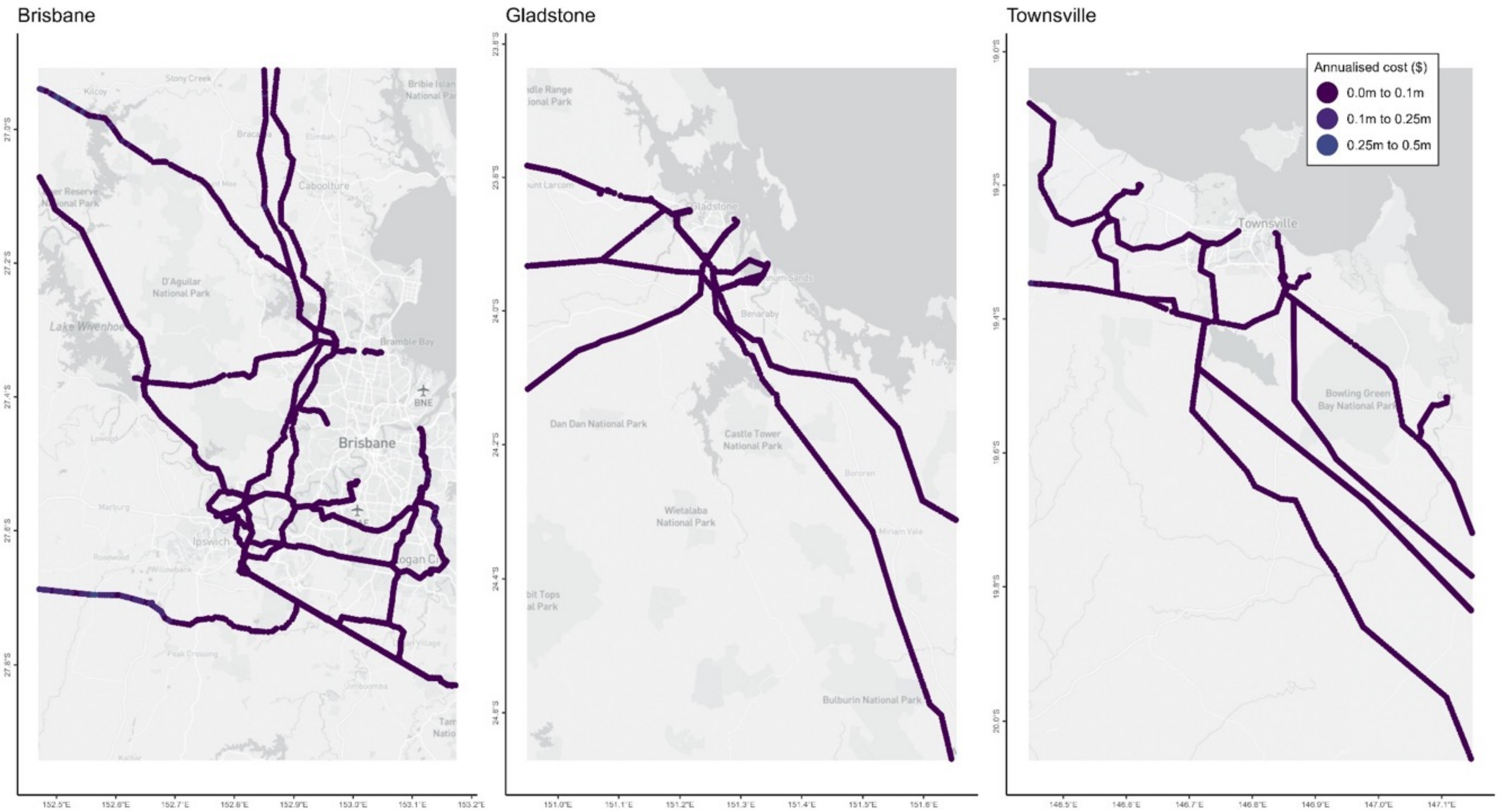

FIGURE 7 ANNUALISED COST FROM THE POWER NETWORK - IND_COST

Metric: Life_Cost

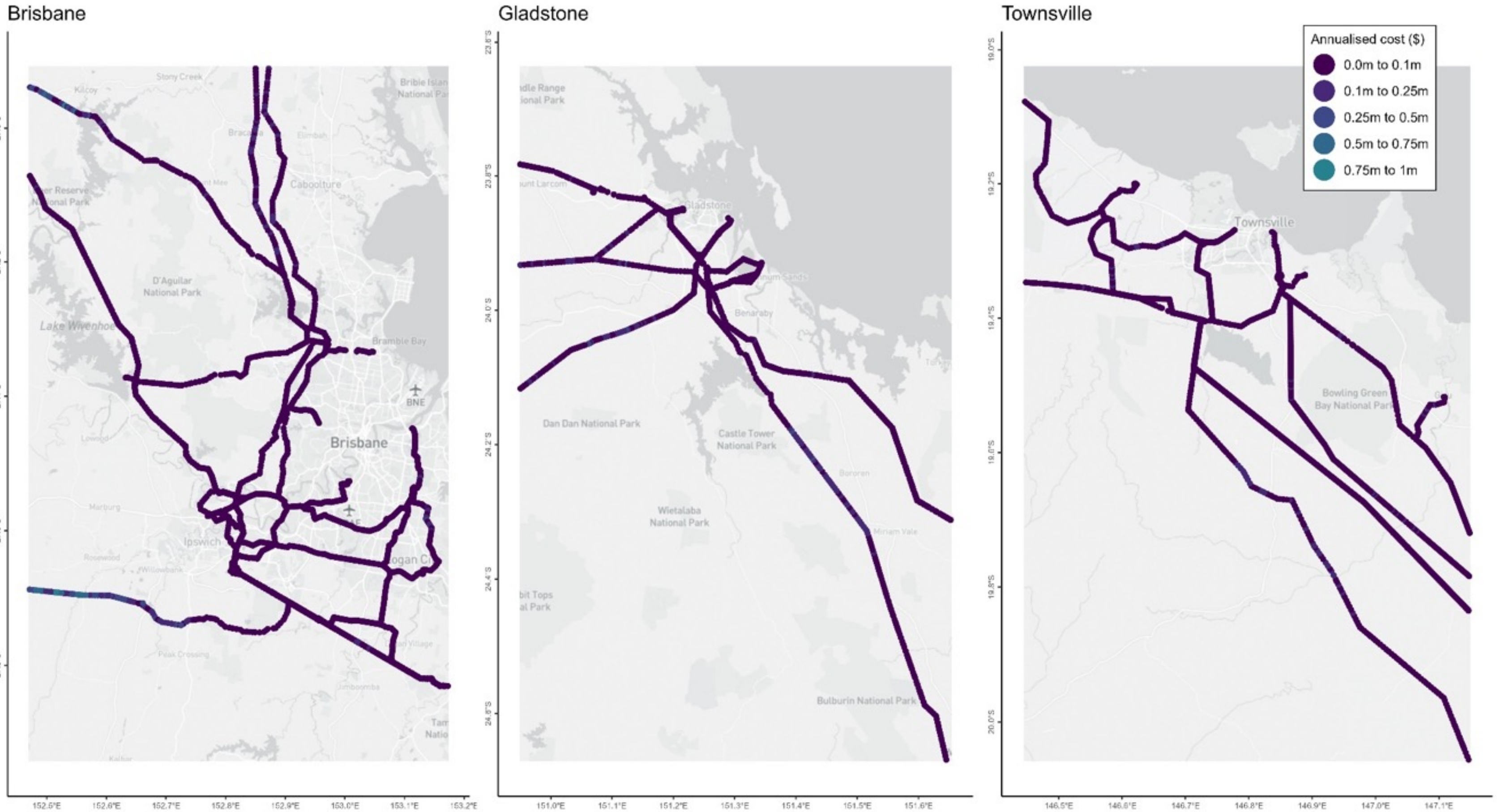

FIGURE 8 ANNUALISED COST FROM THE POWER NETWORK - LIFE_COST

Metric: Livestock_Cost

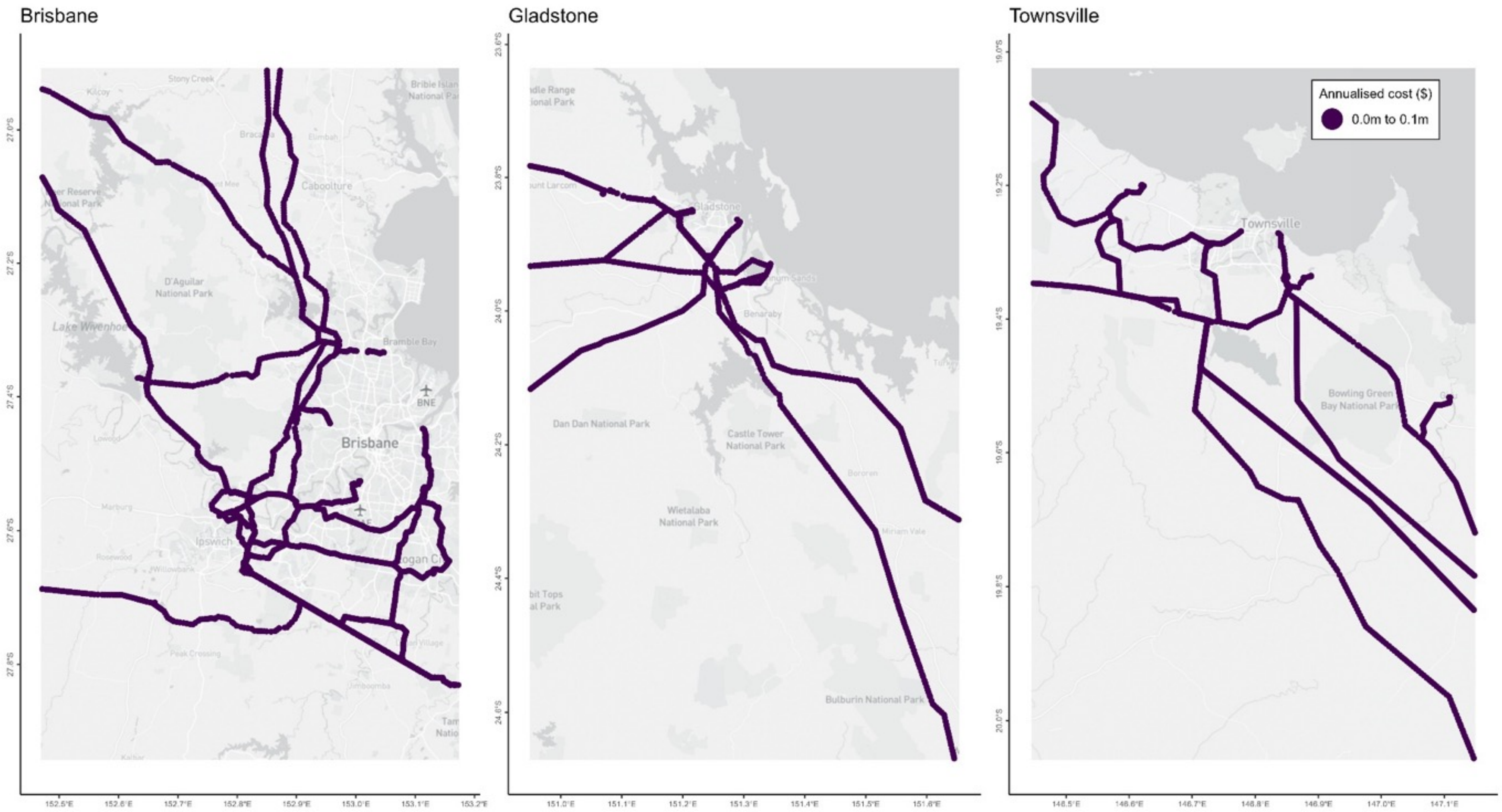

FIGURE 9 ANNUALISED COST FROM THE POWER NETWORK - LIVESTOCK_COST

Metric: Plantation_Cost

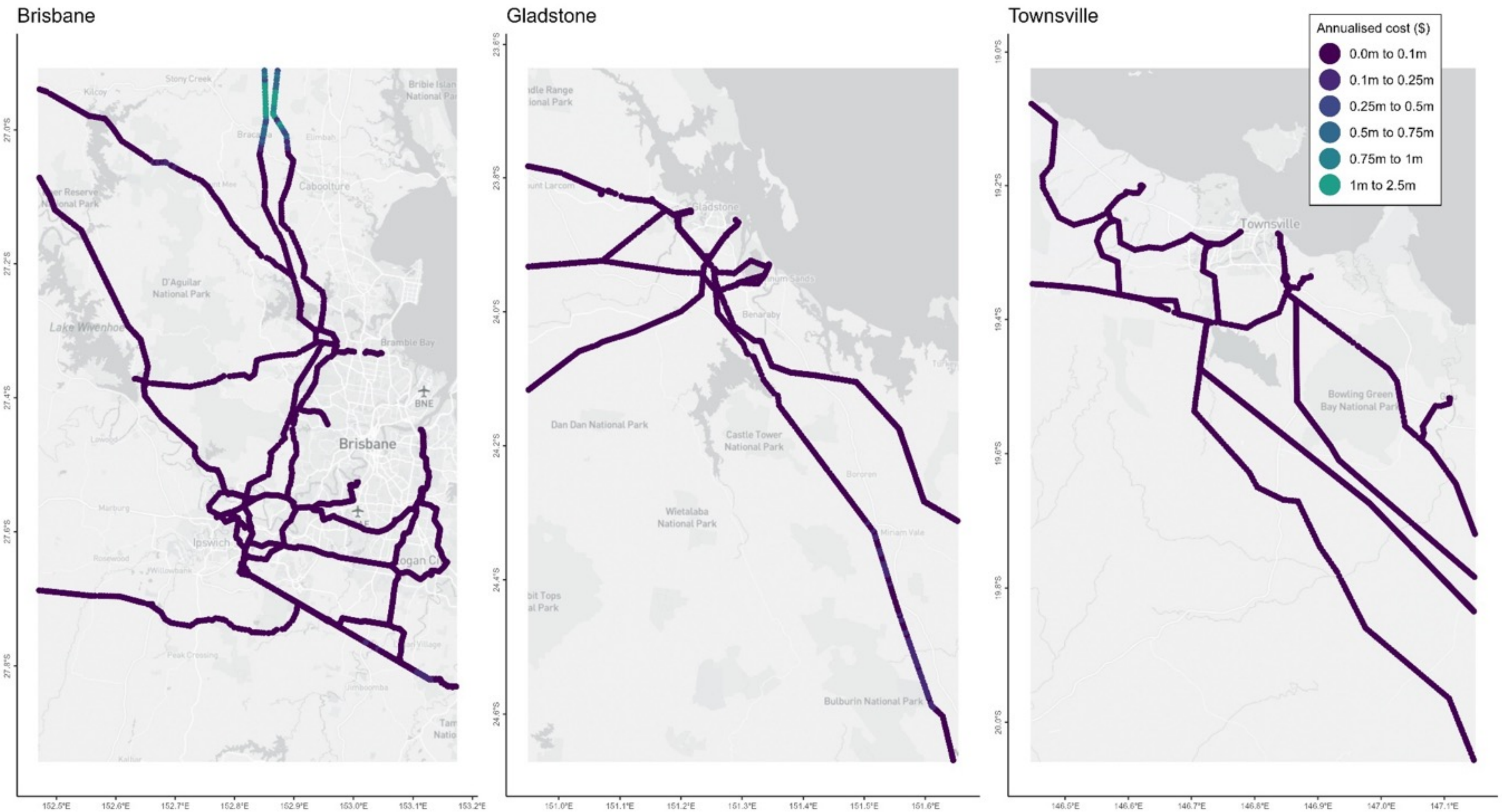

FIGURE 10 ANNUALISED COST FROM THE POWER NETWORK - PLANTATION_COST

Appendix C: Measuring bushfire impacts: economic values (Dr V Florec)

This section provides detail on the assets included in the economic assessment and their values. It also outlines the methods used to measure the value of each type of asset and how total bushfire losses are calculated using those values. In line with sound economic principles for economic analyses, we selected the most conservative values for each type of asset and pointed out instances where the value of an asset could be much higher. This helps provide unbiased and rigorous information about the potential bushfire losses that could be caused by the simulated fires. We used a consistent approach for similar assets across the whole state of Queensland, which then allows for the impacts of different fires to be comparable and risk assessments to be based on the level of impact.

Types of impacts

Assessing a wide range of bushfire impacts is important in order to capture the full picture of losses (economic, social and environmental). Bushfire impacts can be direct or indirect, tangible or intangible (Stephenson *et al.* 2013).

- **Direct impacts** are those that are caused directly by the fire, as a result of direct contact with the flames or smoke (e.g. houses burned).
- **Indirect impacts** are those that arise as a consequence of the fire occurring (i.e. flow-on effects) but not as a result of direct contact with the fire (e.g. business interruptions).
- **Tangible impacts**, sometimes called economic impacts, are those for which a cost can be readily estimated in dollar values, because they are associated with assets that are usually exchanged in markets and already have prices (e.g. contents of a house). Economists refer to these as market impacts or market values.
- **Intangible impacts**, sometimes called social and environmental impacts, are those affecting things that are not normally bought or sold. Because these assets are not exchanged in markets, they do not have prices (e.g. biodiversity, life). Economists refer to these intangible impacts as non-market impacts or non-market values. Because there is not a price that can be readily attached to intangible assets, estimating the damage in dollar values for intangible impacts requires the use of specialised techniques, known as non-market valuation (Appendix 1).

Figure 1 shows some examples of different types of impacts and how they are categorised as either direct or indirect, tangible or intangible. Although a wide range of impacts are included in this Figure, other impacts may occur, and some impacts may be categorised in more than one category.

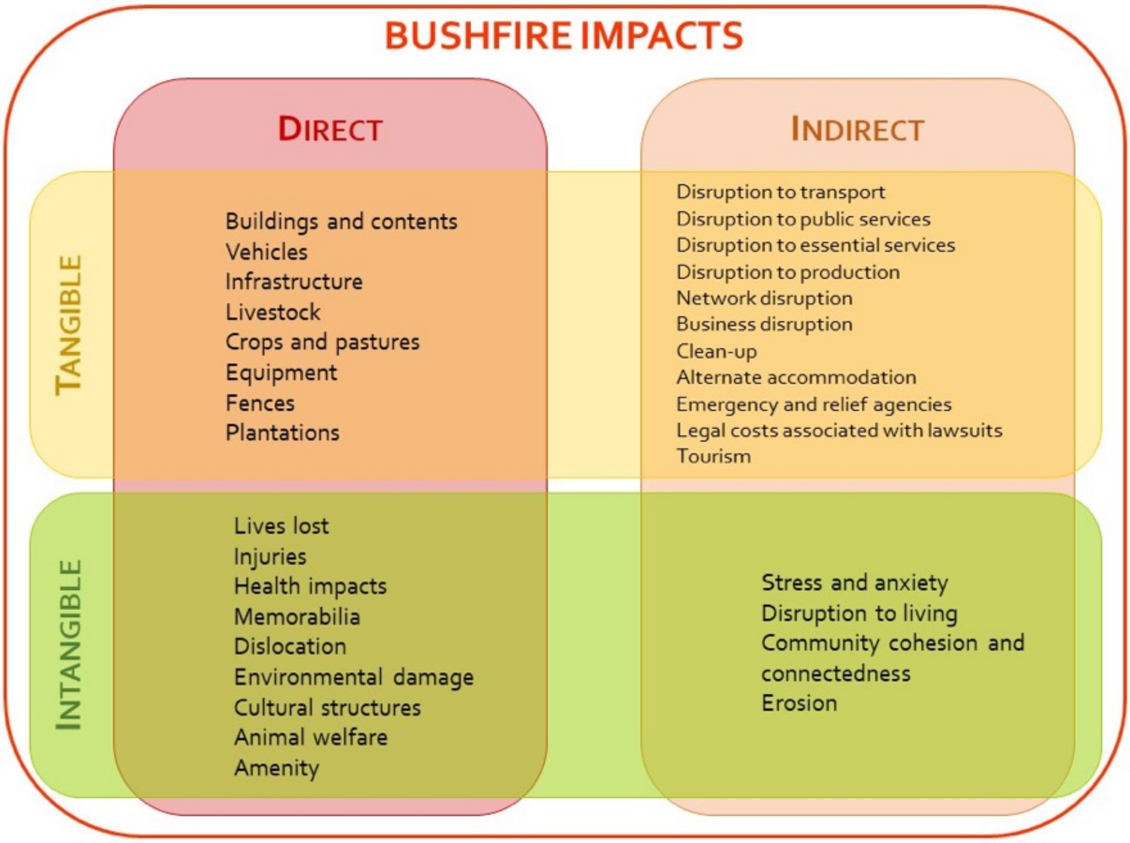

FIGURE 1. TYPES OF IMPACTS. SOURCES: BUREAU OF TRANSPORT ECONOMICS (2001), HANDMER (2003), STEPHENSON *ET AL.* (2013).

Methodology for estimating bushfire losses

When a bushfire occurs, we look at what the fire damaged and how severe was the damage to estimate bushfire impacts. Economists estimate impacts using the reconstruction costs of an asset. In other words, they measure what it would cost to reinstate the asset to its formal state, before it was damaged or destroyed by the bushfire. This can sometimes be different to the market value of an asset. For instance, the market value of a house (what it can be sold for) is different to its reconstruction costs. The market value of a house depends on how the real estate market is performing at any given point, which includes the price of the land where the house is located. However, when a house is damaged by a bushfire, the land is not damaged per se.[1] Thus, we measure the impacts on the house by measuring it reconstruction costs, i.e. what it would cost to replace the structure and the contents of the house to how it was before it was destroyed by the fire.

In simulation studies, which is what we are doing in this analysis for Queensland, we apply the same economic principle and use reconstruction costs to estimate economic impacts. The only difference is that instead of knowing where the fire has been, a simulator tells us where the fires are likely to go and the potential damage they are likely to cause to different assets.

We have collected data to estimate the dollar values of different tangible and intangible assets. This process is explained below for each type of asset. In the case of intangible assets, it is better to assign an approximate value than to assign no value at all (Pannell and Gibson 2016). If we do not allocate a dollar value to an intangible asset, we are in effect assuming that its value is equal to zero or that it has little to no importance and its value is negligeable. However, we know that neither of these assumptions is true and intangible impacts from natural hazards are substantial and can sometimes be greater than tangible impacts (Deloitte Access Economics 2016).

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[1] The value of the land may vary temporarily after the bushfire, but as time passes and people think less and less about the bushfire event, land prices return to their original trend.

Asset values

Buildings

The value of buildings was sourced from the Australian Exposure Information Platform (AEIP), which provides estimates on the value of residential, commercial and industrial buildings in a given area (Geoscience Australia 2022). To extract information from the AEIP, the user selects the shape and size of the area of interest for which the data is to be extracted. If we had used the whole state of Queensland as the area of interest, we would have obtained an average value for residential, commercial and industrial buildings for the whole state and would not have captured any differences in value for each type of building between different locations. In order to capture these differences and obtain more refined data, we extracted building exposure information for each Local Government Area (LGA).

For residential buildings, the AEIP provides information on the value of the structure and the value of the contents, which matches exactly what we need to estimate the total reconstruction value of residential buildings. For commercial and industrial buildings however, the AEIP only provides information on the value of the structure. This means that even though the value of industrial and commercial buildings is much higher than the value of residential buildings, it still underestimates the total value of these buildings as their contents could account for most of the reconstruction value, depending on the industry.

To illustrate the differences between LGAs, Table 1 illustrates the average value of residential, commercial and industrial buildings in 10 different LGAs and Table 2 shows the differences in the total number of each type of building.

Local Government Area	Residential buildings (structure and contents)	Commercial buildings (structure only)	Industrial buildings (structure only)
Brisbane	$ 613,545	$ 15,462,633	$ 2,459,258
Cairns	$ 742,120	$ 7,943,448	$ 1,583,856
Cook	$ 1,066,748	$ 57,179,762	$ 8,107,500
Flinders (Qld)	$ 921,813	$ 149,296,667	$ 1,380,000
Gladstone	$ 646,271	$ 29,715,245	$ 3,400,047
Gold Coast	$ 625,224	$ 22,977,363	$ 1,848,782
Isaac	$ 500,918	$ 24,807,442	$ 3,351,096
Maranoa	$ 539,168	$ 3,073,314	$ 4,476,250
Toowoomba	$ 637,860	$ 8,431,142	$ 2,208,505
Townsville	$ 715,180	$ 21,428,817	$ 2,496,513

TABLE 1. AVERAGE RECONSTRUCTION VALUE OF RESIDENTIAL, COMMERCIAL AND INDUSTRIAL BUILDINGS IN TEN DIFFERENT LOCAL GOVERNMENT AREAS IN QUEENSLAND.

Local Government Area	Residential buildings	Commercial buildings	Industrial buildings
Brisbane	371,533	5,203	7,492
Cairns	57,408	1,102	1,281
Cook	2,386	42	20
Flinders (Qld)	943	3	4
Gladstone	20,708	490	423
Gold Coast	188,889	3,660	3,464
Isaac	9,523	344	73
Maranoa	5,155	172	72
Toowoomba	57,841	1,086	1,030
Townsville	71,516	1,403	1,391

TABLE 2. NUMBER OF RESIDENTIAL, COMMERCIAL AND INDUSTRIAL BUILDINGS IN TEN DIFFERENT LOCAL GOVERNMENT AREAS IN QUEENSLAND.

Agricultural values

Agricultural commodities

We estimated the value per hectare for different types of commodities using two datasets from the Australian Bureau of Statistics (ABS) and created a spatially explicit dataset using a land use map for the whole state of Queensland. We used the following datasets:

a) ABS (2022b) Value of Agricultural Commodities Produced. This dataset contains the total gross value of all agricultural commodities in each LGA for the 2020-2021 financial year.

b) ABS (2022a) Agricultural Commodities. This dataset contains the area planted or the volume produced for all agricultural commodities in each LGA.

c) Queensland Government (2019) Land use mapping. This dataset has three different levels of classification. The primary level has five classes, identified in order of increasing levels of potential impact on the natural landscape. Water is included separately as a sixth primary class. The secondary level contains additional information on the principal use of the land in terms of the objectives of the land manager. The tertiary level includes data on commodities or vegetation (e.g. crops such as cereals and oil seeds). We used this tertiary level to create a spatially explicit dataset with values per hectare for different commodities.

The vast majority of the state can be classified as land used for grazing from native vegetation or modified pastures, which corresponds to production from relatively natural environments (see Figure 2). However, agricultural land around the Powerlink network is a lot more varied (see Figure 3) and values per hectare can fluctuate greatly between different commodities (see Table 3). In addition, values for the same commodities vary between LGAs. As fires caused by failures in the network can cause substantial damage to agricultural commodities produced in proximity to the Powerlink network, it is important to capture the differences in value for different commodities. The tertiary level of the land use map produced by the Queensland Government allowed us to have a spatially explicit dataset with value per hectare for the following commodities:

- Cropping (cereals): includes wheat, oats, rice, sorghum, maize, and all other cereals for grain or seed.
- Beverage & spice crops: mostly barley.
- Hay and silage: includes pasture (including lucerne), cereal and other crops cut for hay.
- Oilseeds: canola and other oilseeds.

- Sugar: corresponds to sugar cane cut or crushing.
- Cotton: includes irrigated and non-irrigated cotton.
- Pulses: includes chickpeas, lupins, lentils, and other pulses.
- Perennial horticulture: includes all fruits and nuts (excluding grapes and berries), e.g. macadamias, citrus, stone fruit, avocadoes, olives, mangoes, bananas, pineapples, and all other fruits.
- Perennial horticulture (grapes): includes grapes for wine production and all other uses.
- Perennial horticulture (berries): includes strawberries and all other berries.
- Seasonal horticulture: includes vegetables, herbs and mushrooms.
- Intensive horticulture: includes production from nurseries, cut flowers and cultivated turf.

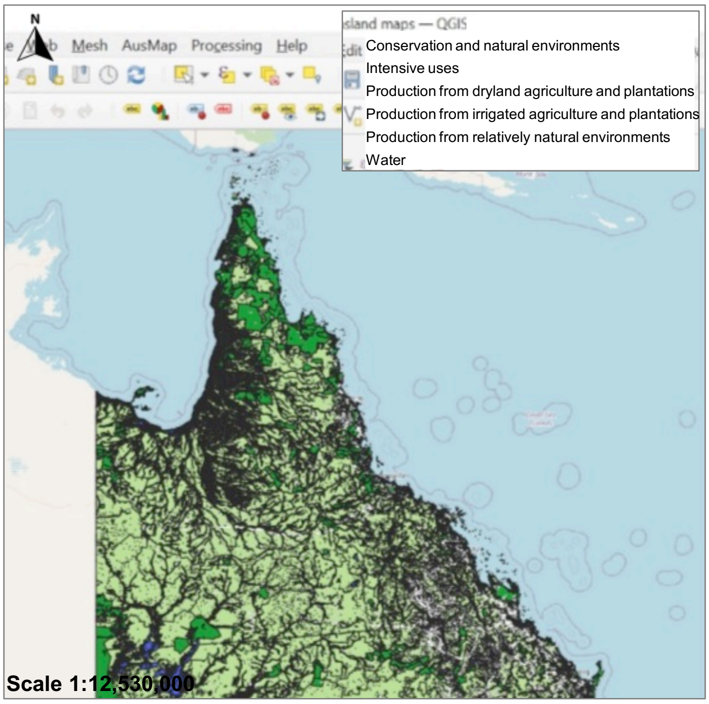

Figure 2. Land use map of Queensland using primary classification.

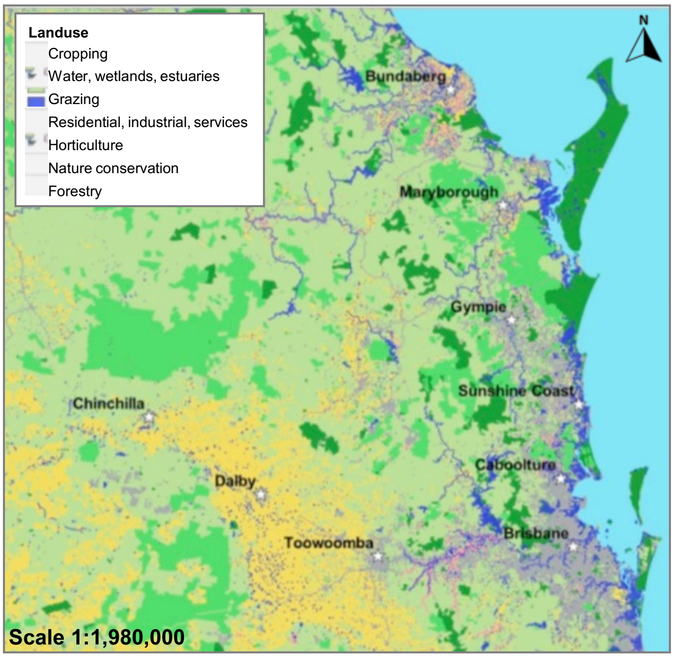

Figure 3. Land use in the south-east corner of Queensland.

To illustrate the differences in value between different commodities, and how these can also vary between LGAs, Table 3 shows the value per hectare of selected commodities in five LGAs.

Local Government Area	Cropping	Perennial horticulture	Seasonal horticulture	Sugar
Brisbane	$ 1,547	$ 58,401	$ 47,624	No sugar crops in Brisbane
Bundaberg	$ 1,888	$ 19,827	$ 49,438	$ 2,958
Gladstone	$ 720	$ 33,095	$ 48,050	$ 2,930
Richmond	$ 2,987	$ 23,038	$ 25,757	No sugar crops in Richmond
Townsville	$ 975	$ 18,849	$ 30,341	$ 3,125

TABLE 3. VALUE PER HECTARE FOR FOUR DIFFERENT COMMODITIES IN FIVE DIFFERENT LGAS.

Livestock – Grazing native vegetation and modified pastures

A large part of the state of Queensland is classified as "Production from relatively natural environments" in the primary classification of land use by the Queensland government (see Figure 2). Almost 98% of the area in this classification corresponds to "Grazing native vegetation" in the secondary land use classification. Queensland produces close to 45% of cattle (by value) in Australia, so the value of native vegetation used for grazing is important for the Queensland economy. Although vast expanses of native vegetation are quite remote and far away from the Powerlink network, the value allocated to native vegetation needs to make sense for areas close and far away from the network.

For such a large area, if we were to use the value of cattle produced in Queensland to find an estimate for grazing areas, the estimates would no longer have any meaning. Such a method is only appropriate for case studies of smaller areas where cattle is more contained. Hence, in this study we used a different value for native vegetation and modified pastures used for grazing. We used the value estimated by Asafu-Adjaye *et al.* (2005), who measured the value of natural capital in Queensland. They estimated the total value of land used for cattle grazing in Queensland over a period of 30 years. We converted their net present value to an annualised figure and divided that figure by the total number of hectares used for grazing. This value, updated with CPI to 2022 dollars is equal to $17 dollars per hectare (see details in Appendix 2). This is a very conservative estimate for native vegetation and modified pastures as it only accounts for one single use: grazing. Native vegetation in particular has also value for other uses, such as environmental services and conservation, but we found no studies specifically looking at native vegetation or modified pastures and estimating their value in dollars for other uses.

Fences

The best data that we have found for fences is the data published by the Victorian government on the costs of repairing fences after the 2019-2020 bushfire season, which includes the costs of cleaning up and repairing or re-building a fence in rural properties when they have been damaged or destroyed by bushfires. The Victorian government estimated the costs of repairing rural fences at $1,000 per kilometre.

Agricultural buildings

The value of agricultural buildings varies greatly depending on the size and type of building (e.g. sheering shed vs machinery storage). The best way to obtain estimates of the reconstruction costs of an agricultural building (usually a shed), is to ask farmers directly about these costs. In the first iteration of project IGNIS, we contacted the Western Regional Panel of the Grains Research and Development Corporation (GRDC), the Mingenew Irwin Group (a grain growers association), and colleagues at the University of Western Australia to obtain information on the costs of different types of agricultural buildings. We obtained data for the reconstruction costs of the structures, which can be more easily generalised, but not for the contents, as these cannot be generalised since they are very different for different industries and different size farms. Table xx shows the information we compiled on the reconstruction costs of different agricultural buildings.

Type of building	Cost
Small machinery shed	$ 120,000
Large machinery shed	$ 300,000
Fertiliser shed	$ 80,000
Shearing shed	$ 100,000
Workers accommodation block	$ 30,000

Forestry (production from native forests and plantations)

If a plantation is damaged or destroyed by a major bushfire, the timber that was going to be produced is lost and new investments need to be made to get the plantation established again. Thus, to estimate the total losses caused by a major bushfire to a plantation, we need to add the value of the timber lost and the costs of re-establishing the plantation (reconstruction costs). We used data from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES, 2022) to estimate the value of timber per hectare and data from Venn (2005) on plantation performance in Queensland to estimate re-establishment costs, and converted all values to 2022 dollars. We estimated a value of $8,900/ha for plantations. This is similar to what Gibson and Pannell (2014) estimated for the impacts of bushfires on plantations in South Australia (they estimated a value of $9,000 in 2014, which is equal to $10,800 in 2022).

Other land uses

In the land use map published by the Queensland Government (Queensland Government 2019) there are a number of land uses for which values could not be found or were either irrelevant or beyond the scope of this study. These include:

a) Land uses containing assets that would not be significantly destroyed by bushfires: Degraded or abandoned land, water[2], marshes and wetlands, estuary and coastal waters.[3]

b) Land uses beyond the scope of this study: Services, intensive animal production, utilities (other than electricity), transport and communication, mining, waste treatment and disposal.

c) Land uses for which a value has already been allocated in a different dataset: Manufacturing and industrial (already in buildings dataset), residential and farm infrastructure (already in buildings dataset and agricultural buildings information).

Electricity network infrastructure

Transmission network

Data on the costs of repairing powerlines if they are destroyed by bushfires was obtained directly from Powerlink. The cost of repairing powerlines varies with the type of line, but for some lines it also varies depending on the distance that needs to repaired (Personal communication, Paul Tester, 2022). Table 4 shows the cost of repairing powerlines and transmission towers in Queensland for different types and lengths.

Type of transmission line or tower	Distance that needs to be repaired				
	0 to 24 kms	25 to 49 kms	50 to 74 kms	75 to 99 kms	100+ kms
275 kV lines	$ 3,250,000	$ 1,670,000	$ 1,640,000	$ 1,620,000	$ 1,610,000
110/132 kV lines	$ 1,700,000				
Large transmission tower	$ 480,000				

TABLE 4. COSTS OF REPAIRING TRANSMISSION LINES AND TOWERS IN THE POWERLINK NETWORK (SOURCE: PAUL TESTER, POWERLINK)

Queensland-New South Wales Interconnector (QNI)

We had several discussions with Powerlink staff and contacted staff at the Australian Energy Market Operator (AEMO) to obtain estimates for the impacts of damage to the QNI caused by a major bushfire. Powerlink staff pointed out that if the QNI was damaged by a bushfire, it would be the highest priority to repair it and re-establish the flow of electricity between the two states. So the QNI would not be out of service for very long. Even with major damage, it would take about 4 to 5 days maximum for the QNI to be operational again, as all resources necessary would be allocated to fix it rapidly (Nathan O'Sullivan, personal communication, 2022). Apart from the costs of repairing the section or sections of the QNI damaged by the bushfire, the largest economic impact of the QNI being out of service would be an increase in electricity prices in NSW (Nathan O'Sullivan, personal communication, 2022).

[2] Bushfires may destroy shrubs and bushes adjacent to water bodies and increase the potential for erosion. If there is substantial erosion after a bushfire, water quality could be reduced. However, estimating post-bushfire erosion impacts on water bodies is beyond the scope of this study.

[3] Bushfires may damage wetlands and estuaries, but these are generally considered low fire risk areas. Climate change and its impacts on wetlands might change that, but estimating bushfire impacts on wetlands and estuaries is also beyond the scope of this study.

Powerlink and AEMO staff informed us of a previous separation event in 2018 where a single lightning strike on a transmission tower resulted in several faults and interrupted the supply from QLD to NSW (870 MW of power were flowing at the time from QLD to NSW) for several hours. This resulted in increases in the spot price of electricity in NSW. AEMO (2019) estimated the changes in spot prices in different states resulting from this interruption. To remain conservative in our estimates, we calculated the difference between the price per MWh during the QNI separation event and price per MWh at maximum operational demand (which is the highest price) in QLD and NSW. We found a total difference of $120 per MWh, and we multiplied this by the possible number of hours that the QNI would be non-operational if it was severely damaged by a bushfire (4 days or 96 hours). This gives us a very conservative estimate for the impacts of a separation event caused by a major bushfire of $10 million dollars, which does not even include the costs of repairing the QNI sections damaged.

Life

It is now generally accepted that the best economic value to use for human life is the value of a statistical life (VSL). This value represents how much society is willing to pay to reduce the risk of death. In Australia, the Office of Best Practice Regulation, which is a branch of the Department of the Prime Minister and Cabinet (OBPR, 2022), publishes a guidance note on the value of a statistical life and updates it every three years. The most up-to-date value from this guidance note is $5,300,000 (in 2022 dollars). We know however that this amount underestimates the value of a life. In 2008, Access Economics conducted a metanalysis of VSL studies from 15 developed countries and estimated the VSL to be closer to $8,400,000 (Access Economics 2008). Although this study performed a more sophisticated and sound analysis of VSL than the guidance note from OBPR, we used the OBPR value in the economic dataset for IGNIS Queensland for two reasons:

a) When conducting an economic analysis, it is important to select the most conservative values for any asset to avoid assigning values based on subjective tendencies. This also helps to err on the side of underestimating benefits while overestimating costs. We do so because if the results of the analysis are positive, then with higher values for the assets affected, we know that the results will be even more positive. In any case, it is always essential to conduct sensitivity analysis on all asset values.

b) Where possible, we have used data from official sources. The value provided by the guidance note (OBPR, 2022) is now recognised and accepted by all Australian government departments as the appropriate value to use for economic analyses that require the VSL.

Environmental values

For environmental values, there have been several studies in Queensland estimating the dollar values of environmental assets. Most of them however focus on specific types of vegetation or endangered species, and would not be appropriate to transfer to this analysis since we are dealing with a very large case study area (i.e. the state of Queensland). For a value to be generic enough to represent the wide range of environmental assets available in the state, we need to use the estimates from a study that was conducted in a more generic manner so that it can be applied to many environmental values. One study in particular was conducted in such a manner and had the goal of creating results that could be as transferrable as possible to different contexts and different areas. The study is van Bueren and Bennett (2000). In this study, the authors estimated dollar values for environmental and social assets in the Great Southern Region of Western Australia and the Fitzroy Basin Region of Central Queensland. We used the average willingness to pay for natural landscape values and divided it by the number of hectares used in their questionnaire. The average willingness to pay per hectare for natural landscapes in Queensland is $121 (see details in Appendix 2).

Traditional indigenous uses

We found no studies that directly estimate the value of land used for traditional indigenous purposes, but we found studies that estimate the value of aboriginal sites in dollars. The estimates in these studies can be used to estimate an approximate figure for the value of land used for traditional indigenous purposes. As mentioned before, assigning an approximate value is better than assigning no value. If we do not allocate a value to traditional indigenous land, it is the same than assuming that its value is equal to zero or that it has no importance, neither of which is true. To estimate the value of land with traditional indigenous uses, we used the value estimated by Rolfe and Windle (2003) and Windle and Rolfe (2003), who estimated the value of aboriginal cultural heritage sites in Central Queensland. We used the lower bound estimate, the most conservative value, and divided that estimate by the total number of hectares in the case study area in the Rolfe and Windle study (i.e. the Fitzroy basin). When converted to 2022 dollars, the estimated value per hectare is $18 (see details in Appendix 2).

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Appendix C.1: Non-market valuation

Non-market valuation is the term use by economist to describe a set of techniques used for estimating the dollar values of intangible goods or services (e.g. life, biodiversity, air quality). These techniques estimate how much people are willing to pay for a change in the quantity or quality of an intangible good or service. With these techniques, we can assign a dollar to the environmental and social impacts of bushfires. When these intangible impacts are estimated in dollar values, they can be fully integrated in economic analyses and compared with tangible economic impacts.

There are several techniques used to estimate non-market values. These can either be revealed preference or stated preference techniques. Each of these is explained below.

a) *Revealed preference* techniques use information that is already available in existing markets associated with the intangible good or service being valued. It may also involve observing people's behaviour in how they use an intangible good and infer from it their willingness to pay for that good. Examples of revealed preference techniques include:

    1. The *travel cost method* looks at the costs associated with making a trip to visit a site to infer how much people are willing to pay for each visit.

    2. The *hedonic pricing method* is used to investigate how the intangible characteristics of a good influence its value (e.g. premiums paid for property near desirable environments).

b) *Stated preference* techniques use surveys to ask individuals how much they are willing to pay for an intangible good or service. Examples of stated preference techniques include:

    1. *Contingent valuation* estimates the value of an intangible good by directly asking individuals how much they would be willing to pay for that intangible good or service.

    2. *Discrete choice experiments* estimate the value of an intangible good by asking people to choose between a set of options that involve different levels of payment and availability of the intangible good of service being valued. By analysing the choices people make, economists can measure how individuals make trade-offs between changes in the characteristics of the intangible good and estimate their willingness to pay for it.

Appendix C.2: Estimating non-market values

In this appendix, we have included the details on how some of the non-market values (i.e. intangibles) have been estimated.

Value of native vegetation and modified pastures for grazing

Asafu-Adjaye *et al.* (2005) estimated the economic return of land used for cattle grazing in Queensland at $21.4 billion. This figure was estimated over a period of 30 years, using a discount rate of 4%. We converted the $21.4 billion to an annualised figure, which is $1.2 billion. When converted to 2022 dollars using CPI, this is equal to $2.4 billion. We divided this figure by the total number of hectares used for grazing in Queensland (approx. 138 million hectares), which gives a result of $17 dollars per hectare.

Value of environmental assets

There are many different types of environmental assets, and if we were to assign a dollar value to each, they would all have different values. Furthermore, environmental assets can be valuable for different reasons or uses, e.g. they provide ecosystem services, the provide habitat for different species, they are aesthetically pleasing, they provide recreation, people appreciate the fact that they exist, etc. For each of these reasons, humans would be willing to pay a different amount in dollars, even if we were to consider one single type of environmental asset, like a single species. Consequently, it is very difficult to assign a value per hectare to natural reserves or conservation areas and use this value homogenously across a case study area. For such a large case study area (Queensland), it is impractical to assign a dollar value to each type of environmental asset, as this would require a lengthy analysis that is beyond the scope of this project and there are not enough studies for all the different environmental assets to accomplish such a task.

In order to include environmental values in our analysis in a practical and meaningful way for the whole state of Queensland, we decided to use a value per hectare for conservation areas that represents only two types of use: existence and aesthetic values, where natural landscapes have value because people appreciate the fact that they exist and that they are aesthetically pleasing. We found a study that estimated the dollar value of existence and aesthetic values for natural landscapes in Queensland (i.e. van Bueren and Bennett 2000) and used these estimates for the whole state. They estimated an average willingness to pay for natural landscape values in Queensland of $0.07 per household (in 2000 dollars) for 10,000 hectares, which corresponds to $0.12 in 2022 dollars. Willingness-to-pay values are always aggregated (i.e. multiplied by the relevant population) in order to find the actual value of the environmental asset. Since van Bueren and Bennett (2000) was a national study, we multiplied the willingness to pay by the total number of households in Australia (10.1 million) and divided it by 10,000 hectares to get a value per hectare. The average willingness to pay per hectare for natural landscapes in Queensland is $121.

Value of land used for traditional indigenous uses

We used the value estimated by Rolfe and Windle (2003) and Windle and Rolfe (2003). They estimated the value of aboriginal cultural heritage sites in Central Queensland (Fitzroy basin) at $189 for all sites (in 2001 dollars). This is their lower bound estimate, the most conservative value. However, this estimate corresponds to the willingness to pay for the protection of those sites by Indigenous Australians only. Thus, we multiplied the willingness to pay value by the total number of Indigenous Australians (881,600 in 2021). We then divided the aggregated estimate by the number of hectares in the Fitzroy basin (15.7 million ha). When converted to 2022 dollars, the estimated value per hectare is $18.