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Forest fire and its key drivers in the tropical forests of northern Vietnam

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ABSTRACT

Fire increasingly threatens tropical forests in northern Vietnam as climate changes and human population grows. Understanding fire occurrence patterns may support more effective forest management and reduce fire risk. We investigated spatiotemporal patterns and drivers of wildfire across three provinces in northern Vietnam and assessed the effectiveness of the Modified Nesterov index (MNI) fire danger rating system. We explored fire occurrence and size within and between years and forest types using descriptive analyses and developed spatiotemporal Maximum Entropy (Maxent) models incorporating variables representing potential drivers of fire, including weather, fuel, topography and human activity. Most fires occurred late in the dry season and fires were most common in natural forest. Maxent models successfully predicted fire occurrence (area under the receiver operating characteristic curve (AUC) values 0.67–0.79). While the contributions of drivers varied among provinces, MNI, temperature, elevation and distance to road were consistently important. The model for combined provinces showed that fire probability was greater under higher temperature and MNI, in areas with lower population, farther from roads, at higher elevations and in natural forests. This study suggests that an assessment integrating multiple drivers better predicts fire occurrence than a system based on weather alone and may support improved fire management and education in northern Vietnam.

Keywords: forest fire occurrence, human activity, Maxent, Modified Nesterov index, plantation forest, rainforest, topography, weather conditions.

Introduction

Increased fire occurrence over recent decades due to global environmental change drivers, including climate-change induced drought (Herawati and Santoso 2011; Vadrevu *et al.* 2019) and human population growth (increasing ignitions; Cochrane 2001), has negatively impacted many tropical forest ecosystems and represents a growing threat to remaining tropical forests (Cochrane 2001, 2003; Corlett 2016; Juárez-Orozco *et al.* 2017). Understanding the occurrence of fire in tropical forests can support management practices to reduce fire risk and assist in the development of more effective forest conservation.

Fire is a major cause of disturbance in terrestrial ecosystems globally (Flannigan *et al.* 2013), and where fire is recurrent within the lifetime of the dominant lifeforms, ecosystems may show a range of adaptations that facilitate system recovery, from seeds stored in the plant canopy or soil (Lamont *et al.* 1991; Enright *et al.* 2014), or from vegetative regrowth (Clarke *et al.* 2013). However, fires historically have been infrequent in wet tropical forests and these systems generally show no *in situ* adaptations to fire, with burned forest recovery largely dependent on recolonisation by propagules from surrounding unburned vegetation (Cochrane 2003; Enright 2011).

Various factors influence fire occurrence, the four most important drivers being weather conditions, fuels, topography and ignitions (Bessie and Johnson 1995; Bowman *et al.* 2011; Taylor *et al.* 2013; Harvey *et al.* 2016; Parks *et al.* 2018). Wildfires are more likely in hot, dry, windy weather, which makes fuels drier and lowers the energy needed for ignition (Parisien and Moritz 2009). Thus, weather conditions are used worldwide to derive indices of forest fire danger that estimate fire risk, and intensity and rate of spread of a fire if an ignition were to occur (Luke and McArthur 1978; Van Wagner 1987; de Groot *et al.* 2007; Su *et al.* 2021). Fuel conditions are another major determinant of fire occurrence (Bradstock 2010; Ye *et al.* 2017; McWethy *et al.* 2018), especially the continuity, amount, moisture and flammability of live and dead fuels that are available to burn (Moritz *et al.* 2005; Pausas and Keeley 2009). Topography (particularly elevation, slope and aspect) indirectly influences fire occurrence and intensity by affecting microclimate, and fuel moisture and availability (Birch *et al.* 2015; Fang *et al.* 2015; Lee *et al.* 2018). Elevation influences fire occurrence via its relationship with temperature, precipitation and prevailing wind, which also affects fuel conditions (Camp *et al.* 1997; Bennett *et al.* 2010). Fuels dry more quickly, more readily supporting ignition and spread, on warmer aspects receiving higher solar radiation (Skinner 2002; Bennett *et al.* 2010; Nyman *et al.* 2015), while fire spread is faster on upper slopes and steeper slope angles (Viegas and Pita 2004; Viegas and Simeoni 2011; Cruz and Alexander 2017).

Finally, forest fire occurrence is affected by a range of human factors. Humans are now the main source of ignitions, supplanting natural ignitions from lightning, in most parts of the world (Goldammer 2007; Lewis *et al.* 2015; Grala *et al.* 2017). Slash and burn farming is a major cause of fires in tropical forests (Stefan and Lindsey 2013), with resultant secondary forests more open, drier and with increased fuels from slash piles and collateral damage, further increasing fire susceptibility (Kauffman and Uhl 1990; Uhl *et al.* 1997; Cochrane 2002; Gerwing 2002). Population density and the proximity of roads are surrogate measures of human impact that also have been found to correlate positively with increased risk of fire (Yang *et al.* 2007; Kwak *et al.* 2012; Knorr *et al.* 2014; Matin *et al.* 2017; Adámek *et al.* 2018).

Many countries have developed Fire Danger Rating Systems (FDRSs) based on daily weather conditions (temperature, relative humidity, rainfall, wind speed) plus an index of dryness (time since last rain event, estimated soil dryness). Other predictors of fire spread and intensity, including fuel characteristics and topography, are recognised in accompanying documentation, but typically are not included in FDRS calculations since their spatiotemporal variation is too complex to readily incorporate in a general FDRS (Deeming *et al.* 1977; Luke and McArthur 1978; Van Wagner 1987; Tian *et al.* 2005). Human factors are generally not used in FDRSs (Martínez *et al.* 2009; Walding *et al.* 2018). Most countries derive their FDRS from those of Australia, Canada and the USA, with minor modifications for local conditions (Tian *et al.* 2005; Elhag and Boteva 2021). In Vietnam, however, the Nesterov index has been used since the 1980s. This index was developed for the boreal forests of the Soviet Union and modified for use in Vietnam (Hung 1988). The Modified Nesterov index (MNI) is a fairly simple FDRS based on the vapour pressure deficit (calculated from current day's temperature and relative humidity) and number of preceding days with <5 mm rain (Hung 1988; Tian *et al.* 2005; Vien 2014; Quy *et al.* 2017, and see *Methods* section below for further details).

To support and improve the temporal and spatial prediction of fires, numerous studies have investigated the effects of fire drivers for non-tropical forest ecosystems around the world (Alvarado *et al.* 2017; Lee *et al.* 2018; Zhang and Lim 2019). However, in tropical forest regions of south-east Asia, such as Vietnam, a comprehensive understanding of the factors affecting fire occurrence remains limited. The northern mountains region of Vietnam has large areas of tropical forest over complex terrain with diverse topographic and environmental conditions (Averyanov *et al.* 2003), an expanding plantation forest estate of highly flammable taxa including *Eucalyptus*, *Pinus* and bamboo (Phuong *et al.* 2012; Doanh and Bao 2014), and is reported as increasingly impacted by fire over recent decades (Le *et al.* 2014; Vadrevu *et al.* 2019; Forest Protection Department 2020). This region is well-suited for examining how fire drivers interact to influence fire occurrence in tropical forests. Here, we address the following questions: (1) what are the spatial and temporal patterns of forest fire occurrence in northern Vietnam; and (2) what are the key driving factors (weather, fuel, topography and anthropogenic) of fire occurrence? Insights obtained from this research will identify how effective the MNI is as an FDRS for this region and what other drivers of fire, if any, might be taken into account to better understand the occurrence and distribution of fires in northern Vietnam forests. Results of this study will enhance our understanding of fire drivers and facilitate better fire management in the tropical forests in northern Vietnam, and comparable tropical regions elsewhere.

Materials and methods

Study area

The study area covers three provinces in north-western Vietnam: Lao Cai, Dien Bien and Son La (Fig. 1), with an area of ~30 000 km^2 (General Statistics Office of Vietnam 2011). The region has a monsoon tropical climate with cold, dry winters and warm, wet summers. The winter drought period of 2–5 months extends from November to March. Average annual temperatures range between 20 and 23°C, with maximum daily temperatures from 37 to 41°C, and minimum temperatures between -4 and -2°C. Annual precipitation across north-western Vietnam ranges from 1700 to 2400 mm, with highest rainfall in July–August (Van 2015). Mean annual relative humidity ranges from

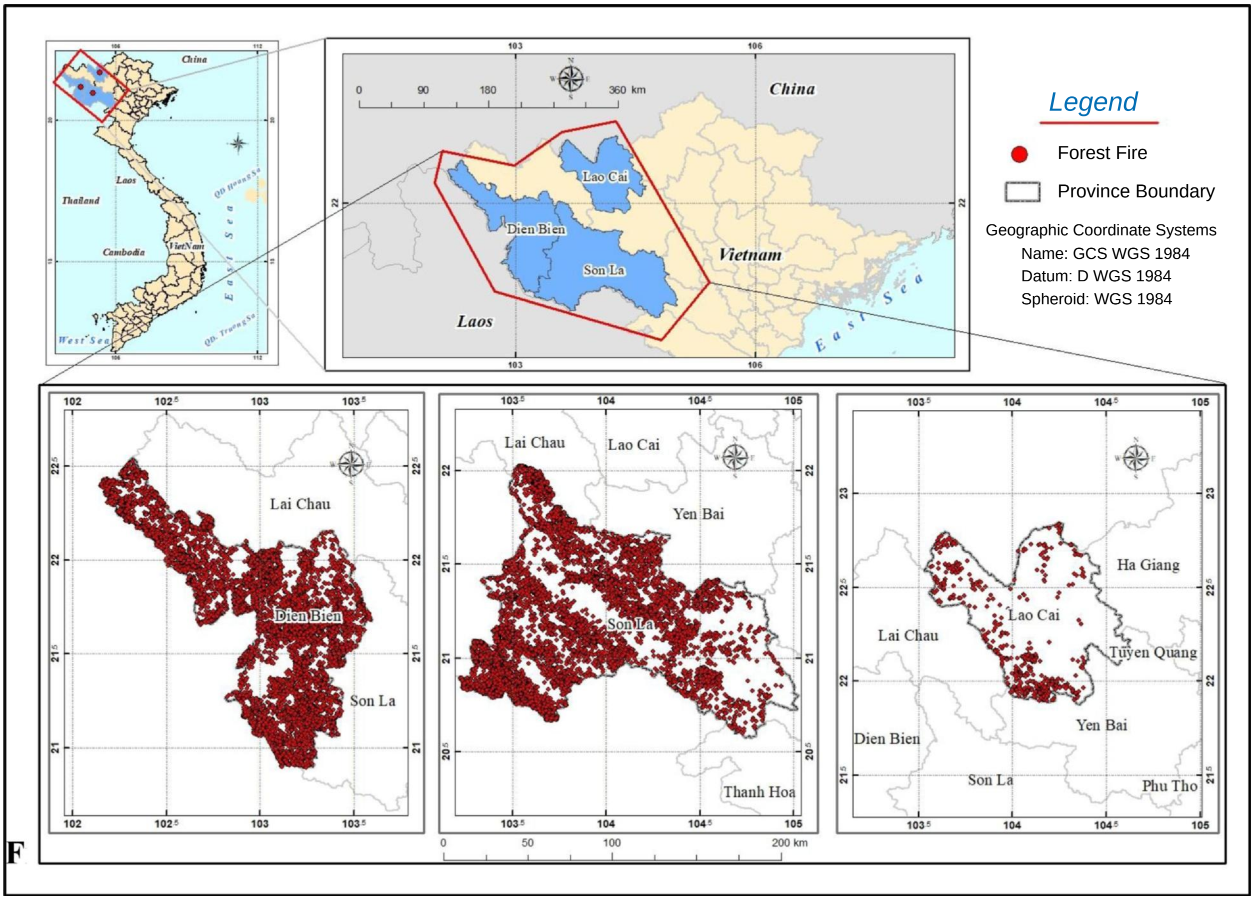

Fig. 1. The study region in northern Vietnam and forest fire occurrence (red dots) in the three selected provinces over the period 2003–2016 inclusive.

80 to 87%, and the region has approximately 12 days of frosts, and 40 days of foehn winds (dry and hot winds from the west) each year (Van 2015). Areas above 1400 m have a montane monsoon tropical climate (Averyanov *et al.* 2003), with later peak rainfall and a less extreme dry season.

We selected the three provinces based on number of fires available for analysis and climate. Dien Bien and Son La experience a monsoon tropical climate and had a high number of fires per year, while Lao Cai has a tropical montane monsoonal climate and had fewer fires. These provinces have tropical forest cover of >50% over diverse terrain (Ministry of Agriculture and Rural Development 2016). Forests of the region are of biodiversity importance and are protected by a national park (Hoang Lien, in Lao Cai) and seven nature reserves.

Fire dataset

We used the Global Fire Atlas dataset (Andela *et al.* 2019), which was developed from the Moderate Resolution Imaging Spectroradiometer (MODIS) burned area product (500-m resolution), to delineate and characterise individual fires over the period 2003–2016 inclusive. The Global Fire Atlas detects fires above a minimum size of 21 ha, given the resolution of the MODIS data it is based on (Andela *et al.* 2019). We used the locations and dates of the estimated ignition point of each fire in our analyses. Fires outside the study area or occurring in non-forested areas based on the forest map of Vietnam (Ministry of Agriculture and Rural Development 2009, 2016) were excluded; 5753 forest fires were included in the analyses (Dien Bien, $n = 2905$; Lao Cai, $n = 272$; Son La, $n = 2576$).

Explanatory variables

To understand the factors influencing fire occurrence, explanatory variables were assembled for four variable groups: weather, topography, fuel condition and human activity (Table 1). All spatial processing of datasets was conducted in ArcGIS (ESRI, Redlands, CA, USA).

Weather

Meteorological variables, including daily measurements of temperature, relative humidity, wind speed and

Table 1. Variables analysed to explain forest fire occurrence in northern Vietnam, including their description, source or reference for the primary data used and spatial data model.

Variables	Variable code	Description	Source or reference	Data model
Weather				
Temperature	Temp	Temperature for a given day at 1300 hours (°C)	Vietnam Meteorological and Hydrological Administration (2003–2016)	
Rainfall	Rain	Rainfall for a given day (mm)		
Relative humidity	RH	Relative humidity at 1300 hours for a given day (%)		
Wind speed	wind_speed	Wind speed at 1300 hours for a given day (km h^{-1})		
Modified Nesterov index	Nesterov_ index	Modified Nesterov index of a given day	Hung (1988) and Chau (2012*a*)	
Fuel condition				
EVI_ Amplitude	EVI2	Two-band Enhanced Vegetation Index (EVI2), Segment maximum – minimum EVI2 for a given vegetation growing cycle	Gray *et al.* (2019) https://lpdaac.usgs.gov/products/mcd12q2v006	Raster/500 m
Vegetation type	*Vege_ type_code*		Ministry of Agriculture and Rural Development (2009, 2016)	Polygon/ 1:100 000
Natural forest	1	Primary and secondary natural forests		
Plantation forest	2	Forests including planted species		
Mixed forest	3	Natural forests including bamboo and/or pine species		
Bamboo forest	4	Forests including only natural bamboo species		
Topography				
Elevation	Elevation	Elevation (m)	Ministry of Agriculture and Rural Development (2016)	Raster/30 m
Slope	Slope	Slope angle (°)		
Aspect	Southwestness	Southwestness is a cosine-transformation of aspect that ranges from −1 (northeast) to 1 (southwest)		
Human activity				
Population density	Population	People per km^2	https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11	Raster/1 km
Distance to nearest road	Road	Distance from forest fire occurrence or background point to the nearest road (m)	Ministry of Agriculture and Rural Development (2016)	Polyline/ 1:100 000

precipitation (Table 1), were obtained from the 11 weather stations within the study area for 2003–2016 (Vietnam Meteorological and Hydrological Administration 2003–2016). We also calculated the MNI (Eqn 1) (Hung 1988; Chau 2012*a*; Doanh and Quynh 2014; Quy *et al.* 2017) as a composite variable:

$$\mathrm{MNI}_i = K \sum_{i=1}^{n} t_i \times d_i \tag{1}$$

where $K = 1$ if daily precipitation < 5 mm, $K = 0$ if daily precipitation ≥ 5 mm, n is the number of consecutive days with daily precipitation < 5 mm and d_i is the air vapour pressure deficit, which is estimated from temperature (t_i) and relative humidity (RH_i) on day i (Hung 1988) (Eqn 2) as:

$$d_i = \frac{\frac{e^{\left(77.345 + 0.0057 \times (t_i + 273) - \frac{7235}{t_i + 273}\right)}}{(t_i + 270)^{8.2}} \times (1 - RH_i)}{100} \tag{2}$$

Topography

We included three topographic variables: elevation, aspect and slope, generated using forest inventory maps of the Ministry of Agriculture and Rural Development (2016). The elevation layer of those maps (30-m resolution) was derived from the Shuttle Radar Topography Mission dataset (Rabus *et al.* 2003; Mota *et al.* 2019; Hung *et al.* 2021). This was scaled to the 500-m resolution of the MODIS fire data using nearest-neighbour resampling, and then used for calculating the slope and aspect. The aspect (α, in degrees) was converted into a southwestness index (Eqn 3):

$$\text{Southwestness} = -1 \times \cos(\text{radians}(\alpha - 45)) \quad (3)$$

Southwestness has values between −1 and 1, indicating the degree to which a slope faces southwest, receiving the greatest potential insolation (Franklin *et al.* 2000; Khatchikian *et al.* 2011).

Fuel condition

A remotely sensed vegetation index was used as a proxy for fuel abundance prior to the fire. Among vegetation indices calculated from satellite imagery, the Enhanced Vegetation Index (EVI) was developed to have improved sensitivity in high-biomass regions (Huete *et al.* 1994; Huete 1997) and has been found to be better correlated with fuel moisture and fuel load than other vegetation indices (Roberts *et al.* 2006; Myoung *et al.* 2018). This index has been updated with the two-band EVI (EVI2), which is less susceptible to saturation with biomass (Jiang *et al.* 2008; Liu *et al.* 2012; Shang *et al.* 2014) and has been used as an indicator of fuel condition favouring fire occurrence (Burapapol and Nagasawa 2016).

In this study, we used estimates of EVI2 summarised over the year before fire occurrence from the MODIS Land Cover Dynamics Product, which estimates characteristics of the EVI2 time series for annual and sub-annual growing cycles (MCD12Q2 Collection 6; (Gray *et al.* 2019)). The range of EVI2 values in a given growing cycle was used as an index of the new production of leaves in the year before fire, and thus the availability of fuel to the fire.

We included the vegetation type where each fire occurred as an additional variable, based on the forest inventory map (Ministry of Agriculture and Rural Development 2016). Forest types were aggregated into four categories (Table 1): closed canopy natural forest including primary and secondary forests (covering 41% of the study area), plantation forest (4%), mixed forest (6%) and bamboo forest (1%).

Human activity

Two variables, population density and distance to nearest road, represented human activity (Table 1). Population density has been correlated positively with potential forest fire occurrence elsewhere (Kwak *et al.* 2012; Matin *et al.* 2017; Ma *et al.* 2020) with human activities now responsible for most fires (de Vasconcelos *et al.* 2013), while roads may act as fire-breaks, and allow improved access for fire suppression but also a source of additional ignitions (Renard *et al.* 2012). Gridded population estimates were extracted from the gridded population of the world dataset (Center for International Earth Science Information Network Columbia University 2016), which provided estimated population count and density at approximately 1-km resolution. The road map was extracted from the digital map of the Ministry of Agriculture and Rural Development (2016), from which a raster distance surface was calculated at 500-m resolution.

Statistical approach

We first conducted descriptive analyses of fire occurrence, exploring intra- and inter-annual patterns in the number of fires and their relationships to weather variables. We used logistic regression to test univariate effects of the predictor variables on fire occurrence. In addition, we evaluated if fire activity differed between forest types using chi-squared analyses of the number of fires, and inspection of the fire size distributions to evaluate differences in burned area. Fire size distributions were skewed to small fires and not well described by typical statistical summaries (e.g. mean). Therefore, a power law distribution was fitted to the observed fire sizes by maximum likelihood using R code found in Clauset *et al.* (2009) and the exponent of the power law distribution was used to compare the distribution of fire size between forest types.

Multivariate Maximum Entropy (Maxent) models were then developed to predict the occurrence of fires and assess the relative importance of the explanatory variables (Table 1). Models were developed using the Maxent software (version 3.4.1, Phillips *et al.* 2020) and were constructed for each province individually and for all three provinces combined. Maxent (Phillips *et al.* 2006) is one of the best-performing approaches to predict species distributions in ecological studies (Elith *et al.* 2006). However, it can be applied to predict the spatial distribution of any phenomenon (e.g. fire: Parisien and Moritz (2009)), or to predict distributions across space and time in response to dynamic environmental conditions (e.g. species: Andrew and Fox (2020); Stoetzel *et al.* (2020); fire: Chen *et al.* (2015)). To do so, Maxent fits the relationships between the modelling target, e.g. fire, and the explanatory variables and projects these across geographic space and/or time. Thus, it can be used to evaluate the effect and the importance of each predictor variable on the occurrence of fire.

Maxent requires samples of fire occurrences and background points to predict fire occurrence. Fire occurrences were represented with the ignition points from the Global Fire Atlas dataset. The background points were a random sample of 8630 points (~1.5 × the number of fire points) within the forested portion of the study area, generated within ArcGIS. Background sample sizes by province were 2416, 2244 and 3970 for Dien Bien, Lao Cai and Son La, respectively, and these were aggregated for the combined provinces model. Each background point was assigned a date randomly sampled from the dates of the fires. Values for explanatory variables were assigned to each fire and background point based on their location, year (EVI2) and date (weather variables) of occurrence. Because the weather dataset did not have continuous spatial coverage, points were assigned observations of daily weather variables from the nearest weather station. Correlations between explanatory variables were low for the sample of points (all Spearman $r < 0.75$); thus, all variables were included in the model (Siljander 2009).

Maxent was run in 'samples with data' mode using default settings for the maximum number of iterations (500) and convergence threshold (0.00001), which are used to determine when to stop iteratively fitting the model. Fire points were randomly subsampled, with 75% for training and the remaining 25% for testing. This was repeated 15 times, with the results of the replicates averaged. Model performance was assessed on the test set using the area under the receiver operating characteristic curve (AUC; Fielding and Bell 1997; Elith *et al.* 2006). AUC ranges from 0 to 1, with values >0.7 generally indicating reasonable performance, and a value of 0.5 indicating performance no better than random (Elith 2000; Elith *et al.* 2006).

To limit model complexity, the regularisation multiplier was set at 2, 4, 2 and 2 for the models of Dien Bien, Lao Cai, Son La and combined provinces, respectively. These values were selected by comparing model performance when evaluated on the training and test datasets (Supplementary Table S1); a large reduction from training to test AUC suggests that the model is too complex and is overfitted to the training data. Lao Cai, which had the fewest fire occurrences, supported the lowest model complexity. Default feature types (linear, quadratic, product and hinge features) were allowed to the model, to give it flexibility to fit a variety of functional forms of the relationship between the predictor variables and the occurrence of fire. Although the hinge feature type can sometimes result in overfitted models that identify unrealistic relationships, this was effectively mitigated by limiting the complexity of the models with the regularisation multipliers described above.

The importance of each variable to predicting fire occurrence was determined by randomly permuting the values of that variable among the training points (both presence and background) and measuring the resulting decrease in training AUC, normalised to percentages (Phillips 2005). A large reduction indicates that the model depends strongly on that variable. Marginal response curves were also produced to illustrate the relationship between the probability of fire occurrence and each environmental variable when controlling for all other variables.

The spatial predictions of the individual-province Maxent models were mapped for three illustrative days with high (MNI > 2500), moderate ($1000 <$ MNI < 2500) and low (MNI < 1000) fire danger in each province. All spatial variables were aligned to 500-m resolution using nearest-neighbour resampling. Weather data were spatialised by delineating a Thiessen polygon tessellation around the weather stations, assigning each polygon the daily weather measurements from the weather station it contains, and rasterising these values to the analysis resolution. This corresponds to assigning each pixel the observations from the nearest weather station, consistent with how fire and background points were attributed with weather data for model development.

Results

Forest fire occurrence varied markedly over 2003–2016, being highest in 2007 (826 fires), and lowest in 2008 and 2011 (57 and 67 fires, respectively) (Fig. 2*a*). Almost all fires occurred in the dry season, especially February–April, when MNI was higher and humidity, temperature and rainfall were lower, than in months with fewer fires (Fig. 2*b*). There were generally few fires per day, but there was a tendency for more fires to burn on days with higher MNI values (linear regression: $R^2 = 0.15$, $P < 0.05$; Fig. 3).

Most fires (nearly 5000; 85%) occurred in natural forest, followed by mixed forest. Fire was infrequent in plantation and bamboo forests, with fewer than 100 fires each (Table 2). Fires were more frequent in natural forest than expected given the area occupied by this forest type (Chi-squared $P < 0.05$), except in Son La where fires were relatively more frequent in mixed forests (Table 2). Fire was much less frequent than expected in plantation forest in all provinces, and in bamboo forests in Dien Bien and Lao Cai (Table 2).

Most fires were small (average size 111 ha). Average fire size was lowest for bamboo forest (48 ha) and highest for plantation forest (141 ha); the largest fire occurred in mixed forest (11 900 ha). Fire sizes followed a power law distribution in all forest types (Kolmogorov–Smirnov $P > 0.05$; Fig. 4). The decline in the cumulative abundance of fires with increasing fire size was steepest for bamboo forest, indicating a greater dominance of small fires (power law exponent $\gamma = 4.02$), and most gradual for plantation forest, indicating a greater proportion of larger fires ($\gamma = 1.73$) (Fig. 4).

Maxent models

Maxent models generally performed well at predicting the occurrence of fire in space and time based on weather, topography, vegetation and anthropogenic variables, with AUC values of 0.7, 0.67, 0.79 and 0.73 for the combined provinces, Dien Bien, Lao Cai, and Son La models, respectively.

The relative contributions of explanatory variables differed between provinces (Table 3). In Dien Bien, variable importance was reasonably balanced between the top

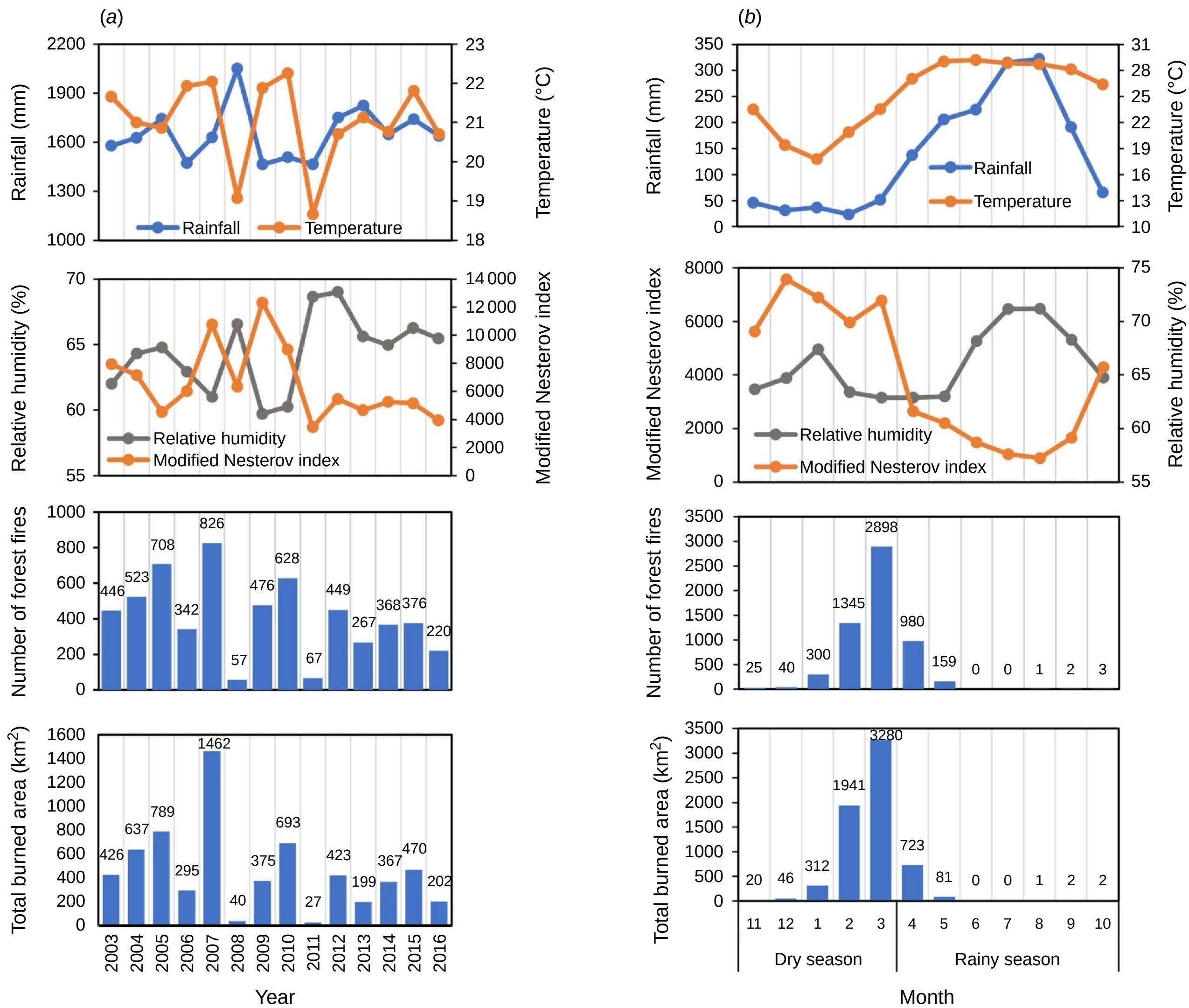

Fig. 2. Yearly (*a*), and monthly (*b*) number of forest fires and total burned area in relation to average weather conditions across 2003–2016 inclusive for the 11 selected weather stations in the three studied provinces, northern Vietnam. Panel (*a*) shows annual rainfall and average dry season values for daily (1300 hours) temperature, relative humidity and Modified Nesterov index. Panel (*b*) shows mean monthly values for the same climate variables.

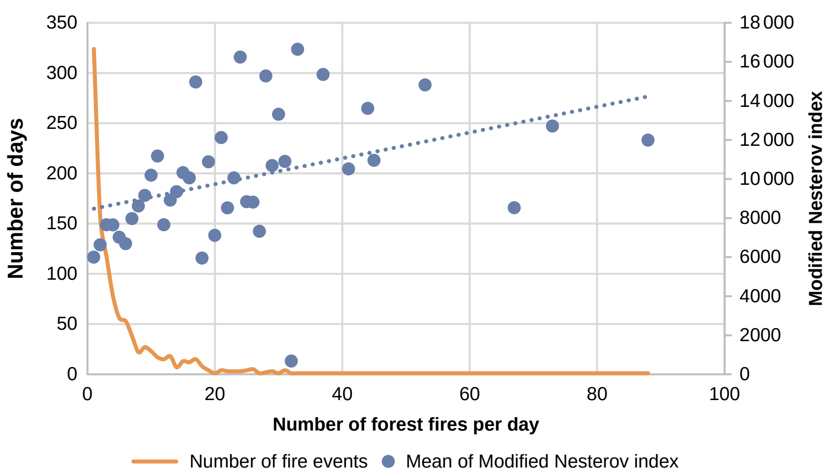

Fig. 3. Relationship between number of forest fires per day and average Modified Nesterov index for all days with a given number of fires in Dien Bien, Lao Cai and Son La provinces, northern Vietnam, from 2003 to 2016 inclusive (number of fires per day also shown). Linear regression line of best fit is also shown (dotted line).

Table 2. Chi-squared (χ^2) tests for the relationship between frequency of fire occurrence (No. of fires, % fires) and area occupied by each vegetation type (% area), for individual and combined provinces, northern Vietnam.

Province	χ^2	d.f.	P	Forest type	No. of fires	% fires	% area
Combined provinces	423.2	3	$<2.2 \times 10^{-16}$	Natural forest	4928	85.7	77.9
				Plantation forest	97	1.7	9.9
				Mixed forest	667	11.6	9.7
				Bamboo forest	61	1.1	2.5
				Total	5753	100	100
Dien Bien	371.2	3	$<2.2 \times 10^{-16}$	Natural forest	2786	95.9	79.2
				Plantation forest	38	1.3	9.0
				Mixed forest	80	2.8	9.6
				Bamboo forest	1	0.0	2.2
				Total	2905	100	100
Lao Cai	30.4	3	1.1×10^{-16}	Natural forest	250	91.9	77.6
				Plantation forest	9	3.3	10.2
				Mixed forest	11	4.0	9.5
				Bamboo forest	2	0.7	2.7
				Total	272	100	100
Son La	317.7	3	$<2.2 \times 10^{-16}$	Natural forest	1892	73.4	77.3
				Plantation forest	50	1.9	10.2
				Mixed forest	576	22.4	10.0
				Bamboo forest	58	2.3	2.5
				Total	2576	100	100

variables; elevation was most important, followed by population, temperature, MNI and vegetation type. In Lao Cai, elevation was again the strongest driver, with 2–3 times greater importance than MNI, distance to road and relative humidity. In Son La, distance to road was the only important driver of fire. The combined provinces model integrated these patterns, finding similar importance of temperature, distance to road, elevation and MNI (Table 3). The remaining variables were never important for predicting fire occurrence (Table 3).

Generally, fire was related positively to temperature, MNI, elevation and slope, and negatively to relative humidity and population density in the univariate analyses (Supplementary Table S2). However, Maxent models found plateauing effects of MNI, and peaked effects of elevation (unimodal at mid-elevations) in Dien Bien and combined provinces (Fig. 5). Distance to road had mixed effects on fire occurrence, being negative in Lao Cai, and peaked in Son La and the combined provinces model (Fig. 5).

Mapped predictions of forest fire occurrence on selected days with contrasting MNI from the individual-province models reveal that the locations of high fire risk vary temporally (Fig. 6, Supplementary Table S3). Between provinces, the probability of fire was lowest in Lao Cai, especially on the days with medium and high MNI; it was low everywhere on the day with low MNI (Fig. 6*c*). On the day with high MNI, moderate fire risk was widespread throughout Dien Bien and Son La, with scattered patches of high predicted fire risk in central Lao Cai and Son La (Fig. 6*a*). On the medium MNI day, areas with moderate fire risk in Dien Bien contracted to the west and were more restricted topographically; in Son La, fire risk was more heterogeneously distributed than on the high MNI day, with prominent patches of especially high fire risk in the centre of the province related to low elevation and high population density; fire risk was evenly low across Lao Cai (Fig. 6*b*).

Discussion

Occurrence of forest fire in northern Vietnam

Most forest fires in northern Vietnam during 2003–2016 occurred in the late dry season (February–March) and the first month of the wet season (April), with 50% of all forest

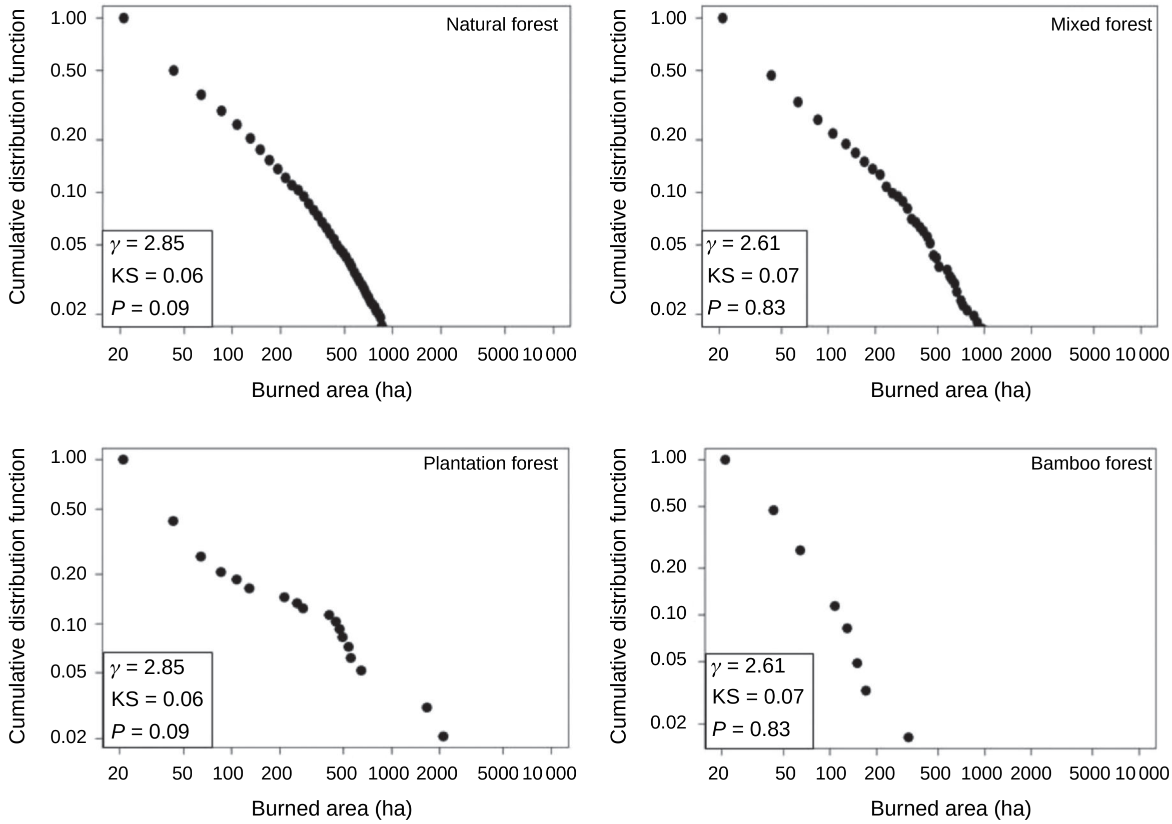

Fig. 4. Power law distributions of fire size by forest type in Dien Bien, Lao Cai and Son La province, northern Vietnam, from 2003 to 2016 inclusive (γ: exponent, KS: Kolmogorov–Smirnov test, *P*: *P* value).

fires in March alone. During this time, temperatures are cool (average temperature 21°C) but low rainfall over the preceding months and low humidity lead to higher daily MNI than at other times of year (Vietnam Meteorological and Hydrological Administration 2003–2016) (Fig. 2*b*). Although the dry season starts in November, the 2-month lag before most forest fires occur is likely due to fuel condition, with live and dead vegetation still containing high levels of moisture early in the dry season. The abundance of fires in April may also be related to fuel moisture and rainfall, with fuels at their driest before the onset of the new wet season, which varies between years. In any given year, part of April may provide similar fire conditions to March. In our study period, wet season onset (defined as the first day receiving >5 mm rain) was generally in the first week of April, but average daily rainfall on onset dates and throughout April was low (<7 mm).

Fire occurrence also varied among years (Fig. 2*a*), likely owing to inter-annual climate variability. The greatest fire activity occurred following an El Niño event from September 2006 to January 2007 that resulted in warm, dry conditions in northern Vietnam; the 2007 dry season was warmer, received less rainfall and had lower humidity than the 2003–2016 average. La Niña events impacted northern Vietnam from August 2007 to June 2008 and mid-2010 to May 2011, resulting in colder, wetter conditions (Boening *et al.* 2012; Gobin *et al.* 2016) and low fire activity (Fig. 2*a*). The La Niña dry season in 2008 was colder, received more rainfall, and humidity was higher relative to 2003–2016 averages (Vietnam Meteorological and Hydrological Administration 2003–2016).

Fire frequency was higher than expected in natural forest given the proportion of land area (77.9% of total land area vs 85.7% of total fires) and was lower than expected in plantation (9.9% area vs 1.7% fires) and bamboo forests (2.5% area vs 1.1% fires; Table 2) over the study period (Ministry of Agriculture and Rural Development 2016). Most plantation and bamboo forests occur near villages, and at lower elevations (Sam *et al.* 2000; Nghia 2006; FAO 2009; Cochard *et al.* 2017; Cuong *et al.* 2020). They are often actively protected from fire, with fuel loads reduced through weeding, collection of fuelwood (Nambiar *et al.* 2015) and regular harvesting in the case of bamboo forest (Nghia 2006; Lobovikov *et al.* 2007; Trang and Hoi 2009). Additionally, bamboo forests tend to occur in moist locations with low fire risk, such as in valleys and along river banks in lowland moist tropical forests or lower montane forests (e.g. *Bambusa, Dendrocalamus, Gigantochloa, Schizostachyum*) (Soderstrom and Calderón 1979; Judziewicz *et al.* 1999; Nghia 2006) or in higher

Table 3. The permutation importance of explanatory variables to the best fit Maxent model for each province and for combined provinces, northern Vietnam. The summed importance of all variables within each variable group is also presented (bold italics).

Variable	Dien Bien	Lao Cai	Son La	Combined provinces
Weather condition	***34.5***	***38***	***13.4***	***47.7***
Modified Nesterov index	14.5	17.3	7.1	14.4
Temperature	19	3.1	5.8	26.1
Rainfall	0.2	0.1	0	0.2
Relative humidity	0.7	12.3	0.2	2.4
Wind speed	0.1	5.2	0.3	4.6
Fuel	***13.2***	***0.9***	***5.6***	***6.9***
Vegetation type	12.1	0.6	2.9	6.4
EVI2	1.1	0.3	2.7	0.5
Topography	***25.6***	***45.3***	***4.9***	***18.1***
Elevation	25.4	42.1	4.6	17.7
Slope	0.2	0.8	0	0.1
Southwestness	0	2.4	0.3	0.3
Anthropogenic	***26.7***	***15.7***	***76.1***	***27.3***
Population	20.5	2.6	0.2	7.1
Distance to nearest road	6.2	13.1	75.9	20.2

montane systems with high precipitation and humidity (e.g. *Chimonobambusa, Indosasa, Arundinaria*) (Soderstrom and Calderón 1979; Judziewicz and Clark 2007; Clark *et al.* 2015; Yakubu *et al.* 2015).

The fire size distributions give greater understanding of differences in flammability and management between forest types. Higher values of the exponent of the power law distribution correspond to increasing dominance by small fires, with values of 2 used as a threshold between disturbance regimes characterised by diffuse, small events, such as observed here for natural forests, and larger disturbances (Fisher *et al.* 2008). However, although fire was less frequent in plantation forests, fires were larger and followed a different size distribution (exponent $\gamma < 2$) that may be due to different stand attributes and management regimes. The dominant plantation species (e.g. *Pinus, Eucalyptus*) are highly flammable owing to high content of essential oils (Peña-Fernández and Valenzuela-Palma 2005; Hirschberger 2016; Tumino *et al.* 2019). Also, these forest types typically have a more open canopy layer than rainforests, leading to lower relative humidity, higher understorey density (Lemenih *et al.* 2004), and increased surface fuel load and dryness (Jimu and Nyakudya 2018), creating favourable conditions for fire (Pauchard *et al.* 2008). In all other forest types, fires tended to be small ($\gamma > 2$). Fires in bamboo forests were most extremely skewed to small sizes ($\gamma = 4.02$), underscoring their low flammability habitat circumstances (Fig. 4).

Drivers of forest fire in northern Vietnam

Identifying the driving factors and understanding their contributions to fire occurrence are essential for forest fire management (Avila-Flores *et al.* 2010). Our Maxent models found that all groups of variables tested – weather, topography, fuel condition and anthropogenic factors – could have a strong influence on forest fire occurrence in northern Vietnam, but their contribution varied among provinces. MNI, temperature, elevation and distance to road were consistently important in explaining forest fire occurrence, while other variables were only occasionally (population, relative humidity, vegetation type) or never important (daily rainfall, wind speed, EVI2, slope, aspect). This is consistent with other recent studies of tropical and sub-tropical forest fire occurrence, which found meteorological (especially temperature) and human drivers to be most important (Guo *et al.* 2017; Su *et al.* 2019; Su *et al.* 2021). The low individual importance of rainfall and relative humidity in our models is likely because they are already, and more effectively, quantified within the MNI fire danger rating measure, and because they have low variance during the dry season period when nearly all fires occur. However, temperature shows a strong effect separate from its contribution in the MNI, which may be worthy of further exploration in terms of potential future refinements of this FDRS index.

For combined provinces, weather conditions, especially temperature and MNI, were collectively much more important than other factors in explaining fire occurrence. This suggests weather is the most important driver over larger regional scales, consistent with previous work (Schulte *et al.* 2005; Parisien and Moritz 2009; Viganó *et al.* 2018), especially Renard *et al.* (2012) who contrasted regional and local models of fire occurrence in the Western Ghats, India. Weather was also slightly more important in Dien Bien, where drivers of fire occurrence were reasonably balanced between weather, topography and anthropogenic factors. Dien Bien is hotter than the other provinces owing to the stronger presence of hot, dry foehn winds (Vietnam Meteorological and Hydrological Administration 2003–2016; Van 2015). We found fire to be associated with higher MNI and temperatures in both of these models (Fig. 5), as expected from their impacts on fuel moisture (Fried *et al.* 2008; Sullivan *et al.* 2012; Chang *et al.* 2013; Corlett 2016; Holsinger *et al.* 2016).

In Lao Cai, topography was the dominant driver of fire occurrence, with secondary influences of weather. Lao Cai is the most mountainous of the provinces studied, with mountain ranges exceeding 2000 m including Vietnam's highest

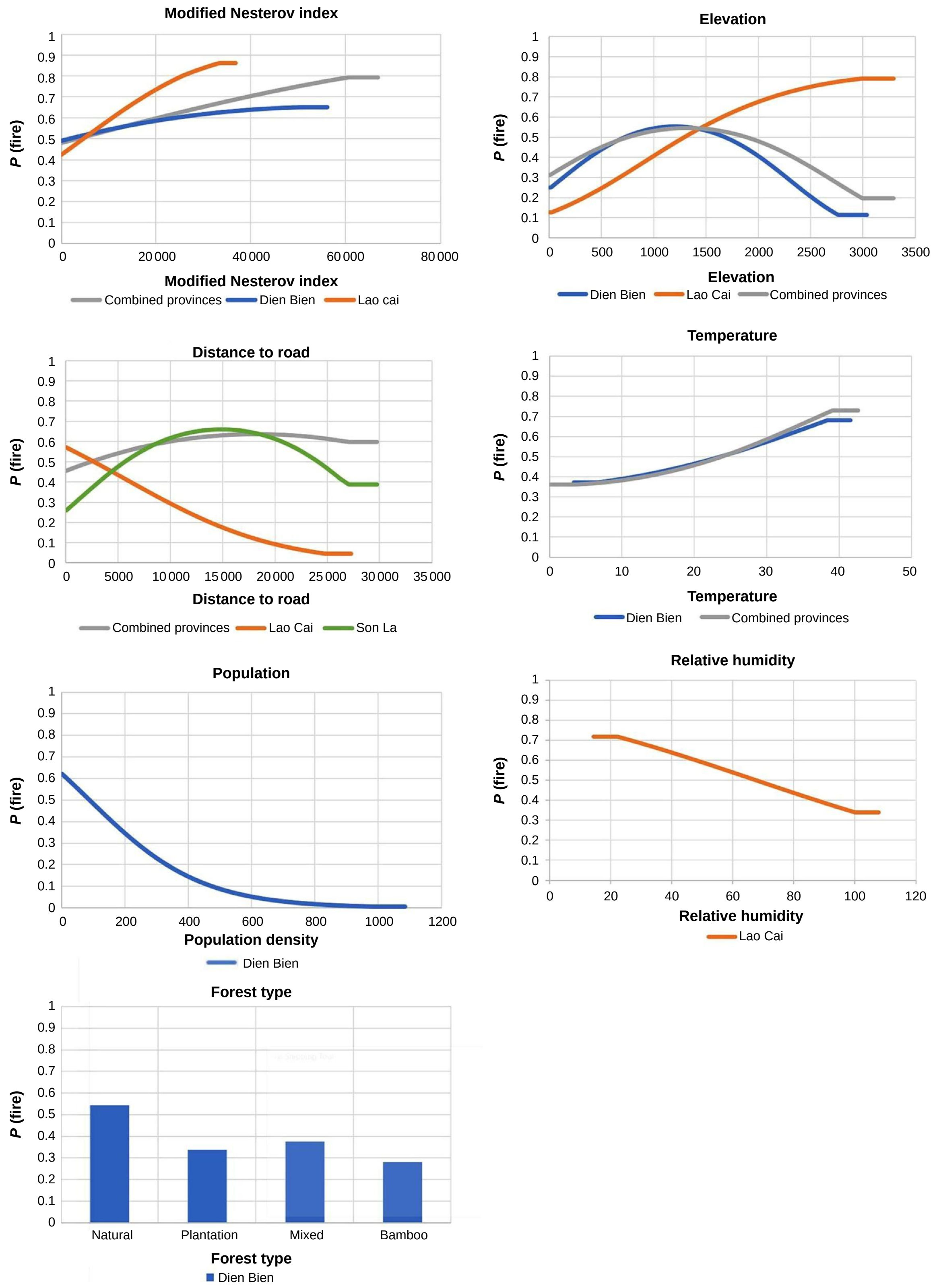

Fig. 5. Relationship between key driver variables – showing above-average permutation importance >8% in Maxent models – and fire occurrence in Dien Bien, Lao Cai, Son La and combined provinces, northern Vietnam.

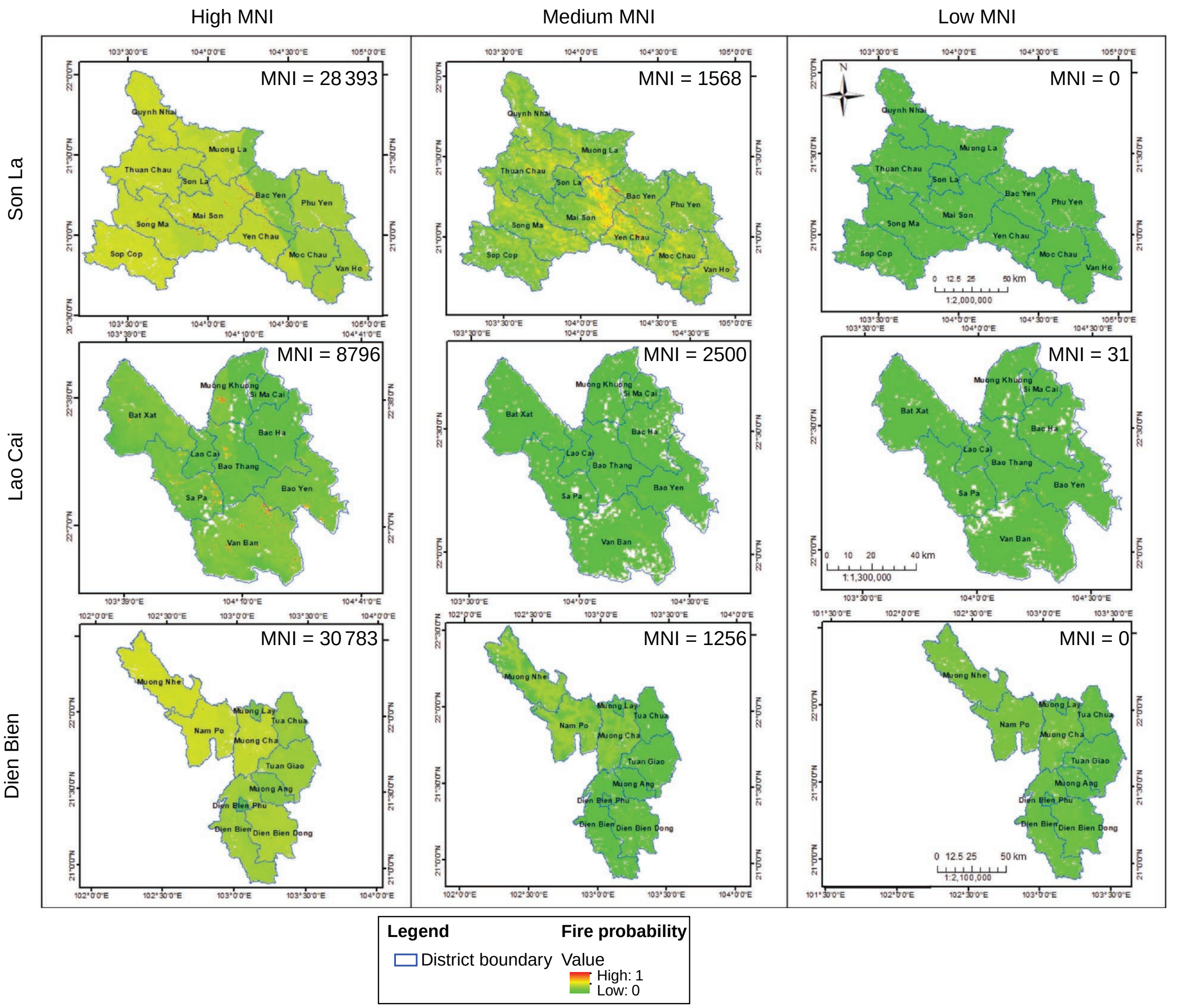

Fig. 6. Spatial pattern of the probability of fire from individual province Maxent models for sample days with (*a*) high MNI (>2500), (*b*) medium MNI (1000–2500), and (*c*) low MNI (<1000) for Dien Bien, Lao Cai and Son La provinces, northern Vietnam.

peak (Fansipan, 3143 m), steep slopes, strongly fragmented terrain and a strong gradient between mountain and lowland areas (Lao Cai Provincial Working Group 2002). Elevation was the only important topographic variable in explaining fire occurrence (Table 3), and it was one of the most consistently important variables of any category, although its effect differed between provinces. Most forest fires occurred at 500–1500 m elevation in Dien Bien and the study area as a whole (Fig. 5), where most natural forests with greater continuous extent are located (Averyanov *et al.* 2003; Phuong *et al.* 2012; Ministry of Agriculture and Rural Development 2016). In contrast, in Lao Cai, natural forest area and fire occurrence (Fig. 5) both increased with elevation. However, because our background was sampled from forested areas, associations of fire with elevation cannot be explained by the elevation distribution of forest alone. Elevation influences all proximate fire drivers, with effects on vegetation composition, water availability, fuel condition (Castro and Chuvieco 1998) and weather (McCutchan and Fox 1986). Other studies in the tropics have also found increased fire occurrence at higher elevation, most likely due to increased solar radiation and lightning incidence (de Bem *et al.* 2019; Su *et al.* 2021).

In Son La, anthropogenic factors were the strongest drivers of fire occurrence, especially distance to road (Table 3). Son La has approximately twice the population of the other provinces (General Statistics office of Vietnam 2019). We found divergent associations of fire with roads between provinces, with fires more likely beyond 5 km from roads in Son La, but within 5 km of roads for Lao Cai. The combined provinces model synthesised these patterns, finding a unimodal response to road distance. Most human activities causing forest fires in Vietnam result from slash and burn farming, use of fire for hunting and trapping wildlife and harvesting honey, and activities related to use of forest products, e.g. cooking and smoking (Hoang 2007; Vien 2014). These activities are often undertaken in natural forests away from towns and villages, but require access, such as by roads. However, roads can be fire breaks and provide access for fire detection and suppression (Renard *et al.* 2012). Our findings support the occurrence of fires away from populated areas (in Dien Bien) and the diverse mechanisms relating fire to roads. In Son La, which had more fires than Lao Cai and greater importance of roads, fires tended not to occur along roads, suggesting fire suppression in accessible locations. This interpretation is supported by previous studies in Asia that have found fires to be more likely farther from roads (Chang *et al.* 2013; Sumarga 2017).

Fire danger rating systems

In Vietnam, the Nesterov index, modified for local conditions, has been used since the 1980s to indicate forest fire danger. MNI is based on weather conditions only, and does not include other factors impacting fire occurrence and spread such as fuel condition, topography and ignition sources (Chau 2012*b*; Doanh and Bao 2014; Vien 2014; Hoan 2018). Use of the MNI is consistent with most widely used FDRSs elsewhere, such as the Canadian Forest FDRS (Van Wagner 1987; Taylor and Alexander 2006), the National FDRS of the USA (Deeming *et al.* 1977) and the Forest Fire Danger Index of Australia (Noble *et al.* 1980). However, although these systems only explicitly include weather conditions, the effects of additional factors such as fuel condition and slope are incorporated into fire behaviour prediction and fire management planning.

Our findings suggest that the MNI is a useful measure for predicting fire danger conditions for forest areas in northern Vietnam but that incorporation of other variables, including anthropogenic, fuel and topographic factors provides a better overall model for predicting forest fire occurrence (Supplementary Fig. S1 shows jackknife measures of variable importance comparing the performance of full models with those using e.g. only MNI). Therefore, this study recommends that important factors beyond weather should be considered to improve the prediction of, response to and education about forest fire occurrence in Vietnam. Topographic and anthropogenic variables were also important and can be obtained easily from digital elevation maps or proxied by remotely sensed data to augment the current FDRS. Fuel conditions are also known to be important, but the fuel variables used in this study showed low importance in all models, possibly because they are indirectly related to the fuel characteristics important to fire occurrence and spread and are not measured at the spatial or temporal scales most relevant to their effects on fire, or because fuel load is not a critical driver of fire in these forests (with all forested areas likely to have sufficient fuel to carry a fire if other conditions are conducive to fire occurrence).

Conclusion

This study provides an improved understanding of patterns of wildfire occurrence in the forests of northern Vietnam through a range of descriptive and quantitative analyses. Generally, the most fire-prone period was the mid-dry season to onset of the wet season, corresponding to February–April. Forest fires occurred mostly in natural forest while they rarely occurred, but tended to be larger, in plantation forests.

Maxent models showed good performance in explaining fire occurrence and identifying its drivers, including weather conditions, fuel, anthropogenic and topographic variables, but found the relative importance of these drivers depended on extent (local vs regional) and the position of each province on these gradients. The findings of these models, including the mapped results, can assist managers and decision-makers to build forest fire management plans adjusted to each province's fire conditions. For instance, forest fire managers and authorities can prioritise areas close to roads at high elevation in Lao Cai, mid-elevation areas with low population density in Dien Bien, and forests distant from roads in Son La for efficient prevention measures to reduce forest fire risk on days with high and moderate MNI in the late dry season to early wet season. Results from our study show that while MNI is a significant predictor of high fire danger days, spatial (Maxent) model analyses provide additional understanding of where fire danger is highest on such high-MNI days. We recommend that this improved understanding of fire occurrence be used to guide education about fire and planning for fire mitigation and suppression in Vietnam.

This study has developed statistical models of fire occurrence that may support improved management in tropical forests in Vietnam and other countries with comparable climate and vegetation. However, further research is needed to assess other aspects of fire regimes such as fire size, severity and impacts, and social factors influencing ignitions, as well as the effectiveness of fire prevention strategies to support forest fire management in Vietnam.

Supplementary material

Supplementary material is available online.

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Data availability. The data that support this study will be shared on reasonable request to the corresponding author.

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