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RESEARCH

Burn probability mapping of Moutohorā (Whale Island), Bay of Plenty, Aotearoa New Zealand

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Abstract: Aotearoa New Zealand's conservation management has had a strong focus on offshore islands, though this investment is at risk from human-influenced factors such as biosecurity incursions and wildfire. During the last century several wildfires have occurred on Moutohorā (Whale Island), Bay of Plenty, which is a location for six threatened plant and three threatened animal species. Conservation and cultural management on Moutohorā over the last several decades has restored the island to become the most densely vegetated it has been since before humans arrived, albeit with a very different composition. The Prometheus fire-growth simulation model was used to produce a series of deterministic fire extent maps, which were compiled into seasonal burn probability maps. The average simulated fire extent was 53.2 ha, with a maximum area of 129.9 ha (or approx. 84% of the entire island), with 23% of fires not growing past 0.01 ha. Fires that start in summer, the western end of the island, and in mānuka and/or kānuka had the highest mean and maximum fire extent. Burn probability maps are a key step in quantifying the spatial fire risk for important conservation locations such as Moutohorā.

Keywords: fire, island, land management, modelling, simulation, wildfire

Introduction

To increase the ecological integrity of Aotearoa New Zealand's (hereafter New Zealand) offshore islands, a biological research strategy has identified a key research area: understanding ecosystem processes and their resilience to long-term environmental change (Towns et al. 2012). Mapping the burn probability of New Zealand's offshore islands (and other most valuable and vulnerable ecosystems) is listed as one of the top twenty wildfire research needs for conservation (Christensen 2019). This short communication mapping the burn probability on Moutohorā (Whale Island), hereafter Moutohorā, represents a site-specific case study, linking the 2012 strategy needs, and the wildfire research needs for conservation.

The pre-human vegetation of New Zealand's northern offshore islands were largely destroyed by human-induced wildfires (Atkinson 2004). Pōhutukawa *Metrosideros excelsa* and kānuka *Kunzea* spp. often dominated offshore island vegetation following wildfires for several centuries, and along with seed and dispersal limitation this potentially retarded the rate of the development of diverse vegetation communities (Atkinson 2004; Bellingham et al. 2010). Pōhutukawa and kānuka are now the dominant vegetation on Moutohorā. Moutohorā was chosen for this study, as it has a high Department of Conservation ecosystem management unit ranking, 34th (from over 1300 sites), and because it is considered of increased fire risk due to the island having one of the highest numbers of recorded fires over the last several decades, due to fuel types (kānuka and grasslands) and high number of ignition sources (Christensen 2012; Hawcroft 2018).

Māori fire history on Moutohorā began around the same time as the fall of the Kaharoa Tephra, c. 700 years before present (Wilmshurst 1998). The pollen evidence from Moutohorā, indicate that after the Kaharoa Tephra fall, a seral vegetation community was present, that was then maintained by frequent burning (Wilmshurst 1998). The earliest known drawing of Moutohorā was from the first voyage of the Endeavour, 1769, possibly drawn by Sidney Parkinson (Anon. 1769). This drawing shows large trees possibly pōhutukawa lining the southern coast cliff edges and scattered on the western end of the island, some shrublands crowning Motuharapiki (the main summit), and the flanks seemingly to be more uniform resembling grassland, likely indicating an island landscape influenced by burning (Christensen 2019). Rāhui (iwi-led suspension of access) and conservation management (targeting goats *Capra hircus*, rabbits *Oryctolagus cuniculus* and Norway rats *Rattus norvegicus*) during the last century, has increased the forest vegetation coverage (Smale & Owen 1990; Fig. 1). Currently, six threatened native plant species: mawhai native cucumber *Sicyos mawhai*, pīngao *Ficinia spiralis*, scrub daphne *Pimelea tomentosa*, parapara *Pisonia brunoniana*, tawāpou *Planchonella costata*, waiu-atua shore spurge *Euphorbia glauca,* are in self-sustaining populations, and three threatened native animal species: crenulate skink *Oligosoma* aff. *infrapunctatum* "crenulate", tuatara *Sphenodon punctatus punctatus*, and North Island brown kiwi *Apteryx*

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Figure 1. Eastern end of Moutohorā vegetation change: 1955 top left, 1988 top right, 1996 bottom left, 2001 bottom right (DOC file photos).

mantelli, exist on the island, with the latter two species being translocated (Sothieson et al. 2016).

The Department of Conservation files have records of wildfires on Moutohorā during 1920, 1939, 1944, 1974, and 1978 all most likely human caused. The largest recorded wildfires possibly occurred in 1939 and 1944, which burnt the southern and western slopes respectively, and the 1974 wildfire which burnt approximately 32 ha of then tussock grassland or almost 20% of the island (Ogle 1990, Sothieson et al. 2016) (Fig. 3). Currently, all activities on the island are closed when the Fire Weather Index (FWI) is > 29 (Extreme), a Build-Up Index (BUI) code > 60 (Extreme) or a grass curing value of 100% (Sothieson et al. 2016). These indices are described in Anderson (2005).

Prometheus fire extent modelling software is used in New Zealand for fire management response (Clifford 2014). The use of burn probability mapping has been developed as a response management and risk assessment tool in Canada (McLoughlin & Gibos 2016; Beverly & McLoughlin 2019). Wildland fire scientists and land managers require spatial estimates of wildfire potential such as burn probability (Parisien et al. 2020). The development of burn probability maps would be a new approach for quantifying the spatial fire risk for important conservation sites in New Zealand, such as Moutohorā.

Methods

Study site

Moutohorā lies about 7 km off the Bay of Plenty, North Island, New Zealand coastline, directly north of Whakatāne (Fig. 2). The island is 143 ha in area, with a foreshore of 78 ha (DOC 1999). It has a steep topography resulting from erosion of a dormant collapsed volcanic cone, with a summit (Motuharapaki) of 353 m above sea level (DOC 1999).

Modelling and analysis

The Prometheus fire-growth simulation model uses geospatial input data (topography, aspect, slope, and vegetation fuel types; Fig. 2, and see below), to produce deterministic fire intensity and extent with the application of Huygens' principle of wave propagation to the fuel conditions and rate-of-spread predictions from the New Zealand Forest Fire Behaviour Prediction System (Tymstra et al. 2010; Pearce et al. 2012; Clifford 2014). Within the model, fires will spread more quickly uphill, with strong winds, through more flammable vegetation, and with drier and warmer conditions. A total of 600 simulations were produced, with probability of burning defined as the as the proportion of simulations in which that location burnt.

To produce seasonal probabilistic maps of example wildfire intensity and extent a Monte Carlo approach was adopted. Ignition of fires occurs where humans are most likely present

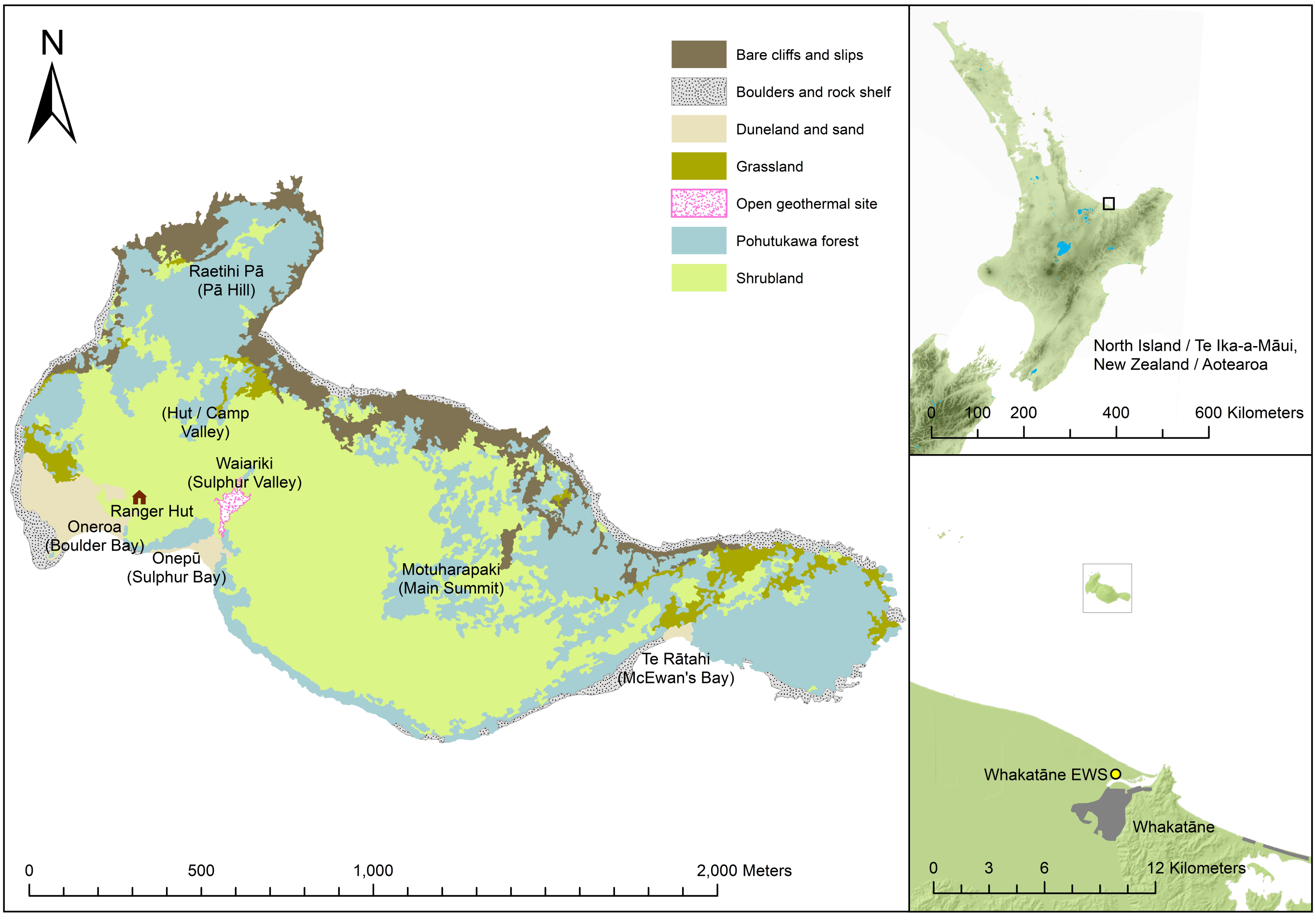

Figure 2. Moutohorā (Whale Island) fuel type landcover map based on (Christensen & Chakraborty 2006). Names in brackets indicate former names. Bottom insert shows the location of the Whakatāne Electronic Weather Station (EWS number 769909).

Figure 3. 1974 fire, camp/hut valley, Moutohorā (Whale Island) (N. Hellyer, DOC file photo; Christensen 2019).

(Anderson et al. 2008). Hence, random ignition points were located in vegetated areas of likely (and previously known) human-induced fire areas (approx. 6 ha), surrounding the Ranger hut, boat landing sites at Oneroa (Boulder Bay), Te Rātahi (McEwan's Bay), the coastal edge at Onepu (Sulphur Bay), and at the flat grassy area above Te Rātahi (McEwan's Bay) (Fig. 2). As fires can occur on any day of the year, a total of 600 (simulation start) days were randomly selected from the dataset for (see below) efficiency, as the simulations can run over an hour in duration (in terms of computational expense). The 8m New Zealand digital elevation model (DEM) 2012 was obtained from the Land Information New Zealand (LINZ) data service. The DEM and a 2000 supervised classification-derived (based on aerial images and ground-truthed data) vegetation map were transformed into ASCII file formats for import into Prometheus (Christensen & Chakraborty 2006; Sothieson et al. 2016). While more recent imagery is available, changes in vegetation extent over the last 20 years is considered nominal and unlikely to affect the predictions. The resolution of elevation and landcover ASCII files created were both 8 m.

Weather streams, fire indices, and seasons

Data streams (18 December 2016 to 22 July 2019) recorded from the Whakatāne electronic weather station (EWS number 769909) were used as weather inputs (Fig. 2). This is one of the closest stations to the island, and also provides the most recent electronic data records. A total of 22 695 hourly data records covering 946 days were downloaded. Prometheus uses the following data: time (NZST), rainfall (mm), temperature (°C), relative humidity (%), wind direction (degrees), wind speed (m s^{-1}). Prometheus does not model the extinguishment of wildfires and can thus over-estimate wildfire extent, especially if it is run for an extended duration (McLoughlin & Gibos 2016). Therefore, all wildfire simulations started at 1200 hours and ran for 52 hours, to cover three (daily) maximum daily FWI values. This 52 hour limit was imposed as fire response actions would be actioned immediately under a "high initial threat plan" as soon as a fire was reported (Sothieson et al. 2016). Fire extent and intensity polygons and data were calculated hourly (depending on the hourly conditions, the simulated fire may not progress), with the final hour (52) used as the sample unit of interest.

Season and FWI values are given in Table 1. The FWI > 29 (Extreme) was never reached on any ignition days during the total simulation period, although BUI code > 60 (Extreme) reached or exceeded this on 12 days, all in summer, with 10 of these in the month of February. The use of satellite imagery for percentage grass curing requires further validation for New Zealand conditions (Anderson et al. 2011). The determination of percentage grass curing was not completed as ground-based visual observations are logistically unfeasible, thus the model default (60%) was used. The following fuel type assignment was used: actual vegetation-fuel type (percentage of island area): kānuka-mānuka/kānuka shrubland (44%), pōhutukawa-podocarp/broadleaf forest (36%), grassland composed of species such as harestail *Lagurus ovatus* and Yorkshire fog *Holcus lanatus*-ungrazed pasture grassland (3%), using descriptions in Pearce et al. (2012). The rate of fire spread varies as a function of the weather, terrain (particularly slope), and the fuel type and load (Pearce et al. 2012). The relative flammability of the fuel types as determined by the equilibrium (on flat ground) rate of spread (m hr^{-1}) using the initial spread index (ISI at value of 1 which was the average for all simulations, and 10 for comparison): kānuka-mānuka/kānuka shrubland (144 m hr^{-1}, 2473 m hr^{-1}); ungrazed pasture grassland (10 m hr^{-1}, 377 m hr^{-1}, at 60% degree of curing); and podocarp/broadleaf forest (0 m hr^{-1}, 75 m hr^{-1}, at BUI value of 15, which was the average for all simulations (Pearce et al. 2012).

Results

Of the 600 simulations, 136 (23%) did not grow past 0.01 ha in area (i.e. did not become fully developed), the average fire extent was 53.24 ha, and the maximum was 129.9 ha (or approx. 84% of the entire island) see (Appendix S1 in Supplementary Materials). Fires starting in kānuka-mānuka/kānuka shrubland had larger areas of fire extents across the three vegetation types, and across most seasons (Fig.4 and Appendix S1). The western end had a higher average in fire size, with the smallest fire in summer and starting in kānuka-mānuka/kānuka shrubland being 3 ha. Fires starting in pōhutukawa-podocarp/broadleaf forest rarely became larger than several hectares. Fires starting in kānuka-mānuka/kānuka shrubland predominantly became fully developed wildfires, with only 6% of these staying at 0.01 ha or less. During winter, 48% of fires did not fully develop into wildfires, i.e. stayed at 0.01 ha or less. During summer, 8% of fires stayed at 0.01 ha or less. Fire maps are shown in Fig. 5, with probabilistic modelling of wildfire extent and intensity (Figs 5c, d).

Table 1. Season, 12-noon weather and fire weather indices value ranges used in simulations.

Parameter values	Spring	Summer	Autumn	Winter
Months	September to the end of November	December to the end of February	March to the end of May	June to end of August
Temperature (°C)	10.7–22.2	15.4–27.6	7.9–22.0	8.3–17.4
Relative humidity (%)	63.3–93.5	57.8–95.5	69.1–96.0	67.6–94.0
Fine fuels moisture code (FFMC)	1.6–84.4	4.3–86.9	3.6–83.5	3.7–83.1
Duff moisture code (DMC)	0.1–22.1	0.1–65.4	0.5–29.9	0.1–7.0
Drought code (DC)	1.9–266.6	3.5–421.1	2.3–275.3	1.9–35.4
Initial spread index (ISI)	0–2.9	0–3.6	0–2.0	0–2.3
Build-up index (BUI)	0.3–30.3	0.3–89.2	0.7–43.8	0.2–8.9
Fire weather index (FWI)	0–4.8	0–10.4	0–4.9	0–0.9

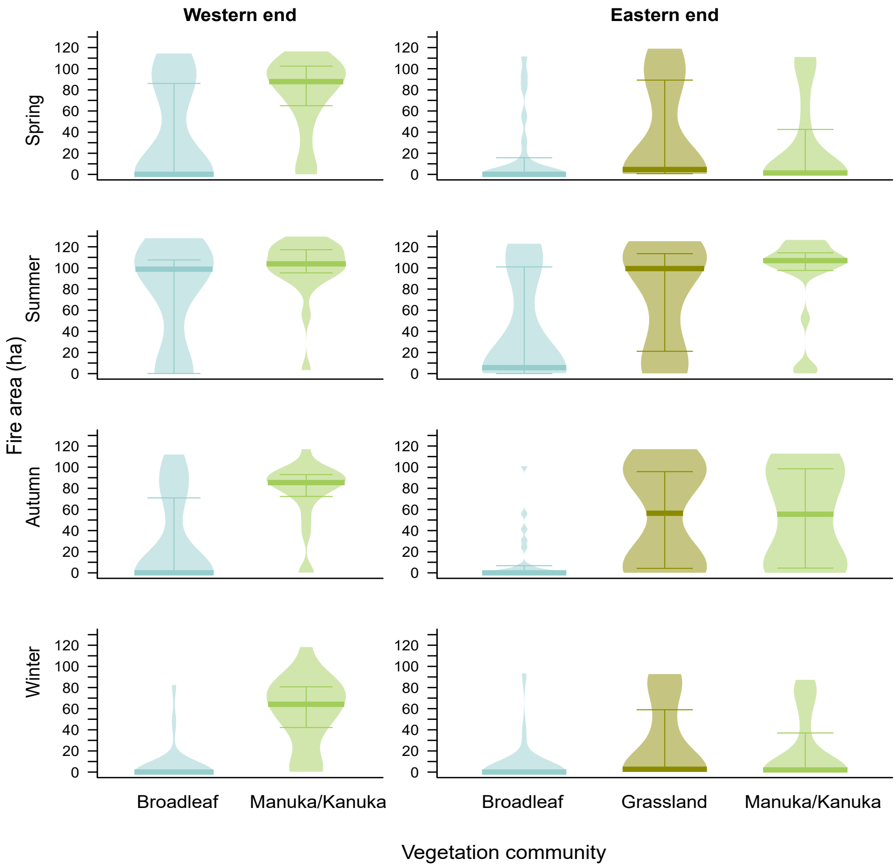

Figure 4. Probability density (violin) graphs of fire area by location, seasons, and ignition points by vegetation community, showing multi-modal nature of the simulations. Thick bars indicate medians, with extended bars showing interquartile range.

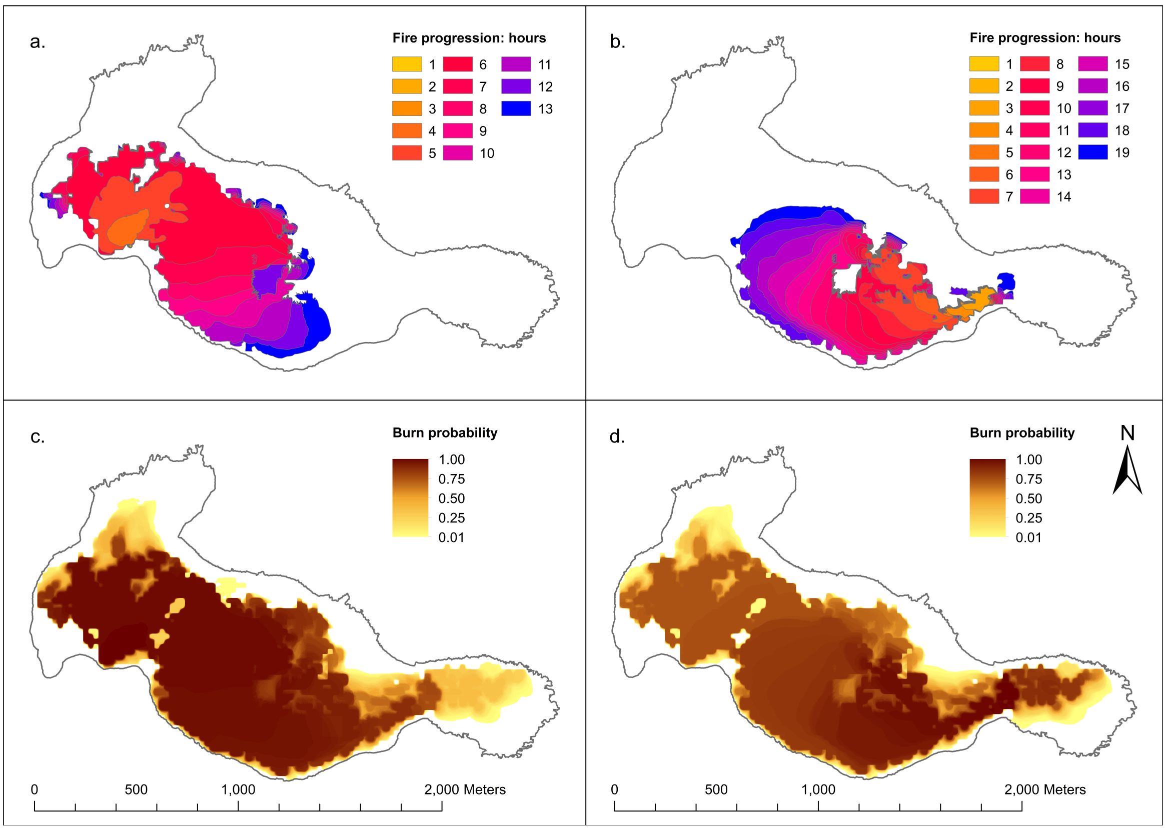

Figure 5. Fire maps for Moutohorā. Example deterministic maps showing hourly fire model progression (light orange to dark violet) over 52 hour duration, both starting in broadleaf forest: (a) Summer (22/01/2017) Western end ignition in vegetation (74.05 ha) with 13 hours total fire progression; (b) Summer (16/12/2017) Eastern end ignition in vegetation (57.82 ha) with 19 hours total fire progression. Summer probabilistic fire simulation maps at two zones of likely ignition areas: (c) Western end; (d) Eastern end.

Discussion

New Zealand hardwood forest has the potential to act as "green firebreaks" such as compared to the other more flammable vegetation communities as grassland and kānuka-mānuka/kānuka shrublands (Curran et al 2018). Moutohorā is likely to be the most vegetated (highest amount of vegetation biomass) it has been since before humans arrived, and like the large proportion of northern New Zealand offshore islands it is dominated by kānuka and pōhutukawa, resulting from previous fires, and seed dispersal limitation. With several decades of conservation and cultural management, the resulting vegetation on Moutohorā is becoming more resistant to fires, though fires still have the potential to cover a large extent of the island across all seasons, as shown by this study.

Management Implications

This work indicates that software such as Prometheus can also be used in New Zealand for probabilistic fire extent scenarios, in addition to deterministic fire response modelling. Prometheus may add additional value by refining the location of escape routes and locations of potential safe areas, such as the south-eastern-end of the island. Such tools as Prometheus are useful for pre-planning and research investigations for fire and natural resource managers (McLoughlin & Gibos 2016). This work could be used as an initial template for determining the spatial burn probability for those New Zealand islands with significant biodiversity and cultural values. Updated finer scale vegetation maps (e.g. 5 m resolution) as well as plant flammability information will improve modelling approaches of fire extent and its behaviour (Fogarty 2001; Mason et al 2016; Wyse et al. 2016). The incorporation of such work into conservation threat plans may add value, as it can determine spatially the burn probability at sites, and then also subsequent invasion potential by weeds (Perry et al. 2010; Christensen et al. 2019). Additionally, this approach could be used to evaluate changes in expected fire area and intensity if an invasive species were to modify the current fuel environment (Wyse et al. 2018).

Islands such as Moutohorā with high conservation and cultural values, that also carry high burn probability relative to their area, even with management of human activity are likely to become under increased threat due to climate change (Towns et al. 2012; Sothieson et al. 2016; Macinnis-Ng et al. 2021). Modelling and research that can produce and improve fire burn probability mapping will have increased value for conservation, resource and cultural site managers.

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Supplementary material

Additional supporting information may be found in the supplementary material file for this article:

Appendix S1. Fire growth simulation statistics.

The New Zealand Journal of Ecology provides supporting information supplied by the authors where this may assist readers. Such materials are peer-reviewed and copy-edited but any issues relating to this information (other than missing files) should be addressed to the authors.