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Reframing Wildfire Simulations for Understanding Complex Human–Landscape Interactions in Cross-Cultural Contexts: A Case Study from Northern Australia

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Supplementary material: Model description

Fire spread calculation

On each cycle of the model landscape and fire weather variables interact to produce an ignition probability, the probability of a fire moving to an adjacent cell. The ignition probability is a product of a cells inherent burnability (burn probability) and spread probability calculated by fire agents. These probability values are a product of the propagation modifier values for each of the variables. Spread is ultimately determined through a stochastic process where on each cycle of the model every fire agent calculates a random value between one and fifty. To ignite this random fire spread value must be equal to or lower than the ignition probability value. The interaction between the model parameters is summarised here;

Burn Probability = Fuel load × Local Curing × Fire Danger

Where fuel load is a function of grass vegetation type, time since last burnt and mapped natural and anthropocentric fire breaks. Local Curing is derived from the topographic wetness modifier. These cell attributes are modified by the overall fire danger.

Spread Probability = Wind × Slope × Time Since Ignition

Spread Probability calculated as a propagation modifier produced by each agent for the surrounding eight cells as a function of wind and slope. The time since ignition for each fire agent reduced the ignition probability by increasing the random fire spread value by 2.5 for each model cycle.

Ignition Probability = Spread Probability × Burn Probability

As soon as a new cell ignites, it is considered 'burnt' and cannot be ignited again.

Model Parameters

Each fire weather and cell variable has a fire propagation modifying factor. The product of these factors determines how fast and where a fire will spread. The propagation modifying factors have been developed to illustrate principles in fire behaviour that can be used to understand guide fire management practices. These principles have been derived from a combination of empirical data and the experience of fire managers. The actual modifying factors were adjusted through model calibration to ensure they produced fire behaviours illustrative of the learning and discussion facilitation objectives described in the main body of this paper. The code underlying the various propagation factors is open and easily modifiable to suites specific learning and idea exchange contexts. The following section describes the fire weather and landscape variables and their associated propagation modifying factors used for the GitHub example model.

Fire weather global variables

Four global variables drive fire weather; fire danger, wind speed and direction and time of day.

Fire danger

Fire danger in this model combines curing, temperature and humidity and is a simplified proxy for seasonal influence. The onset of the dry and wet seasons can vary significantly from year to year, so no seasonal value is placed on the fire danger setting. Rather a scale from one of ten where low values indicate wet-season conditions and the higher settings apply to hot, late dry season, fires. The effect of fire danger (humidity, temperature, and curing) on propagation increases rapidly after the Wet Season ends, levelling out later in the year. To reflect this a logarithmic curve was set from a minimum propagation value of 0.1 (Wet Season) to a maximum propagation value of 3.4 (Figure s1). The relationship between the Propagation Modifier Value (PMV) and the fire danger (FD) shown in figure one is produced by the following equation:

PMV= -0.039*(FD^2))+(FD *0.8)-0.7)

Figure S1. The propagation value curve as a function of the fire danger value setting.

Wind speed

Wind direction has four settings; none, light, medium and high. Whilst wind speed is a global variable the propagation modifier values are produced individually by each fire agent for surrounding cells. Fire spread propagation values in the eight surrounding cells are altered based on wind speed and direction. The propagation modifiers were calibrated through multiple runs to produce a fire spread ellipse that illustrated meaningful shape and rate of spread. This is illustrated in figure S2 where the propagation modifier is shown for each cell surrounding based on an active fire for a southerly wind.

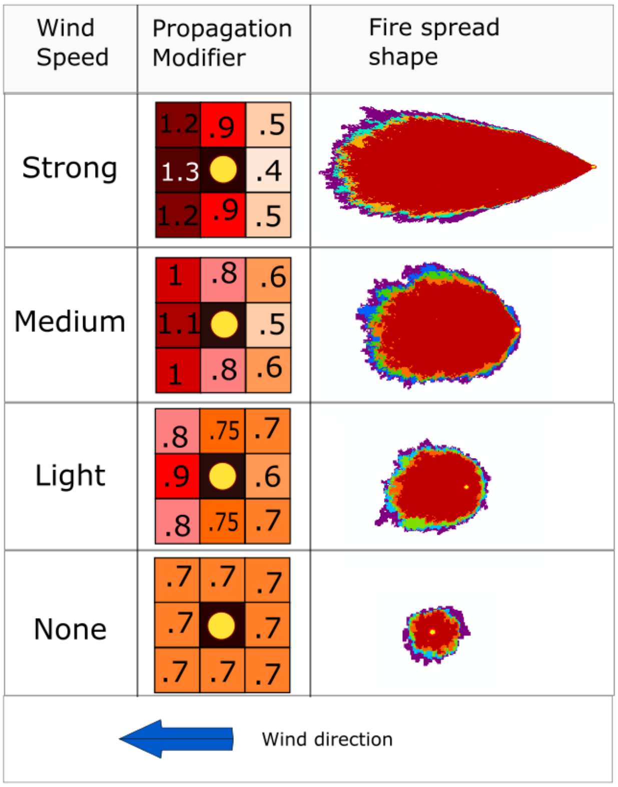

Figure S2. Shows the propagation modifying values for the eight cells surrounding a burning cell based on an easterly wind under the four wind speed settings and an example average fire spread shape from these settings.

With a strong wind speed setting burning cells can throw embers ahead of the fire front. The spotting function ignites cells a random distance in the prevailing wind direction ahead of the initiating agent. Spotting distance is calculated as a random value between zero and seven cells ahead of the fire front. A road or river will not be 'jumped' unless the spotting is greater than the equivalent of two cells ahead of the fire front. Figure S3 shows the number of cells ahead of the fire front a spotting ignition will occur derived from a random value between zero and fifty. The spotting curve was produced so that approximately half the spotting occurs less than two cells ahead of the fire front. The maximum spotting distance based on an eighty-meter cell size is 560 meters. The relationship between the spotting distance (SD) and the Random Value (RV) is described by the following equation: SD= ROUND(((0.0031 * (RV ^ 2)) + (-0.0176 * (RV)) + 0.2))

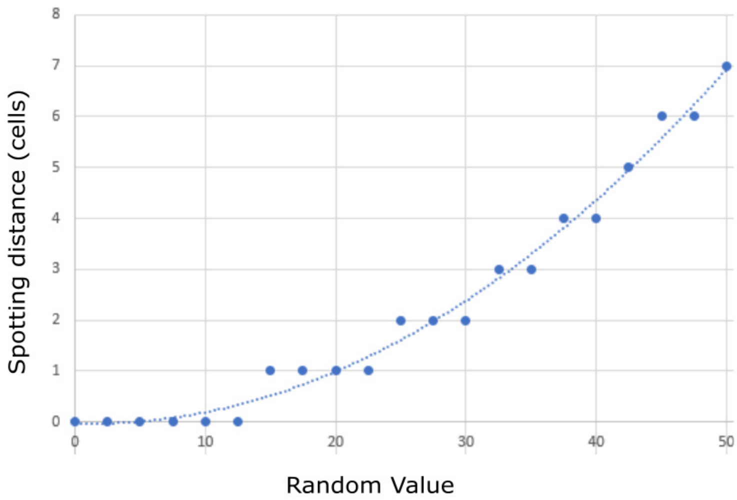

Figure S3. The number of cells ahead of the fire front a spotting ignition will occur as indicated by blue dots in relation to a random value between zero and fifty. The dotted line indicates the polynomial curve to which the spotting-distance values are derived.

Spotting only occurs under the strong wind speed setting. However, fluctuations in wind speed are modelled using a Markov chain function that allows wind speed to change temporarily around an initial setting. This means that spotting can occur from the medium wind setting when fluctuations to the strong wind setting occur.

Time of day

Time of day modifies windspeed and fire danger settings. Fire danger moves around the initial setting through the diurnal cycle (Figure S4), being highest during mid-afternoon when the temperature is usually at its highest and humidity the lowest. Mid-afternoon is modelled as a one-level increase in fire danger. This decreases during the evening and is lowest at dawn when humidity is highest temperature is the lowest. Diurnal variation in wind speed is modelled as a reduction in average wind speed by one factor during the late evening to the dawn cycle of the model.

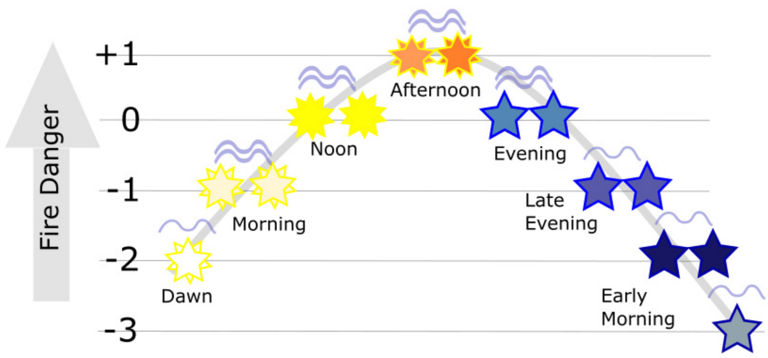

Figure S4. The diurnal weather cycle showing an increase in fire danger from noon through to the evening. Wind influence, shown by wavey lines, also decreases by one intensity level from late evening to morning.

1.7 Cell/Landscape variables

Each cell is attributed with four landscape attributes, grass type, time since last burnt, fire breaks and topographic wetness (Figure s6), derived from empirical datasets and one fuel load attribute derived from the first three of these landscape datasets.

Grass type

Data is derived from extensive grass fuel load mapping conducted across northern Australia that underpins the savanna burning carbon farming methodology Yates et al [67]. These data sets were simplified to the two main grass types showing significant differences in fuel loads related to the time since fire; hummock grasses (Spinifex/Triodia spp.) and tussock grasses (Poaceae spp.). These occur in mixed assemblages and where one or the other is dominant (Figure S4).

Time since last burnt

This free, public domain data is downloaded from the NAFI website (firenorth.org.au, 2019). The data is produced from MODIS satellite imagery at a 250m cell size scale. The previous four years of fire history are shown within the model interface (Figure S6).

Landscape fire break layers

This data combines anthropogenic features, rivers and cliffs. Each of these features has a fuel load setting of zero and will not be breached except via a spotting event. Anthropogenic breaks include roads, fence lines and fire breaks which were obtained from Northern Territory Government infrastructure mapping vector data. These datasets were augmented by using Google Earth imagery to update the data with new features and add a break-width factor or stopping power attribute to each feature. Major Rivers and cliff features that act as significant fires breaks were derived from national level topographic mapping.

Fuel Load

Fuel load incorporates grass cover, time since last burnt and the landscape fire break layers. Fuel load accumulation combines grass cover and time since last burnt, using logarithmic curves based on research by Yates et al [67]. The fuel load accumulation equations as a function of time since last burnt for Tussock, Hummock and mixed grasslands are shown below in figure S4. These curves are designed to illustrate how tussock grasses regrow every year but do not continue to accumulate large quantities of fuel over subsequent years in contrast to hummock grasses that take longer to regrow after fire but accumulate large, highly flammable loads over after 4-5 years. In addition to grass fuel, rivers, cliff lines, major roads, fence lines and other significant fire breaks are given a propagation modifiers value of 0.1, making them not burnable. Fire will only propagate past these barriers with a spotting event. Smaller, unmaintained fence lines and tracks are allocated a propagation modifier value of 0.6 which results in them being effective at stopping fires only under more mild conditions.

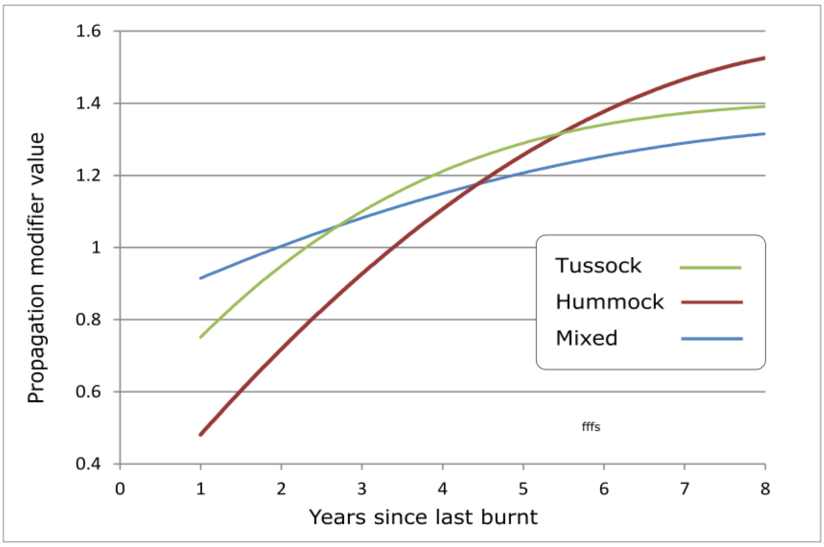

Figure S5. The fuel load accumulation equations as a function of time since last burnt for Tussock, Hummock and mixed grasslands.

The Propagation Modifier Value (PMV) equations as a function of time since last burnt (tslb) for (1) Tussock (2) Hummock and (3) mixed grasslands are shown below.

PMV = ((-0.0054 × (tslb2)) + (0.0966 × tslb) + 087) (1)

PMV = ((0.0014 × (tslb3)) + (-0.0421 × (tslb2)) + (0.4243 × tslb) + 0.115) (2)

PMV = ((0.0011 × (tslb3)) + (-0.03 × (tslb2)) + (0.28 × tslb) + 0.5) (3)

Topographic wetness

Topographic wetness models water flow and accumulation and provides a proxy for differential curing post wet season and grass growth rates. For fire danger settings below 7, related to earlier in the dry, topographic wetness is scaled to between values of 0.7, for areas of high-water accumulation and 1.3 for areas likely to dry first. For fire danger settings greater than 7, indicating late dry season conditions, the propagation modifier values are inversed. This models the fact that the areas that cure last are the wettest longest, generally grow more grass fuel and that the areas that cure first are likely to have the least fuel. The modelled relationship between early and late dry season influence on fuel curing and fuel accumulation is shown in figure S5.

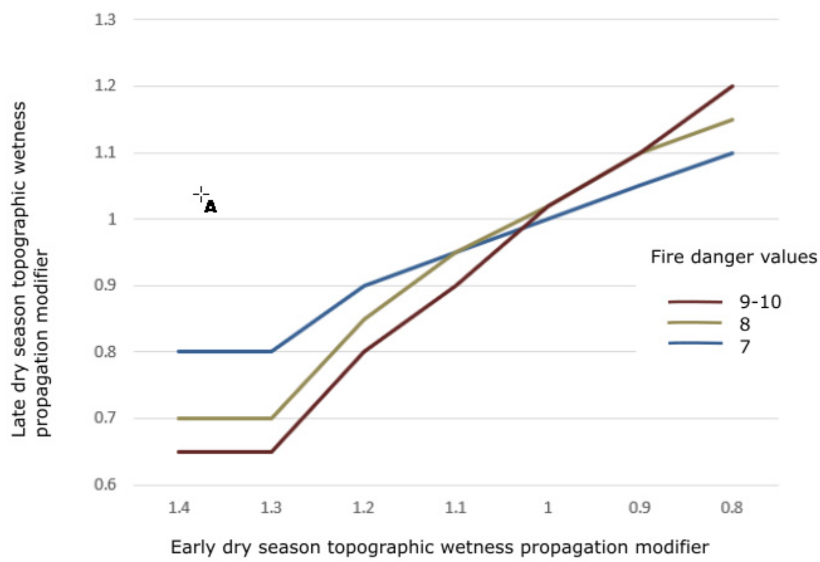

Figure S6. The modelled relationship between early and late dry season influence on fuel curing and fuel accumulation due to topographic wetness. The base topographic wetness propagation modifier operates for fire danger values greater than 7.

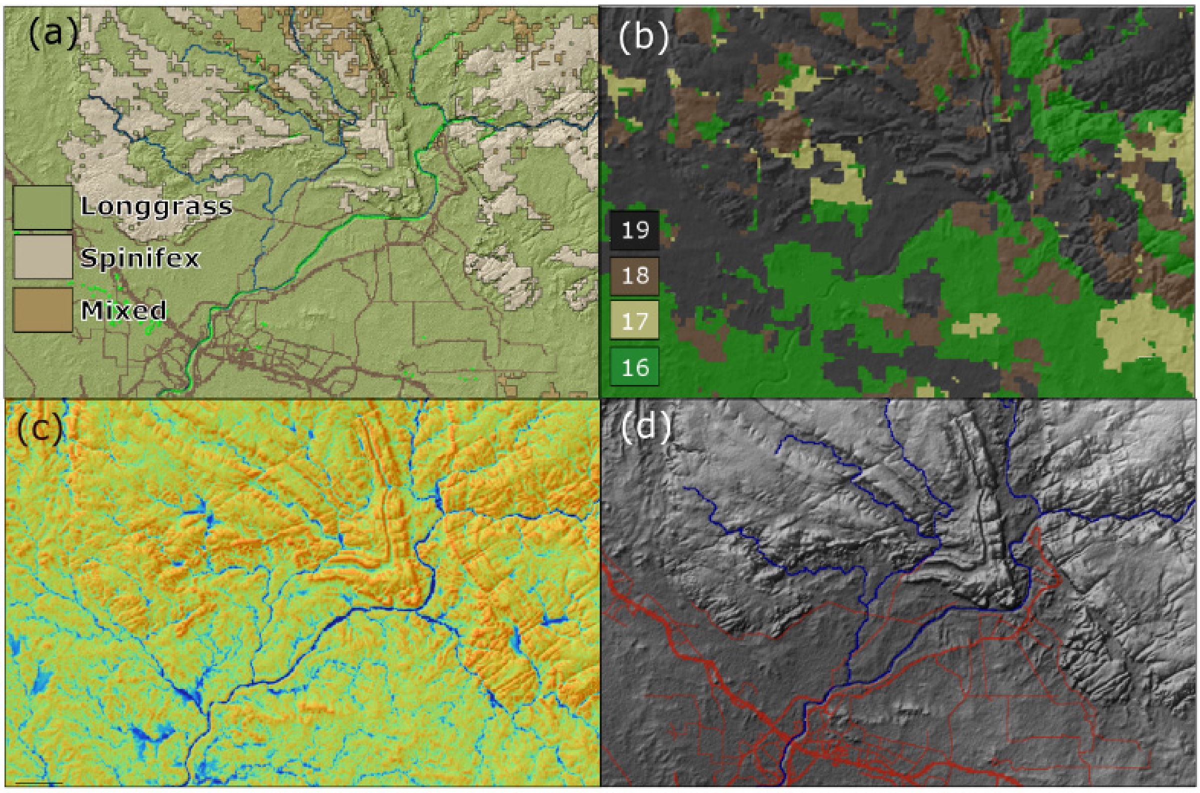

Figure S7. The four landscape datasets as seen in the model interface; (a) showing the grass vegetation layer (b) the time since last burnt from 2016 ro 2019 (c) topographic wetness and (d) fire breaks with roads and tracks shown in red and perennial water-0ways shown in blue.,.

Fire agent attributes

Fire agents calculate two attributes; spread direction probability and time since ignition. Spread direction probability is a function of wind direction and slope. Each fire agent calculates a spread probability in each of the eight surrounding cells based on slope, wind direction and wind speed. In addition, each fire agent monitors its time since ignition and reduces the spread probability over time. Each cycle of the model, the probability of a fire spreading is reduced by two per cent. After sixty cycles of the model fires agents 'die'.

Slope

Slope is calculated as the relative difference in elevation between the current cell and the eight surrounding cells of each fire agent. The slope influence on propagation is calculated using the function developed by Nobel et al. [70]:

$$Rs = Rf \times 2^{\theta/10} \tag{4}$$

Where *Rs* is the slope effect on spread, *Rf* is the flat ground rate of spread, and θ is the angle of slope. This is modified for downslope spread using the Kataburn [71] function:

$$Rs = Rf \times \frac{2^{-\theta/10}}{2(2^{-\theta/10}) - 1}$$

The Kataburn function reduces the rate of spread errors observed in complex terrain [71]. The overall slope effect is shown in Figure S7.

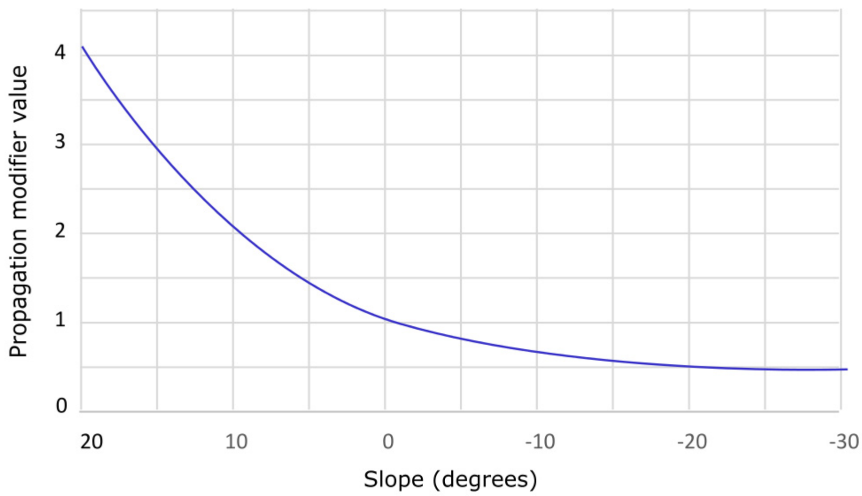

Figure S8. The propagation modifying value based on slope.

Time since ignition

Each fire agent monitors its time since ignition and reduces the spread probability over time. Each cycle of the model the probability of a fire spreading is reduced by around two per cent. This allows fires to stop spreading during mild conditions, as often seen as night-time, and reignite with more favourable conditions during the day. After sixty cycles of the model fires agents 'die'.