Universität für Bodenkultur Wien
University of Natural Resources
and Applied Life Sciences, Vienna

Ugyen Wangchuck Institute for Conservation and Environmental Research
Department of Forests and Park Services
Ministry of Agriculture and Forests
ROYAL GOVERNMENT OF BHUTAN

The UNIVERSITY of VERMONT

Climate change effects on wildfire hazard in the wildland-urban interface – blue pine forests in the Himalayas

- *Final research paper Marshall Plan* –

Submitted by:

Lena Vilà Vilardell

Master of Science in Mountain Forestry, University of Natural Resources and Life Sciences, Vienna, Austria.

Supervisor:

William S. Keeton, Prof. The Rubenstein School of Environment and Natural Resources, The University of Vermont, Vermont, USA.

Co-supervisors:

Georg Gratzer, Ao.Univ.Prof. Dipl.-Ing. Dr.nat.techn. Institute of Forest Ecology, University of Natural Resources and Life Sciences, Vienna, Austria.

Dominik Thom, Dr. The Rubenstein School of Environment and Natural Resources, The University of Vermont, Vermont, USA.

ABSTRACT

Wildfires play an important role in blue pine *(Pinus wallichiana*) forest ecosystems in Bhutan. Forest fires are considered one of the biggest threats to forest resources availability in the country, and blue pine ecosystems are highly susceptible to fires. Due to the social and geographical characteristics of Bhutan, the region is very sensitive to climate change and prone to suffer its effects. With the expected increase in wildfire impacts on blue pine forest ecosystems due to climate change, a tool to assess fire hazard would represent a major step towards better and more precise fire management strategies in Bhutan. This paper analyzes fire hazard in the wildland-urban interface of two valleys of Bhutan – Thimphu and Jakar-, surrounded by blue pine forests. We applied FlamMap, a spatially-explicit wildfire simulation model, to simulate fire behavior and growth in blue pine ecosystems under four climate scenarios. Climate scenarios were built based on climate change projections in the Himalayas, and symbolize scenarios of monsoon failure and warmer temperatures. The output indicators of FlamMap for assessing fire behavior and growth were flame length, rate of spread, crown fire activity, burn probability and fire size. Our results indicate a two-fold increase in fire hazard in the wildland-urban interface of both valleys due to climate change. Thimphu has on average higher potential fire behavior and growth than Jakar. To determine the most susceptible areas to forest fires, we created a fire hazard map by integrating the fire behavior and growth indicators into a common fire hazard index. Results of this study can be used to more precisely allocate fire management resources in the wildland-urban interface and plan suburban development.

Keywords: forest fire, blue pine, *Pinus wallichiana*, fire hazard, fire behavior, fire simulation, FlamMap, climate change, Bhutan, Himalaya.

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Acronyms

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CBD	Canopy bulk density
CBH	Canopy base height
CF	Community Forest
CFL	Canopy fuel load
CWD	Coarse woody debris
DBH	Diameter at breast height
DEM	Digital Elevation Model
DoFPS	Department of Forests and Park Service of Bhutan
EMC	Equilibrium moisture content
ENSO	El Niño-Southern Oscillation
FBFM	Fire behavior fuel model
FMC	Fuel moisture content
FWD	Fine woody debris
RH	Relative humidity
SAV	Surface area-to-volume ratio
T	Temperature

1 INTRODUCTION

Natural disturbances play a central role in ecosystem dynamics, shaping vegetation distribution, structure and composition, both at different spatial and temporal scales. The potential that climate change and the increasing anthropogenic pressure on natural resources have to alter natural disturbances frequency and severity as well as disturbance drivers has long been studied (Seidl et al., 2011). Mountainous regions are especially susceptible to climate change – in the Himalayas a retreat of glaciers has already been reported. Cascading effects due to climate change in the Himalayas will affect water availability, biodiversity, global feedbacks (as monsoon shifts and reduction of carbon storage) and local livelihoods (Xu et al., 2009).

As all natural disturbances, wildfires can alter significantly the ecosystem, affecting vegetation composition and distribution and wildlife habitat, and can become a danger for people and assets. Yet, it is the only natural disturbance that can be directly caused by humans. In Bhutan almost all forest fires are human-caused (Chhetri, 1994). Disturbances become a risk for people when they affect socio-economic values (Scott et al., 2013; Chuvieco et al., 2010; Finney, 2005), thus the wildland-urban interface is amongst the most vulnerable areas for people to disturbances (Keeton et al., 2007).

To allocate functional and optimal fuel treatments for fire risk reduction as well as planning good suburban development it is necessary to understand the potential behavior of fire, when it is more likely to occur and the areas where it might cause greater damage (Chuvieco et al., 2010).

In this paper fire hazard is defined as the physical properties of wildfire, i.e. fire behavior and growth indicators (Scott et al., 2013; Finney, 2005) – through flame length, rate of spread, fire crown activity, burn probability and fire size-. Fire risk includes fire effects (Finney, 2005), i.e. the potential of fire to damage socio-economic values; nonetheless it is not analyzed in this study.

Bhutan is a small landlocked country of 38.394 square kilometers (NSB, 2013), mostly mountainous – elevations from 160 meters to more than 7.000 meters above sea level- and highly forested – total forest cover is 70,46% (NSSC, 2011)-. Most of the population work on their own land and relatively few have regular wages (23,9%). The forestry and agriculture sector plays a critical role in the household's economy, employing a 62,2% of the active population, from which two thirds are women (NSB, 2013). Webb and Dorji (2004) estimated that a 79% of the population was dependent on forest resources for their livelihoods. In this context, forests play a central role in rural development and rural livelihoods. Due to the social – low economic resilience- and geographical – steep terrain, shallow and erodible soils- characteristics of Bhutan, the region is very sensitive to global climate change and is expected to be highly influenced by its effects (Tse-ring et al., 2010; Xu et al., 2009). Bhutan's economy is highly dependent on hydropower, forestry and agriculture, all of them climate-sensitive sectors very vulnerable to climate change impacts (MoAF, 2016).

Blue pine (*Pinus wallichiana* A.B. Jackson) forests are semi-mesic (dry) ecosystems that grow at mid elevations (2100-3200m), where precipitation ranges from 450 to 1500mm per year (Tenzin, 2001) and represent a 3.7% of the total forest cover in Bhutan (DoFPS, 2016). Blue pines characteristics are those of early successional species: they form secondary monospecific even-aged stands, present rapid growth rate (Tenzin, 2001), are light demanding (Gratzer et al., 2004) and grow adjacent to human settlements, mostly in previously abandoned agricultural fields (Dukpa et al., 2018; Gyeltshen, 2016; Tenzin, 2001). Blue pine is a fire prone species native to the Himalaya; it is sensitive to wildfires due to its thin bark and high flammability (Tenzin, 2001). Because blue pine forests grow next to settlements they undergo high anthropogenic pressure (Dukpa et al., 2018; FAO, 1999) and are therefore more prone to wildfires (Tenzin, 2001).

Blue pine is a highly valued economic species in Bhutan, used for construction, firewood, fencing and as prayer flag poles (CF-Members, 2018; Phuntsho et al., 2011; Tenzin, 2001). Non-timber forest products from blue pine forests also play an important role in rural livelihoods – resin, mushrooms, pine needles and medicinal plants (*Paris polyphylla*)- (CF-Members, 2018). The ongoing out-migration to urban areas in Bhutan (World-Bank, 2014) forces the settlements to sprawl into the surrounding forests, increasing the human pressure on those ecosystems (Dukpa et al., 2018). The loss of part of those forests due to uncontrolled wildfire would imply a loss in rural people livelihood, whose subsistence is greatly based on the use of forest resources.

The most common blue pine disease in Bhutan is dwarf mistletoe (*Arceuthobium minutissimum*), which is usually found in degraded and heavily grazed blue pine stands (Tenzin, 2001). Dwarf mistletoe's effects on trees, such as witches' brooms and accumulation of dead fuel due to tree mortality, increase the total fuel load and therefore the fire behavior potential (Alexander and Hawksworth, 1975). Virtually all blue pine forests surrounding the settlement areas are grazed (Gyeltshen, 2016). Livestock grazing decreases fire frequency and intensity by reducing the density of grasses (which burn easily under dry conditions) (Tenzin, 2001). Yet, Gyeltshen (2016) found out that grazing in Bhutan is related to increased fire risk, since the burning for new grasses, a common management practice to improve pastures, may escape and burn the forest.

Forest fires in Bhutan are caused almost entirely by human related activities such as debris burning, pasture management to improve grazing, uncontrolled camp fire, cooking fire and road maintenance (Gyeltshen, 2016; Chhetri, 1994). Wildfires occur mainly during the dry winter months (fire season extends from November to April) and are considered one of the biggest threats to forest resources in Bhutan (Chhetri, 1994). However, fire dynamics are changing with more frequent monsoon failures during the wet season (Hijioka et al., 2014), with a consequently increase in wildfire risk due to a subsequent drier fire season (MoAF, 2016). An increase in the frequency and intensity of forest fires in blue pine ecosystems would threaten the fragile mountain ecosystem, affecting soil stability and nutrient availability, biodiversity, water availability, carbon storage and limiting the access of rural people to forest resources.

There is concern that climate change and monsoon failures can strongly alter fire frequency and increase fire intensity in the future (Hijioka et al., 2014), yet there is no literature about natural fire regime in blue pine forests and past forest fire records are inconsistent. Despite the important role that wildfires play in blue pine forest ecosystems in Bhutan (Chhetri, 1994), so far there has been little scientific documentation on forest fires in the country (Gyeltshen, 2016; Dema, 2014; Tshering, 2006). Previous studies have emphasized the need of developing a framework to spatially assess fire likelihood and hazard. It is thus crucial to enlarge the literature on wildfire in blue pine forests as well as to consistently record fire events to be able to efficiently plan fire management strategies for the future.

Gyeltshen (2016) identified and characterized the main drivers that increase wildfire probability in blue pine forests in Bhutan – distance to nearest road, grazing intensity, wind speed, relative humidity, canopy bulk density and nearest land-use type-. His results give a clear overview on which are the factors that need to be tackled to reduce the impact of wildfire in such forests as well as on human lives and assets. A more detailed knowledge about the main drivers of wildfires in blue pine ecosystems, such as a tool to spatially assess potential fire hazard, would represent a big step for enhancing fire management strategies, for instance to determine the areas were fuel treatments to reduce fire hazard are more necessary.

In this study we applied an already existing fire behavior and growth model, FlamMap (Finney et al., 2016), to blue pine forest ecosystems to characterize the effect of climate change on wildfire hazard in the wildland-urban interface. This study will contribute to a better understanding of fire disturbances in blue pine forests of Bhutan by providing a spatially-explicit assessment of fire hazard under different scenarios of climate change.

Research objectives:

- To identify the effects of climate change on wildfire hazard in the wildland-urban interface of blue pine forest ecosystems.
- To characterize and map fire hazard in blue pine forest ecosystems.

Hypothesis:

- Climate change will increase fire behavior and growth potential in blue pine ecosystems in Bhutan.

2 MATERIALS AND METHODS

2.1 Study area

This study focuses on two valleys of Bhutan (Thimphu and Jakar), characterized for being surrounded entirely by blue pine forests and being the main settlement areas of their respective districts (Fig. 1). The area analyzed comprises the so-called wildland-urban interface and covers 7723ha in Thimphu and 4075ha in Jakar. Thimphu is the capital and largest city of Bhutan, with 92,929 inhabitants. Jakar is the capital city of Bumthang district and has a population of 16,116 inhabitants (OCC, 2005). Forest fires in Thimphu are more frequent than in Jakar (Lotay, 2015; DoFPS, 2014; NLC, 2014), yet in both areas the interaction human-forest resources is strong.

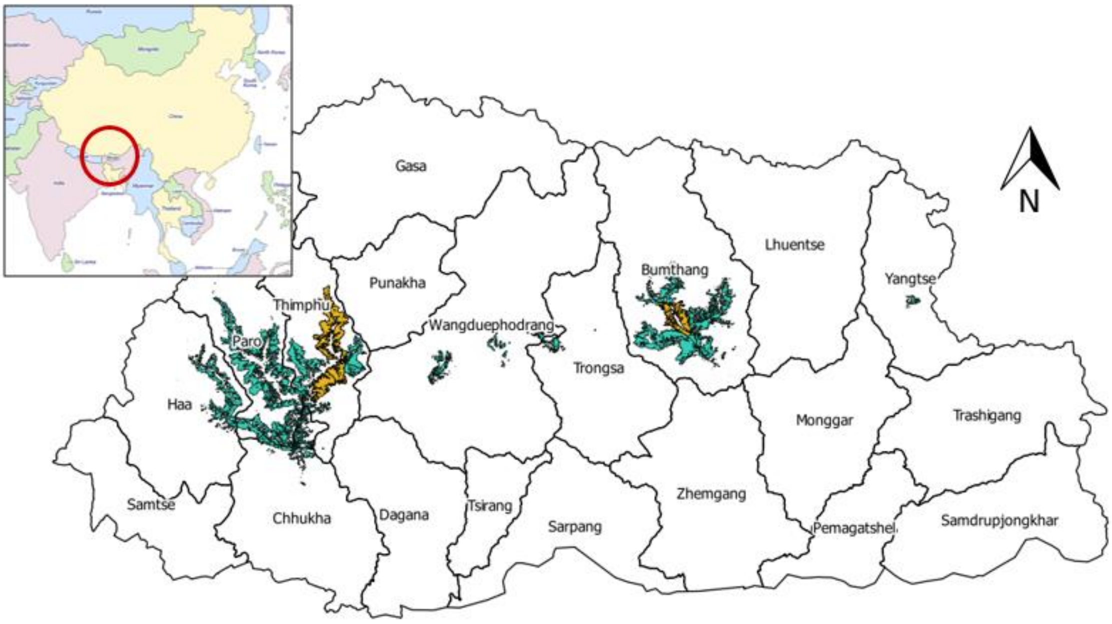

Figure 1. Map of Bhutan districts. In blue, distribution of blue pine forests; in orange, study areas. On the upper left corner, situation of Bhutan in Asia.

The capital of Bhutan sits at 2,310m above sea level and the mountains that surround it reach 4,000m. Jakar lies at 2,470m above sea level and the surrounding mountains reach 4,100m. Blue pine forests grow up to 3,100m. Forests at higher elevations are dominated first by conifer mixed forests – Sikkim spruce (*Picea spinulosa)* and Himalayan hemlock (*Tsuga dumosa)*- and then by Bhutan fir forests (*Abies densa)*. Blue pine forests are largely dominated by blue pine, especially in Jakar, where hardly other tree species were found in association. In Thimphu, the most common tree species in association to blue pine are *Quercus griffithii*, *Populus ciliata*, *Quercus semecarpifolia*, *Rhododendron arboreum* and *Picea spinulosa* (named decreasingly according to its abundance).

Climate in both valleys is characterized by warm and wet summers and cold and dry winters. The Southwest monsoon occurs from June to September, providing with the 73.12% of the total precipitation per year in Thimphu – mean annual precipitation is 607mm-, and 64.27% in Jakar – mean annual precipitation is 752mm- (HydroMet, 2017). Fire season in Bhutan stretches from November to April, and the peak fire month is February (Chhetri, 1994). In February, average precipitation is 0.3mm in Thimphu and 0.4mm in Jakar; average minimum and maximum temperatures are 0.6ºC and 16.7ºC in Thimphu, and -1.1ºC and 13ºC in Jakar (HydroMet, 2017) (Fig. 2). Wind is a highly variable parameter on a daily basis. In February, average wind speed in Thimphu is 4.3km/h (southwest direction), and in Jakar 6.3km/h (southeast direction).

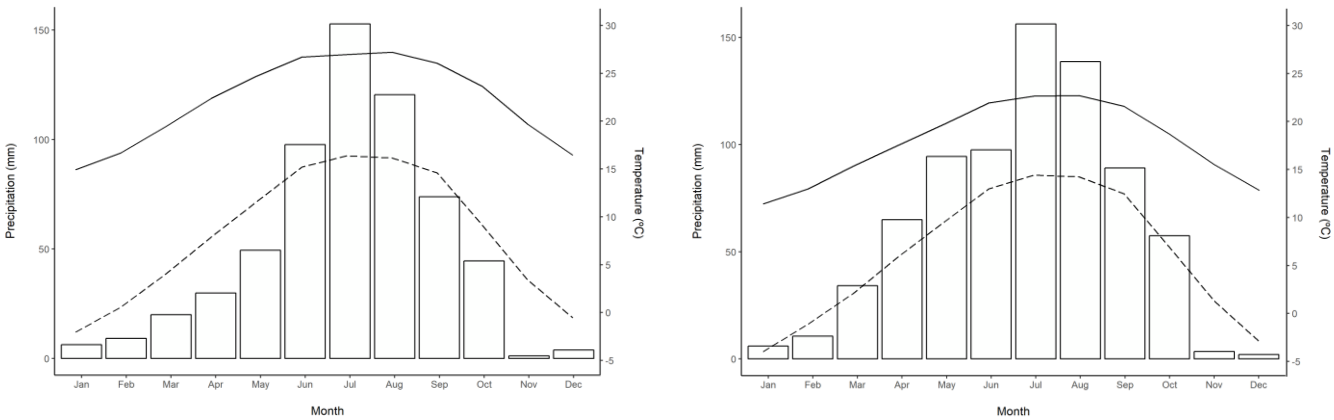

Figure 2. Mean monthly precipitation and mean monthly maximum and minimum temperature in Thimphu (left) and Jakar (right). Average values from 1996 to 2017 (Source: HydroMet (2017)).

2.2 Data collection

2.2.1 Vegetation data

Plots were selected randomly considering a minimum distance to the road (500m in Thimphu, 1km in Jakar) and a minimum distance between plots (500m). We measured a total of 58 plots in Thimphu and 44 plots in Jakar between December 2017 and January 2018 (Fig. 3).

In each plot we collected data on site, individual live and dead standing trees and woody debris, following the design shown in Figure 4. Site information recorded consisted on: elevation, slope, aspect, fire evidence, grazing evidence, canopy cover, shrub cover, herbaceous cover, litter and duff depth and closest land use. We estimated shrub cover in a fixed 8m radius plot, and herbaceous cover and litter and duff depth through three $1m^2$ subplots placed along a 25m transect (Fig. 4). Herbaceous plants include nonwoody plants, ferns, moss, lichens and grasses (Woodall and Williams, 2005).

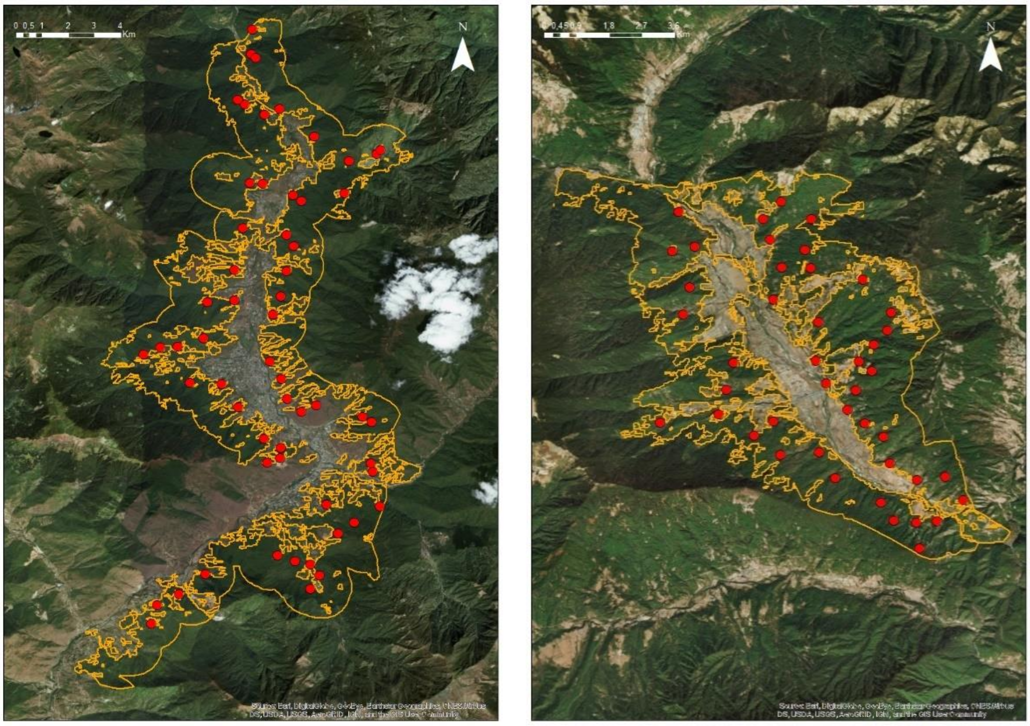

Figure 3. Plot distribution in Thimphu (left) and Jakar (right). In orange, borders of the study area.

We measured live and standing dead trees greater than 5cm diameter at breast height (DBH) and higher than 1.37m using a variable radius plot approach, with a basal area factor of 2.3. For each tree we measured DBH, decay stage -rating 0:9 (Bartels et al., 1985)-, total height and height to crown base, percent live crown, dwarf mistletoe presence -rating 0:3-, and crown class.

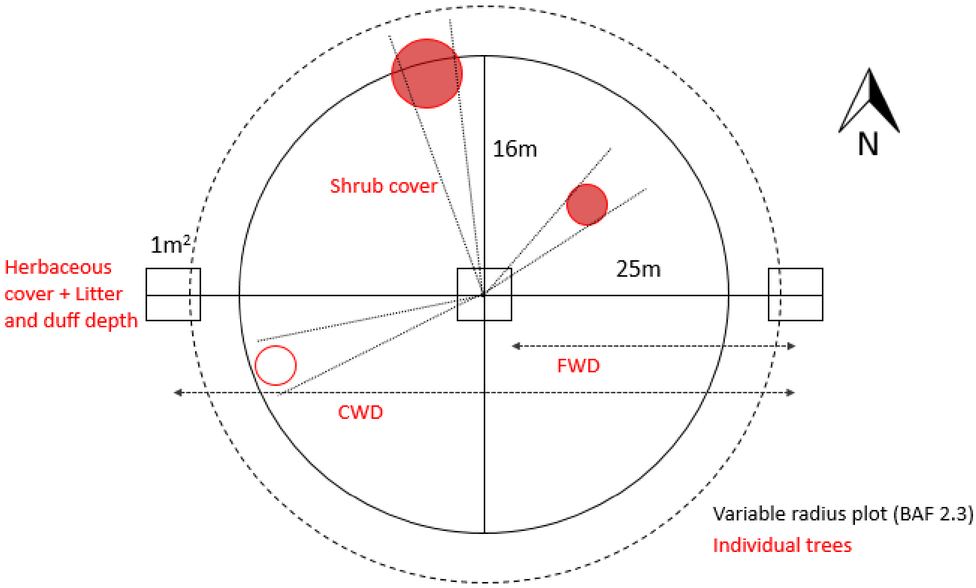

Figure 4. Plot design. Individual trees are represented as red circles: filled ones would be tallied, empty one would be out. FWD was measured on a 12.5m transect, CWD on a 25m transect. Shrub cover was estimated within a fix area plot of 8m radius (200m^2). Herbaceous cover and litter and duff depth were estimated three times along a 25m transect, in a 1m^2 subplot.

The woody debris inventory was adapted from the line intersect method (Van Wagner, 1968). Fine woody debris (FWD) are those branches and twigs larger than 1cm and less than 10cm diameter. Coarse woody debris (CWD) are those logs larger than 10cm diameter and longer than 1m. We measured diameter at intercept and leaning angle of FWD in a 12.5m transect, and diameter at intercept and decay class -rating 1:5 (Bartels et al., 1985)- of CWD in a 25m transect (Fig. 4).

2.2.2 Topography, weather and fire data

The Forest Resource Management Division, from the Department of Forests and Park Services (DoFPS) of Bhutan provided a digital elevation model (DEM) of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) at 30-meter resolution, and a land use land cover thematic map from 2016.

The National Center for Hydrology and Meteorology of Bhutan provided weather data from 1996 to 2017, which includes daily measures of temperature, precipitation, relative humidity, wind speed, wind direction and cloud cover. The weather stations used were Simtokha in Thimphu (27° 26' 29.31"N latitude, 89° 39' 45.98"E longitude, 2310m above sea level), and Chamkhar in Jakar (27° 32' 43.43"N latitude, 90° 45' 13.41"E longitude, 2470m above sea level).

The Forest Protection and Enforcement Division, from the DoFPS, provided forest fire records from 1992 to 2014. Those records were not consistent and were only used to calculate an average fire size for each valley.

2.3 Data processing

2.3.1 Vegetation data

We calculated stand structural metrics and canopy fuel characteristics following the equations presented on Table 1 (Table 2).

To characterize fire behavior, canopy base height (CBH), canopy fuel load (CFL) and canopy bulk density (CBD) are key parameters. CBH determines the occurrence of torching. It is an important predictor of crown-fire behavior (Reinhardt et al., 2006; Reinhardt and Crookston, 2003). CFL is the sum of available fuel loads over all trees and contributes to crown fire intensity, as it represents the potential energy available to be released from the canopy layer (Reinhardt et al., 2006; Cruz et al., 2003). The CFL

Table 1 (a). Equations used. BA= Basal area (m^2), TH= Tree height (m), FF= Form factor, SG= Specific gravity, BEF= Biomass expansion factor, RF= Reduction factor, L= Transect length (m), d= Diameter (cm), c= Slope correction factor, CCF= Carbon conversion factor, k= Constant for unit conversion, a= Nonhorizontal lean angle correction factor, fw= Foliar weight (kg), TEF= Tree expansion factor, CL= Crown length (m), cbh= Crown base height (m), RH= Relative humidity (%), T= Temperature (°F), YMC100= MC100h previous day, BNDRYH= Weighted 24h average moisture condition, HCover= Herbaceous cover (%), ShCover= Shrub cover (%), LD= Litter depth (cm), UD= Understorey depth (cm), h= Mean understorey height (cm), C= Understorey cover (%).

Parameter	**Equation**	**Reference**
Volume (m^3)	V= BA*TH*FF	FF - Tenzin et al. (2016)
Stem biomass (kg/m^3)	StB= V*SG*1000	SG - Neumann et al. (2016), Wani et al. (2014), Sheikh et al. (2011), Zhang (1995), Lawton (1984), Jain and Seth (1979)
Aboveground biomass (kg/m^3)	AGB= StB*BEF	BEF - Teobaldelli et al. (2009)
Standing dead wood biomass (kg/m3)	SDW.B= StB*RF	RF - Harmon et al. (2011)
Aboveground carbon (kg/m3)	AGC= AGB*0.5	Ford and Keeton (2017)
CWD volume (m^3/ha)	CWD.V= $(pi^2/8L)*\sum d^2*c$	Van Wagner (1968); c - Brown (1974)
CWD biomass (kg/ha)	CWD.B= CWD.V*SG*1000	SG - Jain and Seth (1979)
CWD carbon (kg/ha)	CWD.C= AGB*CCF	CCF - Harmon et al. (2008)
FWD volume (m^3/ha)	FWD.V= $(kac/L)*\sum d^2$	Woodall and Williams (2005)
FWD biomass (kg/ha)	FWD.B= FWD.V*SG*1000	SG - Jain and Seth (1979)
Canopy fuel load (kg/m^2)	CFL= $((\sum(fw_i*TEF_i))/10000)*RF$	Cruz et al. (2003); RF - Reinhardt et al. (2006)
Canopy bulk density (kg/m^3)	CBD= CFL/CL	Cruz et al. (2003)
Canopy base height (m)	CBH= $\sum(cbh_i*TEF_i)/ \sum TEF_i$	Cruz et al. (2003)
Equilibrium moisture content (%)	EMC= 2.227+0.16*RH-0.015*T	Simard (1968)
Moisture content 1h (%)	MC1h= 1.03*EMC	Cohen and Deeming (1985)

Table 1 (b). Equations used. BA= Basal area (m2), TH= Tree height (m), FF= Form factor, SG= Specific gravity, BEF= Biomass expansion factor, RF= Reduction factor, L= Transect length (m), d= Diameter (cm), c= Slope correction factor, CCF= Carbon conversion factor, k= Constant for unit conversion, a= Nonhorizontal lean angle correction factor, fw= Foliar weight (kg), TEF= Tree expansion factor, CL= Crown length (m), cbh= Crown base height (m), RH= Relative humidity (%), T= Temperature (ºF), YMC100= MC100h previous day, BNDRYH= Weighted 24h average moisture condition, HCover= Herbaceous cover (%), ShCover= Shrub cover (%), LD= Litter depth (cm), UD= Understorey depth (cm), h= Mean understorey height (cm), C= Understorey cover (%).

Parameter	**Equation**	**Reference**
Moisture content 10h (%)	MC10h= 1.28*EMC	Cohen and Deeming (1985)
Moisture content 100h (%)	MC100h= YMC100+(BNDRYH-YMC100)*(1-(0.87*exp$^{(-0.24)}$))	Cohen and Deeming (1985)
Herbaceous biomass (Mg/ha)	HB= HCover*2.1262/100	Muukkonen et al. (2006)
Shrub biomass (Mg/ha)	ShB= ShCover*0.8416/100	Muukkonen et al. (2006)
Fuelbed depth (cm)	FD= LD + UD	Fernandes et al. (2006)
Understory depth (cm)	UD= h-h*((100-C)/100)	Fernandes et al. (2006)

equation includes an adjustment factor that accounts for the reduction of foliage biomass per tree (i.e. depending on its crown class) (Reinhardt et al., 2006). CBD is the amount of fuel within a unit volume of the canopy and it is an important predictor of crown-fire occurrence (Reinhardt et al., 2006; Cruz et al., 2003). The method used to compute CBD is referred to as "load-over-depth" approach, which assumes uniform vertical distribution of available fuel within a forest canopy (Reinhardt et al., 2006).

Table 2. Stand structural metrics and canopy fuel characteristics. Average values and standard deviation. *: statistically significance (alpha= 0.05).

	Thimphu	**Jakar**	
Blue pine (% of total BA)	88.2	99.9	
Basal area (m^2/ha)	22.13 ± 10.3	28.02 ± 10.7	*
Density (trees/ha)	1050.98 ± 1073.7	950.29 ± 978.0	
Volume (m^3/ha)	212.36 ± 152.1	308.96 ± 149.0	*
Aboveground biomass (Mg/ha)	135.74 ± 97.3	196.51 ± 94.7	*
Carbon storage (Mg/ha)	67.71 ± 48.5	98.05 ± 47.3	*
Volume CWD (m^3/ha)	22.3 ± 68.7	13.57 ± 26.8	
Biomass CWD (Mg/ha)	7.21 ± 24.3	4.19 ± 8.3	
Carbon CWD (Mg/ha)	3.55 ± 11.8	2.09 ± 4.1	
Volume FWD (m^3/ha)	4.85 ± 6.2	10.13 ± 9.5	*
Biomass FWD (Mg/ha)	2.31 ± 2.9	4.81 ± 4.5	*
Stand height (m)	12.6 ± 7.0	16.2 ± 5.8	*
Canopy fuel load (kg/m^2)	1.43 ± 1.1	2.15 ± 1.1	*
Canopy base height (m)	4.77 ± 3.5	5.84 ± 2.5	*
Canopy bulk density (kg/m^3)	0.23 ± 0.2	0.27 ± 0.2	

2.3.2 Interpolation to a landscape level

We applied ordinary kriging using ArcGIS to scale up the data from plot level to a landscape level. Kriging is a geostatistical interpolation method that predicts the value of an unmeasured location by a weighted sum of the surrounding measured values. The weights are not only determined by the distance of the measured points to the prediction location but also by a variogram model fitted to the measured points, which represents the spatial autocorrelation between the sample points. Kriging is a suitable interpolation technique since it provides the prediction errors of the interpolated points by performing a cross validation (Harman et al., 2016; Sajid et al., 2013; Oliver and Webster, 1990). The variables interpolated were canopy cover, stand height, canopy base height and canopy bulk density.

The interpolation was limited to a 1km buffer distance from the sample plots to get more accurate predictions for the landscape. Besides, we integrated data from Gyeltshen (2016) of Thimphu into the interpolation. Kriging allowed the creation of 30m resolution raster layers at the landscape level of the input variables needed for the wildfire simulation in FlamMap.

2.4 Simulation model

To simulate wildfire behavior and growth, FlamMap 5.0 was used (Finney et al., 2016). FlamMap is a spatial wildfire simulation program that calculates potential fire behavior and growth under constant environmental conditions, showing the effect of fuels and topography on fire behavior (Ager et al., 2007; Finney, 2006). FlamMap calculates fire behavior by assuming that every pixel from the landscape burns, i.e. fire behavior is calculated on each pixel independently (Finney, 2006).

2.4.1 Input data

To run a wildfire simulation with FlamMap the following data is needed: (1) weather data (temperature, relative humidity, precipitation, wind direction, wind speed and cloud cover), (2) fuels data (canopy cover, stand height, canopy base height, canopy bulk density, fuel moisture content and fire behavior fuel model) and (3) topography data (elevation, slope and aspect).

2.4.1.1 Weather data

FlamMap simulates fire behavior and growth holding environmental conditions constant, thus showing the effect of topography and fuels spatial arrangement under the specified weather conditions (Ager et al., 2007). Precipitation, minimum and maximum temperature, minimum and maximum relative humidity, wind speed, wind direction and cloud cover are the input weather parameters in FlamMap. Precipitation, temperature and relative humidity are directly correlated with fuels moisture content, which influences rate of fire spread and fire intensity (Simard, 1968). Cloud cover affects the moisture content of the fuels since it determines the amount of sunlight fuels receive. Wind provides oxygen and carries the fire across a landscape.

Weather parameters were calculated as the average values of February (peak fire month) from the past 21 years. To account for the wind direction variation at finer scale, we used the WindNinja extension from FlamMap. WindNinja simulates the spatial variation of the wind flow considering the topography of the landscape and the wind speed and direction set as input. The resolution of the grid was set at 90m.

<u>*Climate scenarios*</u>

To assess the wildfire sensitivity in the wildland-urban interface to climate change, we created a factorial design with four climate scenarios symbolizing climate change projections of monsoon failures and higher temperatures (Fig. 5). To portray scenarios of climate change, we represented extremes of temperature and relative humidity – parameters that highly affect fire hazard since they are directly related to fuel moisture content (Agee, 1993). Scenario A represented the baseline weather from the last 21 years. Extreme temperature, for scenarios B and D, was taken from the average value of the 97th percentile of the baseline weather, and relative humidity, for scenarios C and D, was taken from the average value of the 3rd percentile (Alcasena et al., 2018; Salis et al., 2013; Ager et al., 2012; Ager et al., 2010). By keeping constant all other variables affecting wildfires, we can isolate the effect that those parameters have on potential fire behavior in blue pine ecosystems.

		Temperature	
		Baseline	Extreme
Relative humidity	Baseline	A	B
	Extreme	C	D

Figure 5. Climate scenarios. Scenario A: Baseline scenario; scenario B: Increase in temperature scenario; scenario C: Decrease in relative humidity scenario; scenario D: Increase in temperature and decrease in relative humidity scenario.

2.4.1.2 Spatial data – fuel canopy characteristics and topography

FlamMap requires spatial data in raster format describing fuel canopy characteristics (stand height, canopy base height, canopy bulk density and canopy cover) and topography (elevation, slope and aspect). All raster layers are of identical resolution (30m x 30m) and extent.

Elevation affects temperature and relative humidity. For the simulation, elevation is used to adjust temperature and relative humidity at the adiabatic lapse rate, from the reference elevation of the weather station to any point on the landscape (1ºC per 100m) (Finney, 1998). Slope has a direct effect on rate of fire spread. Fire will spread faster on steeper slopes due to the greater transfer of heat to fuel particles (preheating of fuels through radiation). Slope position of the fire is also important, if the fire starts at the very bottom of the slope, the odds of burning a larger area are higher, since fires moving upslope spread faster (Agee, 1993). FlamMap uses slope to calculate fire spread (Finney, 1998). Aspect in combination with slope influence fuel moisture content. South facing aspects receive higher solar radiation – temperature is higher and relative humidity lower-. Steep south facing aspects are drier than north facing and the fuel moisture content is lower, thus fuel particles are easier to ignite (Agee, 1993). FlamMap uses slope along with aspect to determine the angle of incident solar radiation (Finney, 1998).

Canopy cover is used to calculate the shading of the surface fuels, which influences fuel moisture content. Along with stand height, they are used to compute the wind reduction factor under the forest canopy (Finney, 1998). Canopy base height is used to define the threshold for transition to crown fire (along with surface fire intensity and foliar moisture content). Canopy bulk density determines the threshold to achieve an active crown fire (Finney, 1998).

2.4.1.3 Fuel moisture content

Fuel moisture content (FMC) is a highly important parameter in any fire behavior model, since it has a direct influence on the rate of combustion of forest fuels, affecting fire intensity and spread (Simard, 1968). FMC depends mostly on two group of factors: meteorological factors (explained above) and fuel characteristics factors (heat content and surface area-to-volume ratio of the fuel particle are among the most important) (Simard, 1968). Heat content depends on the chemical composition of the fuels (e.g. high resin content translates to high heat content). Some mineral components of fuels, such as phosphorus, dampen pyrolysis and are used as fire-retardant compounds. Surface area-to-volume ratio (SAV) is a measure of the ability of the fuel particle to gain and lose heat and moisture. Smaller particles have higher SAV ratio, hence they undergo changes on moisture content more easily. Small size particles' moisture varies on a daily basis reflecting the immediate weather, whereas bigger size particles react more slowly to changes on weather and reflect the seasonal trends (Agee, 1993).

Any FlamMap simulation requires information on initial FMC of 1h (0 – 0.62cm), 10h (0.62 – 2.54cm) and 100h (2.54 – 7.62cm) time-lag class dead fuels as well as the moisture content of live herbaceous and live woody fuels.

Dead fuels

Dead fuels are classified in size classes according to the time-lag they require to reach a new moisture equilibrium. The equilibrium moisture content (EMC) is defined as *"a steady state moisture content of dead woody material, which is achieved under constant* [atmospheric] *conditions for a sufficiently long adjustment period*" (Cohen and Deeming, 1985). EMC is derived from temperature and relative humidity, and it is more sensitive to changes in relative humidity than to temperature (Agee, 1993). The smallest fuel particles have a short time-lag of 1 hour, the largest ones can exceed 1000 hours of time-lag (Agee, 1993).

EMC was used to calculate moisture content of dead fuels (Table 1). We calculated EMC following the equations developed by Simard (1968), with the corrections for intensity of insolation (a function of cloud cover), introduced by Cohen and Deeming (1985). With this correction it is possible to infer the relative humidity and temperature values of the immediately surrounding air of the fuel particles, in contrast to the values at instrument height.

FMC of 100h time-lag fuels shows a slower response to changes in atmospheric conditions. The EMC used in that case represents a 24h period, reflecting the average drying-wetting potential of the atmosphere. The equations consider the duration of the daylight – through the latitude of the weather station, the Julian date and the solar declination-, the maximum and minimum EMC, and the hours of precipitation (for a comprehensive explanation of the equations see Cohen and Deeming (1985)).

In FlamMap, the initial fuel moisture of dead fuels is locally modified by a conditioning period that accounts for weather, topography and shading, before fire behavior and fire growth are calculated (Finney et al., 2016).

Live fuels

Live fuels moisture changes are more complex, since its moisture content not only depends on direct weather changes but also on the balance between moisture loss by transpiration and replacement of this loss from water stored in the stem or soil moisture uptaked by roots (Agee, 1993).

When fuel moisture of live fuels is high enough, they will act as a heat sink, reducing fire intensity and the rate of fire spread. Yet, if fuel moisture decreases to a certain level, live fuels will be add to the available fuel load and they will no longer be a heat sink but act as a heat source (Burgan, 1979). Live fuels are divided into herbaceous and woody fuels. During the dry season, herbaceous fuel will have a moisture content lower than 50%, and shrubs fuel moisture values will be between 50 and 80% (Burgan, 1979).

Foliar moisture content

Foliar moisture content is used along with the canopy base height to calculate the threshold for transition to crown fire. A value of 100% moisture content is considered good for drought conditions (Scott and Reinhardt, 2001). For the baseline scenario, we used 100% foliar moisture content, for scenarios B and C (increase in temperature or decrease in relative humidity) 90%, and for the most extreme scenario, we used a value of 80%.

2.4.1.4 Fire behavior fuel model

A fire behavior fuel model (FBFM) consists of a set of fuelbed inputs which provide a description of the surface fuel structure (Finney, 1998). FBFM are grouped according to the main fire-carrying fuel type (i.e. grass, grass-shrub, shrub, timber with understory, timber litter and slash-blowdown) (Scott and Burgan, 2005).

To create a FBFM for Thimphu and Jakar, we parameterized an already existing FBFM developed by Scott and Burgan (2005) with own data. Its code is TU5 and belongs to the timber-understory group (grass or shrubs mixed with litter from forest canopy). The main fire carrier of TU5 is forest litter in combination with herbaceous and shrubs fuels, the fuelbed is characterized by high load of conifer litter with shrub or small tree understory (Scott and Burgan, 2005). A FBFM requires the following data: fuel loading (1h, 10h and 100h time-lag class dead fuels, live herbaceous and live woody fuels), type of live herbaceous fuel load, SAV ratio (1h time-lag class dead fuels, live herbaceous and live woody fuels), fuelbed depth, moisture of extinction and heat content (Table 3).

We applied formulas from Muukkonen et al. (2006), developed for pine forests understory, to convert herbaceous and shrub percent cover to biomass (Table 1). Both fuel models have a live herbaceous load that is considered “dynamic”. That means, the load of herbaceous fuels moves from live to dead depending on their moisture content. If the herbaceous moisture content is between 30 and 120%, part of the load is transferred to dead herbaceous, and the same moisture content of 1h time-lag class fuels is assigned to that new group. If moisture content is below 30%, all the herbaceous load will be transferred to the dead herbaceous class (Scott and Burgan, 2005).

Table 3. Fire behavior fuel model of Thimphu and Jakar. **: data from TU5. *: field data from Thimphu and Jakar.

		Thimphu	**Jakar**	
Fuel model code		FM58	FM44	
Fuel loading (Mg/ha)	1h	8.97	8.97	**
	10h	0.11	0.12	*
	100h	0.88	0.84	*
	liveH	0.31	0.38	*
	liveW	0.96	1.01	*
Type		Dynamic	Dynamic	
SAV ratio (1/cm)	1h	48	48	**
	liveH	58	58	**
	liveW	23	23	**
Fuelbed depth (cm)		81.29	83.12	*
Moisture of extinction (%)		25	25	**
Heat content (J/kg)		18594	18594	**

Fuelbed depth is calculated as the sum of litter depth und understory depth. To calculate understory depth, we applied the formula from Fernandes et al. (2006) with the average shrub height from the data collected by Gyeltshen (2016).

The moisture of extinction is the moisture level above which the fire will no longer spread. Above moisture of extinction, flaming combustion cannot occur because the heat required to vaporize the water content of the fuel is greater than the heat available in the firebrand, thus ignition may not occur or fire spread may be hindered (Simard, 1968). Live fuels have a higher moisture of extinction than dead fuels as they generally have higher content of oil and resin, which are highly flammable components (Agee, 1993). Moisture of extinction is also associated with climate – dry areas have lower moisture of extinction than humid areas- (Scott and Burgan, 2005).

SAV ratio and heat content have been discussed above (*2.4.1.3 Fuel moisture content*).

2.4.2 Wildfire simulation

2.4.2.1 Fire behavior

Fire behavior is a function of weather, topography and fuels (Agee, 1993). FlamMap characterizes fire behavior under constant environmental conditions. In this study, three indicators of fire behavior have been chosen to compare between climate scenarios: flame length, rate of spread and crown fire activity. For the fire behavior simulation, FlamMap assumes that every pixel of the landscape burns and the calculation of the fire behavior outputs is done for each cell independently (so each cell output is independent of any adjacent cell), thus it is possible to distinguish areas were fuel treatments for fire prevention are more needed and to compare the effect of different scenarios on the landscape (Stratton, 2004).

Flame length (m) is derived from the fireline intensity (energy release per unit time) with which the fire front is burning (Byram, 1959). We computed flame length, a surrogate of fire intensity, because of its easier conceptualization. The rate of fire spread (m/min) displays the maximum rate at which the fire front spreads for each cell, which is highly influenced by the windspeed but also by slope and aspect (Finney, 1998). Crown fire activity is calculated by comparing the surface fireline intensity with the critical intensity threshold for transition to crown fire, which is a function of the canopy base height and the foliar moisture content. If the surface fireline intensity is less than the critical threshold, a surface fire occurs, if the threshold is exceeded, a crown fire will occur (Finney, 1998). The output of crown fire activity is categorical: 1 (surface fire), 2 (passive crown fire) and 3 (active crown fire).

2.4.2.2 Minimum travel time – fire growth

The minimum travel time algorithm calculates fire growth as a function of the minimum time required for the fire to travel across the landscape, or in other words, it calculates fire growth by searching the fastest pathway for the fire to move across the landscape (Finney, 2002). The fire growth is simulated at constant environmental conditions, making it possible to identify the effects of both topography and spatial fuels arrangement on fire growth (Ager et al., 2007). For this study, burn probability and fire size are the outputs of the minimum travel time algorithm using random ignition locations within the study area.

Burn probability is a measure of the likelihood that a pixel of the landscape will burn given a random ignition and must not be confused with the future likelihood of a wildfire ignition in the landscape. Burn probability in FlamMap is defined as the ratio between the number of times a pixel burns and the number of simulated fires (Ager et al., 2007).

Each random ignition simulated burns a certain area, which is then used to calculate an average fire size among all the simulated wildfires on the landscape (Ager et al., 2007), and can be compared to historical data on total burnt area.

The number of random ignitions simulated should ensure that most of the pixels of the landscape were burned at least once (Ager et al., 2010). These conditions were met when simulating 2000 ignition points in Thimphu and 1000 in Jakar. In both valleys and for all climate scenarios the maximum simulation period was set to 3 hours and the resolution of the calculations was set at 90 meters, to accelerate the processing time (Ager et al., 2012; Ager et al., 2007). The maximum simulation time affects mostly the fire size output; it was set to 3 hours in order to obtain an average fire size output similar to the average historical fire size (Alcasena et al., 2018; Kalabokidis et al., 2014; Salis et al., 2013; Ager et al., 2012) – in Thimphu average fire size for the last 20 years is 39ha and in Jakar 78ha (DoFPS, 2014).

2.5 Statistical analysis

The Lilliefors normality test (*nortest* package, R) indicated that the data was not normally distributed. To compare stand structural characteristics between Thimphu and Jakar we applied a non-paired Wilcoxon signed-rank test (*stats* package, R), with 0.05 significance level. To assess the effect that extreme weather has on fire behavior and growth, we tested the outcomes of FlamMap with the paired Wilcoxon signed-rank test (*stats* package, R) (Thom et al., 2017), with a 0.05 significance level. The statistical tests were applied to compare scenario B against scenario A (increase of temperature while holding relative humidity as baseline), scenario C against scenario A (decrease in relative humidity while holding temperature as baseline), and scenario D against scenario A (increase in temperature and decrease in relative humidity). As a paired non-parametric test, the null hypothesis tests whether the median difference between the paired observations is zero, i.e. each pixel of the landscape of one scenario is compared to the same pixel of another scenario.

The null hypothesis significance testing is a useful approach to measure the probability that an observed difference between two or more groups is due to chance (Dahiru, 2008). Yet, since it does not provide with an estimate of the magnitude of the effect and the precision of that estimate (Nakagawa and Cuthill, 2007), and because large sample sizes are more likely to return a significant effect (Dahiru, 2008), the effect size of the different climate scenarios (the difference between the medians) was calculated and plot against a zero effect, with the interquartile range as a measure of the spread of values (Thom et al., 2017).

2.6 Fire hazard map

To identify those areas with higher fire hazard, we created a fire hazard index by combining the outputs of the FlamMap simulation – flame length, rate of spread, crown fire activity and burn probability-. Fire size was excluded from the fire hazard map since it only contains information at a pixel level of total area burned per simulated fire (2000 in Thimphu, 1000 in Jakar). To combine those variables in both valleys, first they needed to be converted to a common hazard scale. For each variable, results of both valleys of all climate scenarios were first standardized (so variables of different magnitude can be compared), then log-transformed (to leave the outliers out and convert to normal distribution), and finally, re-scaled to a 0-1 range. We considered all variables to have the same weight in defining the wildfire hazard, therefore they were summed up in each raster cell, and the resulting 0-4 range was converted to a categorical scale: low, moderate, high, extreme.

3 RESULTS

3.1 Characterization of fire behavior and growth in Thimphu and Jakar

3.1.1 Stand structural characteristics

Plots from Thimphu and Jakar differed considerably in terms of vertical and horizontal structure (Table 2, Table 4). The forest in Jakar was largely dominated by blue pines (99.9% of total basal area). In Thimphu blue pine represented an 88.2% of total basal area, and the tree species in association occupied mostly the under-canopy (Fig. 6). All variables related to live and standing dead trees were higher in Jakar than in Thimphu (Table 2). Basal area, volume, aboveground biomass, carbon storage, stand height, canopy fuel load and canopy base height were statistically significant (p-value<0.05); density and canopy bulk density not (p-value>0.05). For woody debris, CWD accumulation was higher in Thimphu, without a statistically significance from Jakar (p-value>0.05) and FWD was higher in Jakar, with a statistically significance from Thimphu (p-value<0.05) (Fig. 1 Appendix).

Table 4. Site information. Average values and standard deviation. *: statistically significance (alpha= 0.05).

	Thimphu	Jakar	
Elevation (m)	2616 ± 140	2807 ± 132	
Slope (%)	45 ± 21	35 ± 19	
Fire evidence (% total plots)	20.7	4.5	*
Grazing evidence (% total plots)	93.1	97.8	
Canopy cover (%)	61 ± 20	75 ± 14	*
Shrub cover (%)	47 ± 25	47 ± 23	
Herbaceous cover (%)	39 ± 25	45 ± 25	
Litter depth (cm)	4.3 ± 3.2	6.4 ± 3.6	*
Mistletoe presence (% trees infected)	29.7	12.4	*

Fire evidence in the sampled plots was four times higher in Thimphu than in Jakar (p-value<0.05). We found grazing evidence in most of the plots of both valleys, in Jakar we found slightly more evidence than in Thimphu (p-value>0.05). Regarding vegetation cover, canopy cover was statistically significantly higher in Jakar (p-value<0.05), herbaceous cover was also higher in Jakar but without statistically significance (p-value>0.05) and shrub cover was very similar in both valleys (p-value>0.05). Depth of the litter layer was higher in Jakar (p-value<0.05). Mistletoe infection in Thimphu was more than twice as in Jakar (p-value<0.05) (Table 4).

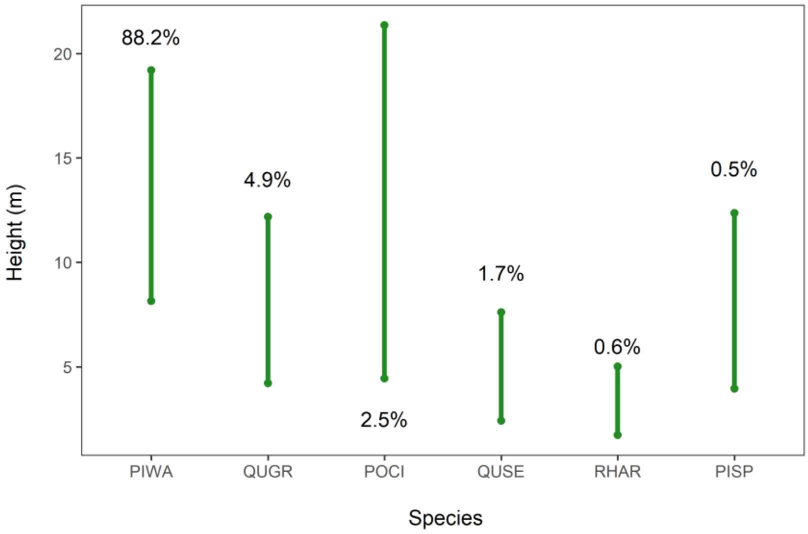

Figure 6. Average total height and average crown base height per species in Thimphu, with percent of total basal area. PIWA: Pinus wallichiana; QUGR: Quercus griffithii; POCI: Populus ciliata; QUSE: Quercus semecarpifolia; RHAR: Rhododendron arboreum; PISP: Picea spinulosa

CWD and Himalayan dwarf mistletoe (*Arceuthobium minutissimum*) presence were not inputs for the wildfire simulation model, yet they could play an important role in fire behavior and growth (Agee, 1993; Alexander and Hawksworth, 1975). CWD volume was twice as high in Thimphu as in Jakar. In Thimphu, 29.7% of the trees measured were infected by dwarf mistletoe, in Jakar only the 12.4% of the total trees (Fig. 7). Of the total trees infected by mistletoe, in Thimphu a 62.7% had an infection in a third of the crown, a 24.2% in two thirds and a 13.1% in the whole crown. In Jakar, in a 67.2% of the trees the infection occupied a third of the crown, a 26.6% two thirds and a 6.2% the whole crown.

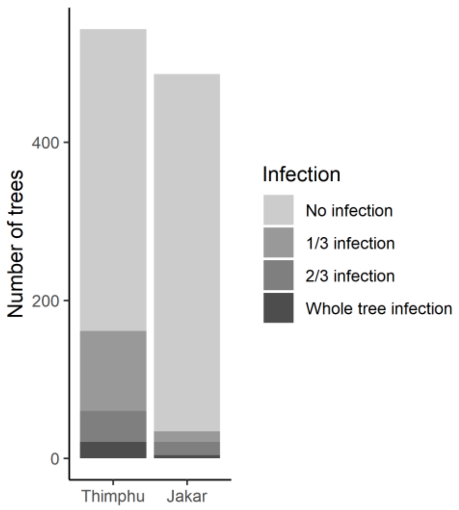

Figure 7. Number of trees infected by dwarf mistletoe, according to extent of infection.

3.1.2 Fire behavior and growth

Thimphu showed a higher potential of fire behavior and growth in all indicators and under all climate scenarios except one: flame length, rate of spread, crown fire activity and fire size were higher in Thimphu, burn probability was higher in Jakar (Table 5).

Table 5. Average values of fire behaviour and growth indicators, per scenario and valley.

		Flame length (m)	Rate of spread (m/min)	Crown fire activity	Burn probability	Fire size (ha)
Scenario A	Thimphu	5.22 ± 5.4	8.29 ± 6.3	1.43 ± 0.7	0.01 ± 0.01	83.01 ± 41.5
	Jakar	3.87 ± 5.1	6.65 ± 4.9	1.18 ± 0.6	0.02 ± 0.01	83.42 ± 39.8
Scenario B	Thimphu	5.47 ± 5.4	8.24 ± 6.3	1.49 ± 0.7	0.01 ± 0.01	83.68 ± 41.0
	Jakar	4.18 ± 5.33	6.57 ± 4.86	1.23 ± 0.61	0.03 ± 0.02	80.36 ± 41.30
Scenario C	Thimphu	7.28 ± 6.4	10.15 ± 7.6	1.67 ± 0.8	0.01 ± 0.01	110.69 ± 53.0
	Jakar	5.05 ± 6.1	7.37 ± 5.5	1.31 ± 0.7	0.02 ± 0.01	93.32 ± 47.5
Scenario D	Thimphu	7.81 ± 6.5	10.42 ± 7.8	1.77 ± 0.8	0.01 ± 0.01	110.69 ± 55.7
	Jakar	5.81 ± 6.5	7.63 ± 5.9	1.42 ± 0.7	0.02 ± 0.01	93.47 ± 49.7

Because FlamMap is a model that considers the interaction among topography, stand structural characteristics and weather to simulate wildfire, it is not possible to disentangle the effect that the different forest structure in each valley has on the potential fire behavior. However, some apparent forest structure differences between the two valleys can be stated: (1) CFL and CBD are higher in Jakar. That means there is more fuel in the canopy layer for the fire to burn; (2) CBH is lower in Thimphu, in part due to the tree species in association which conform the under-canopy. When the vertical structure of the forest is complex, a surface fire is more likely to become a crown fire (Alexander, 1988); (3) denser canopy cover, as in Jakar, provides the fuels from the under-canopy with shading (Finney, 1998), thus their moisture content is less likely to drop to the ignition point (Agee, 1993). Besides, the denser the canopy is, the less wind seeps under the canopy, lowering the rate of fire spread; and (4) FWD volume in Jakar is more than the double than in Thimphu. FWD contributes largely to fire ignition, since these fuel particles have higher surface area-to-volume ratio and in sunny and dry conditions their moisture content is very low and can ignite easily.

With the construction of the fire hazard map we were able to determine the regions that are more prone to fire in each area (Fig 8). Under all scenarios most part of both valleys is categorized as having a “moderate” fire hazard (Table 6). In Thimphu the fire hazard is higher than in Jakar, as more area falls within the “high” category.

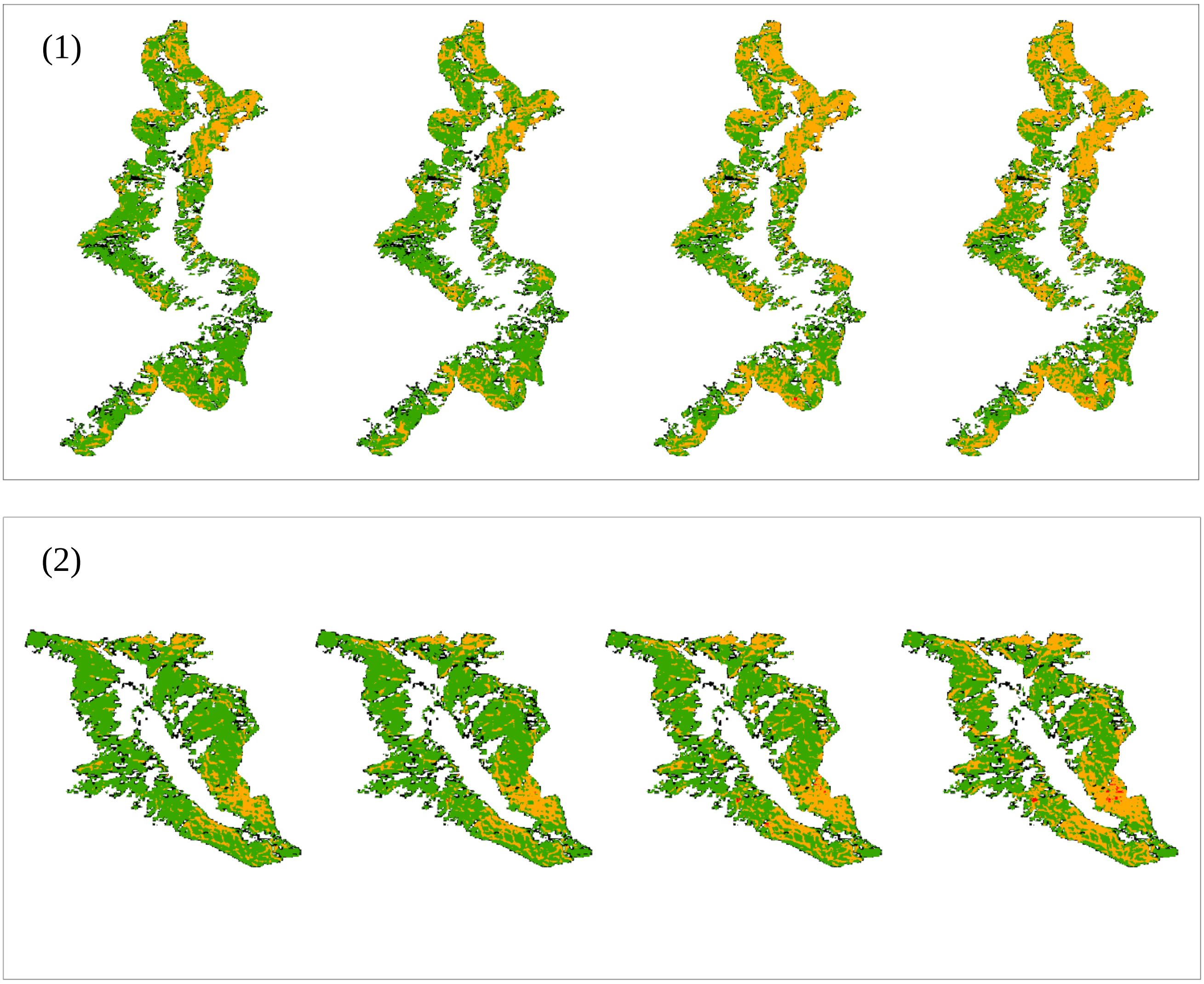

Figure 8. Fire hazard in Thimphu (1) and Jakar (2). From left to right: scenario A, scenario B, scenario C and scenario D. In black, areas of low fire hazard; in green, areas of moderate fire hazard; in orange, areas of high fire hazard; in red, areas of extreme fire hazard.

Table 6. Percent of area under each category of fire hazard, per valley and scenario.

Thimphu	Low	Moderate	High	Extreme
Scenario A	13.70	65.40	20.90	0.00
Scenario B	13.70	63.77	22.53	0.00
Scenario C	11.44	52.60	35.91	0.04
Scenario D	11.38	48.99	39.60	0.03

Jakar	Low	Moderate	High	Extreme
Scenario A	13.38	72.21	14.41	0.01
Scenario B	13.71	68.87	17.40	0.02
Scenario C	12.58	64.89	22.34	0.18
Scenario D	12.48	58.34	28.84	0.33

3.2 Climate change effects on fire behavior and growth

Our results reinforce our hypothesis and confirm that extreme weather has an effect on fire behavior in blue pine ecosystems (Fig 9). The statistical test showed a highly significant difference in all fire behavior indicators between climate scenarios (increase in temperature, decrease in relative humidity and combination of both). No statistically significance was found for burn probability and fire size under scenario B in Thimphu, and for fire size under scenario B in Jakar.

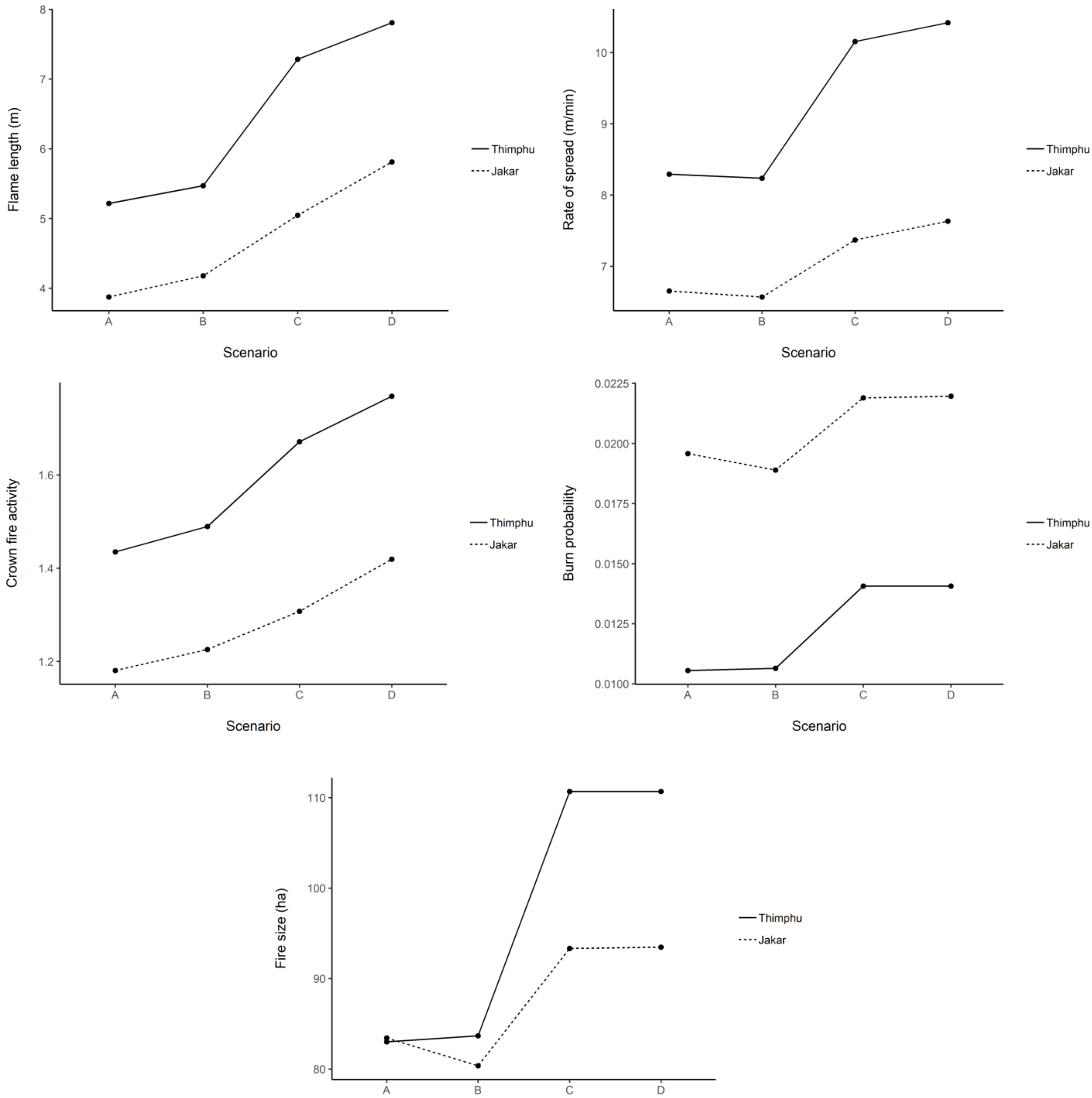

Figure 9. Average values of fire behaviour and growth indicators per scenario and valley.

Figure 10 illustrates the effect size of the different climate scenarios on each fire behavior indicator. This figure allows a good interpretation of the results, since it reveals which scenario had a greater effect on each indicator. In both valleys the greatest change was consequence of either the combination of an increase in temperature and decrease in relative humidity (scenario D) or a decrease in relative humidity (scenario C). An increase in temperature (scenario B) did not cause on average any change compared to the baseline scenario.

The greatest changes in flame length, rate of spread and crown fire activity were under scenario D both in Thimphu and Jakar (average increase of 2.59m and 1.94m in flame length; 2.13m/min and 0.98m/min in rate of spread, and 0.34 and 0.24 in crown fire activity, respectively). The greatest increase in burn probability was under both scenario C and scenario D in Thimphu and in Jakar (increased an average of 0.4% and 0.3%, respectively). Regarding fire size, the greatest increase was under scenario C and D in Thimphu and scenario D in Jakar (average increase of 27.68ha and 10.05ha, respectively). These results suggest that blue pine ecosystems in Thimphu are more susceptible to extreme weather than in Jakar. (Fig. 2 Appendix).

Under extreme weather conditions fire hazard in both valleys experiences an almost two-fold increase (Table 6). The proportion of areas with “low” fire hazard does not change much under different climate conditions, yet a great part of the areas that under baseline weather conditions are considered to have a “moderate” fire hazard, when simulating extreme fire weather conditions, the hazard turns into the category “high”. “Extreme” fire hazard areas also increase under extreme weather yet remaining always a small proportion of the landscape (Table 6, Fig. 8).

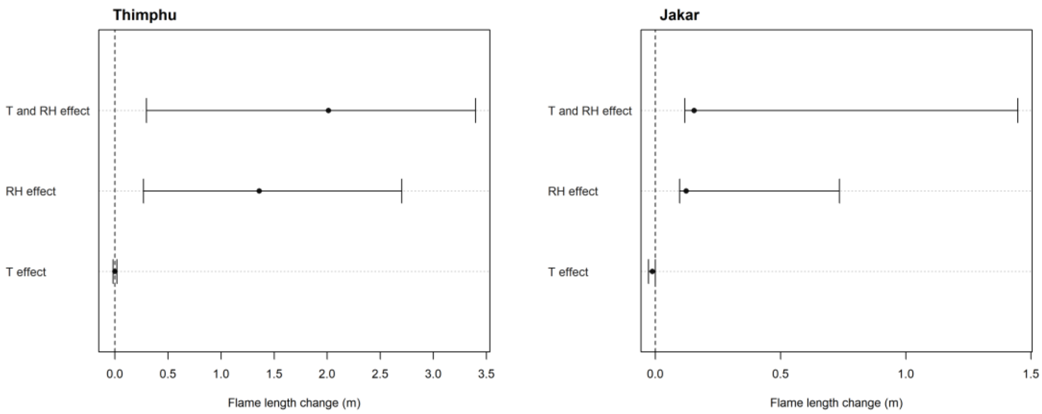

Figure 10 (a). Effect size (difference of the median) and precision of the effect (interquartile range) per scenario change and fire behaviour and growth indicator. “T effect” compares scenario B against scenario A; “RH effect” compares scenario C against scenario A; “T and RH effect” compares scenario D against scenario A.

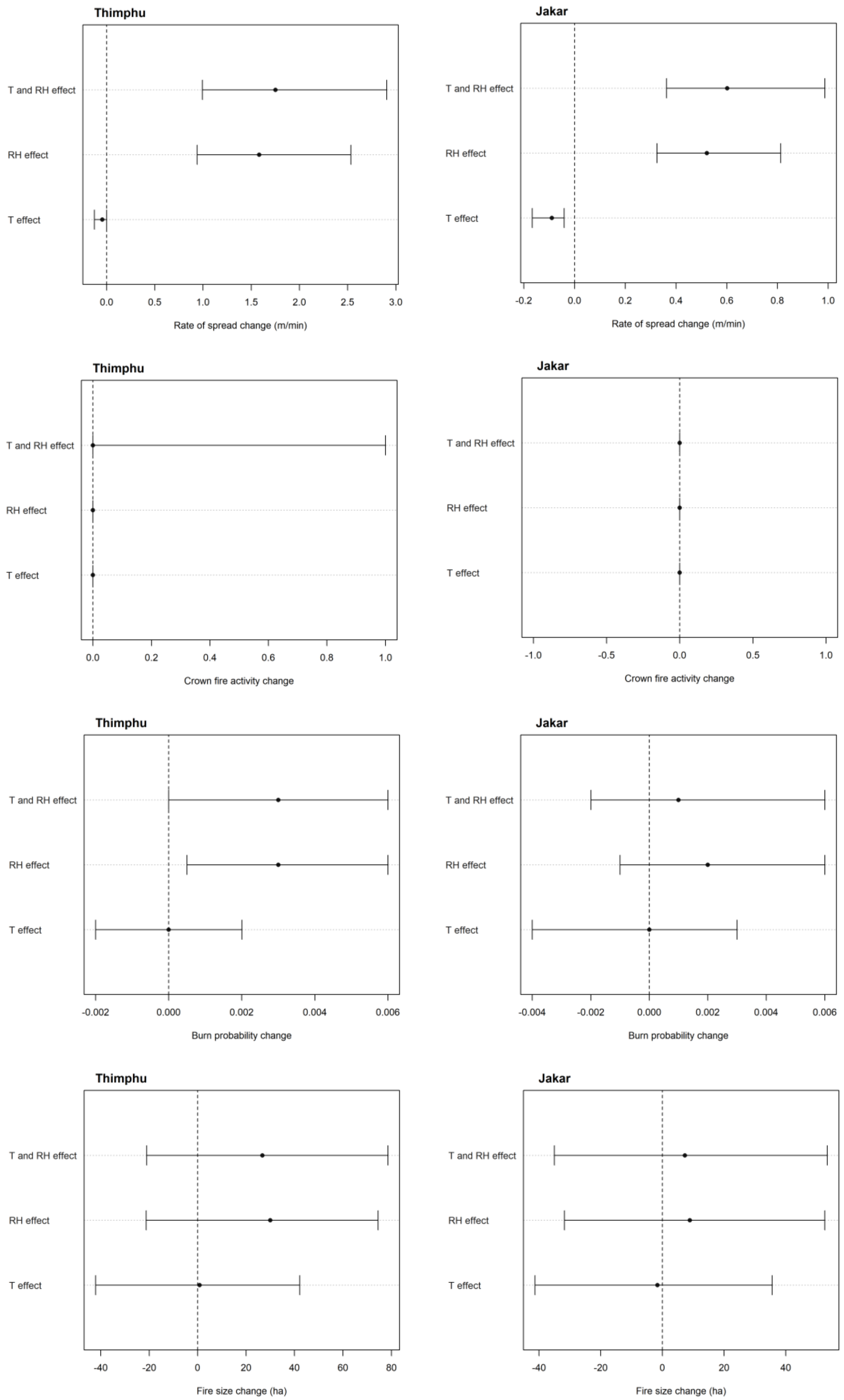

Figure 10 (b). Effect size (difference of the median) and precision of the effect (interquartile range) per scenario change and fire behaviour and growth indicator. “T effect” compares scenario B against scenario A; “RH effect” compares scenario C against scenario A; “T and RH effect” compares scenario D against scenario A.

4 DISCUSSION

Fire hazard in Bhutan is a rather unexplored subject within the scientific community, as it is the effects of climate change on wildfire behavior and fire regime in the country (Gyeltshen, 2016; Dema, 2014; Tshering, 2006). This study brings novel insights on the sensitivity of wildfire behavior to climate change in blue pine ecosystems of the Himalayas. Through studying two different valleys dominated by blue pine forests, we could test how extreme weather brought by climate change affects those forests and may affect likewise similar ecosystems of the Himalayan mountains.

Our results reflect a high sensitivity of wildfire response in blue pine ecosystems as a consequence of extreme weather, as they illustrate an increase on the potential fire behavior in both valleys due to climate change, consistently agreeing with our hypothesis.

4.1 Forest structure and fire behavior and growth

Forest vertical and horizontal structure as well as spatial continuity of fuels greatly affect wildfire behavior (Agee, 1993). Blue pine forests in both valleys are rather young ecosystems – mean DBH is 20.2cm in Thimphu and 23.2cm in Jakar, and the average height is 12.6m in Thimphu and 16.2m in Jakar-. Yet, blue pine can grow up to 45m (Tenzin, 2001).

Vertical structure in those ecosystems is complex. Ladder fuels are regarded as the connectivity between surface fuel layer and canopy layer and influence the transition from surface to crown fire by carrying the fire upward to tree canopy. Crown fires are of major concern since they burn with higher intensity and are therefore more difficult and dangerous to extinguish. The transition from surface to crown fire depends on canopy base height, foliar moisture content and fire intensity (Alexander, 1988). Once the crown fire has started, its continuity will depend on canopy bulk density and the rate of fire spread (Alexander, 1988) – that is, if fuel load is low and winds are not too strong fire will not transfer enough heat to the neighboring crowns and will not burn actively-. Canopy cover and stand height indirectly affect transition to crown fire, since they influence wind speed under the canopy and moisture content of dead fuels (Reinhardt et al., 2006).

In the areas analyzed for this study, shrubs cover almost half of the ground (47% in both valleys). Shrubs average height in blue pine ecosystems of Bhutan is 1.72m (Gyeltshen, 2016) and canopy base height is on average 4.77m in Thimphu and 5.84m in Jakar. Based on these results, there is a substantial window between shrub and canopy layer, making it more difficult for the fire to transit from surface to crown fire. FlamMap outputs also reflected this behavior, as on average all simulated wildfires behaved as surface fires – only under scenario C and D in Thimphu some areas underwent crown fires. Accordingly, Gyeltshen (2016) analyzed scorch height in blue pine ecosystems and concluded that most past fires were of low intensity, i.e. surface fires. Another approach to analyze crown fire probability is by comparing flame length to canopy base height. The simulated flame reached the height of the canopy base under all climate scenarios in Thimphu, while in Jakar it never reached the canopy (Table 5). This behavior is consistent with crown fire activity outputs, which suggest that blue pine ecosystems in Thimphu have higher chances to experience crown fire (Fig. 9).

It is nevertheless not necessary for the flame to reach the tree canopy to initiate a crown fire, since wind and slope also play a role in the transition from surface to crown fire (Alexander, 1988). If canopy cover is sparse, dead fuels are drier due to more solar irradiation and easier to ignite, and more wind can seep under the canopy, increasing fire intensity and the chances that fire reaches the canopy layer. Steep slopes facilitate the preheating of fuels and fire can spread faster or climb easier to the tree canopy. Canopy cover was higher in Jakar (75%) than in Thimphu (61%), and mountains surrounding Thimphu are steeper than in Jakar (on average 45% and 35%, respectively). Therefore, the chances of a crown fire in Thimphu are higher than in Jakar, given the favorable fire weather conditions.

Dwarf mistletoe infection tends to increase fire behavior potential. Stands heavily infected by mistletoe accumulate greater amounts of dead fuels. Branches infected by mistletoe have slower decay rates than non-infected branches, increasing fuel load in the canopy (Alexander and Hawksworth, 1975). In Thimphu trees were more infected by dwarf mistletoe than in Jakar.

Horizontal structure of fuels is also a key factor for fire spread. The more gaps without fuels in the forest, the fewer chances has the fire to spread. The compactness of the litter and herbaceous layers influences fire behavior as well. Compact litter and grasses will not supply enough oxygen and fire may extinguish (Agee, 1993). Herbaceous cover and litter accumulation are higher in Jakar than in Thimphu (Table 4). If we regard the surface fuel layer as a whole, summing up grasses, litter and shrubs, we can assume that, given an ignition and favorable wind, the horizontal continuity of fuels is enough for the fire to spread under the tree canopy in both valleys, but higher in Jakar.

For fire ignition, the surface area to volume ratio of dead fuels is a highly important factor (Agee, 1993). Dead fuels moisture content varies with weather changes. Smaller particles moisture content is greatly influenced by daily weather. Bigger size fuels moisture content reacts more slowly to weather changes, thus rather reflecting seasonal trends (Agee, 1993). Smaller particles, which in this study are represented as FWD, will therefore have a greater influence on fire ignition. FWD volume in Jakar is more than twice the volume in Thimphu (10.13m^2/ha and 4.85m^2/ha, respectively), thus fire ignition is easier in Jakar. This is consistent with the burn probability output of FlamMap, where under all scenarios Jakar has higher burn probability than Thimphu (Fig. 9). As a reminder, burn probability in FlamMap is not a measure of fire ignition likelihood but rather a measure of the likelihood that an area will burn given a random ignition (Ager et al., 2007). In Bhutan almost all forest fires are human-caused (Chhetri, 1994), and ignition probability depends highly on the distance to the road and type of nearest land use (Gyeltshen, 2016).

4.2 Climate change effects on fire behavior and growth

Mountainous ecosystems are highly susceptible and vulnerable to climate change (Dimri et al., 2018; Tse-ring et al., 2010; Xu et al., 2009). Climate change is expected to affect natural disturbances in several ways, including forest fires and their interaction with other disturbances (Dale et al., 2001). It is thus important to gain more knowledge on the effects climate change may have on wildfires in blue pine ecosystems of the Himalayas.

Our results indicate an increase on fire hazard in the wildland-urban interface in blue pine ecosystems of Bhutan under extreme weather conditions, i.e. simulating years of weaker monsoons and warmer temperatures. Weather is one of the three cornerstones of fire behavior, and the one that has a stronger relation to forest fire behavior (Bessie and Johnson, 1995). Bhutan receives most of the precipitation during the monsoon months, from June to September. Among the scientific community there is concern that climate change will bring weaker monsoons more frequently (Hijioka et al., 2014), which would threaten not only Bhutanese forests but also water resources and people livelihoods. Yet, long-term spatiotemporal variability of summer monsoons over Asia is unclear (Cook et al., 2010). Analyses of the past monsoon precipitation patterns indicate that there is no clear overall trend in monsoon precipitation, i.e., there is a high interannual and regional variability of precipitation amount (Varikoden et al., 2018; Cook et al., 2010; Shrestha et al., 2000). Several studies have found a positive relation between El Niño-Southern Oscillation (ENSO) and monsoon failures (Cook et al., 2010; Shrestha et al., 2000; Thompson et al., 2000). Tenzin et al. (2018) analyzed fire scars of chir pine (*Pinus roxburghii*) in Bhutan and found a positive relation between increased fire events and ENSO periods. However, Asian monsoon variability is not explained by ENSO alone, but other spatiotemporal forces, such as dust and chloride accumulation, influence it (Cook et al., 2010; Thompson et al., 2000).

The comparison between each extreme weather scenario with the baseline scenario allows us to distinguish the effect that an increase in temperature and/or a decrease in relative humidity have on each fire behavior indicator – flame length, rate of spread, fire crown activity, burn probability and fire size-. In both valleys, maximum change in fire behavior was under scenario D, followed by scenario C (Fig. 9), yet in Thimphu the change in potential fire behavior brought by extreme fire weather was more pronounced than in Jakar. This behavior might well be explained by differences in weather conditions in each valley (Bessie and Johnson, 1995). Jakar sits on a higher elevation valley than Thimphu and presents lower temperatures and higher relative humidity, also under extreme weather conditions. Our results suggest that relative humidity has a stronger effect on potential fire behavior than temperature, and the combination of both induces the highest change. That predisposes the forest to undergo more severe wildfires in years of weaker monsoons.

Climate change will affect fire regimes by modifying fuel conditions, i.e. vegetation composition and structure, fuel loading and connectivity (Hessl, 2011). This change in fuel conditions and arrangement will result in changing fire regime as well (Hessl, 2011; Flannigan et al., 2000), making therefore difficult to model future fire disturbances and their effects. Fire regime is consequence of the interaction between fuel conditions (type, structure, loading, moisture and spatial continuity), topography, weather (temperature, relative humidity, wind speed and precipitation) and ignitions (Flannigan et al., 2000). Natural fire regime in blue pine is not well understood (Gyeltshen, 2016; Dema, 2014). Gyeltshen (2016) pointed out that blue pine ecosystems do not present a stand replacing fire regime. Yet, humans have altered the landscape by modifying fuels amount and continuity since the early days (Pausas and Fernández-Muñoz, 2012), and as Chhetri (1994) analyzed, ignitions in Bhutan are almost entirely human-caused, thus it becomes very difficult to define a natural fire regime in those areas.

Accordingly, an increase in temperature or a decrease in relative humidity cannot be directly translated to greater fire disturbances, as fires are a product of the interaction between weather, fuels, topography and ignitions (Flannigan et al., 2000). A consequence of an increase in temperature is the lengthening of the growing season due to longer snow-free periods, increasing therefore the volume of available fuel and its continuity, and the dryness of fuels (Hessl, 2011), which could increase intensity of fire disturbances. However, these long-term changes in fuel structure as a result of an increase in temperature are not contemplated in our wildfire simulation; a vegetation growth model would be required to reflect it.

Our study does not consider changes in fuel loading and continuity nor changes in human pressure in blue pine ecosystems. We analyzed the effect of changing climate under the same fuel arrangement, thus presenting the impact that dry and warm years may have on potential fire behavior and growth. To construct climate scenarios, we did not use future projections of climate, but we utilized the extremes in weather from the last 21 years (HydroMet, 2017) to represent years with favorable fire conditions. By applying a spatially-explicit fire behavior model as FlamMap, we can identify the areas that are more susceptible to dry and warm years, thus revealing the areas were fire management resources should be allocated.

Changes in fire regime and length of fire season may also threaten post-fire regeneration (Flannigan et al., 2000). Blue pine shed their seeds in October and November and they germinate at the beginning of the monsoon season (Dema, 2014). Repeated longer fire seasons over the years in Bhutan could threaten blue pine regeneration and change the landscape composition in those ecosystems. Fire size may also affect regeneration, as it determines the distance seeds need to travel for regeneration (Flannigan et al., 2000). Blue pine seeds are dispersed through animals (zoochory) and can reach far disturbed areas (Darabant et al., 2012). Forest fires in blue pine ecosystems tend to be of low intensity and burn not so big areas (DoFPS, 2014). However, given the extreme fire weather conditions, fire could burn big areas with high intensity, not only threatening people and infrastructure from the wildland-urban interface but also post-fire regeneration.

4.3 Social dimension of forest fires in Bhutan

Since the area analyzed for this study comprises the wildland-urban interface and forest fires in Bhutan are almost entirely human-caused, it appears essential to include a section that shortly analyses the interrelation between human activities and wildfires in blue pine ecosystems.

Blue pine forests experience high human pressure because of their location, growing adjacent to settlements, and the social characteristics of the rural population, whose subsistence livelihoods are highly dependent on forest resources. Two social structure characteristics of Bhutan increase fire hazard in the wildland-urban interface: rural abandonment, as blue pine colonizes those abandoned fields and increases fuel continuity, and the sprawl of cities into forest land, as the chances of escaped ignitions are higher (Dukpa et al., 2018; Gyeltshen, 2016; World-Bank, 2014; Tenzin, 2001).

In 2000 a program to establish Community Forests (CF) was launched, and by 2009 CFs already occupied an area of 24,000ha, covering a 2% of total forested area (Phuntsho et al., 2011). CFs are regarded as a strategy to involve local people into forest management in order to engage them in the conservation and protection of the forest and the sustainable use of forest resources, as well as a method to reduce poverty and improve rural livelihoods (Phuntsho et al., 2011). CFs raise awareness among members in fire prevention and firefighting, as members feel responsible for their forest and are afraid of losing their products (CF-Members, 2018). CFs members receive trainings on how to make fire breaks, but rather as a firefighting technique than a fire prevention method (CF-Members, 2018).

Forest management is the key to fire prevention. In Bhutan prescribed burning was legalized in 2012, yet the benefits of this fire management strategy are still to be seen, since its operational conditions are to date under development (Darabant et al., 2014). Highly stock stands are less stable and have higher mortality rates, thus increasing fuel load (Darabant et al., 2012). Yet, thinning to reduce fuel load might be counterproductive, as dead fuels get more sun and are drier, and more wind can seep through the canopy, increasing the risk of a crown fire (Reinhardt et al., 2006). Besides, thinning can favor the growth of dwarf mistletoes since they receive more light (Darabant et al., 2012). Thinning from below the canopy would be consequently better, as canopy closure is kept continuous and wind penetration under the canopy does not increase that much, plus it can be combined with fire break for fire prevention creation (Darabant et al., 2012). Dukpa et al. (2018) found that moderate intensity thinning (25% of volume removal) is best for blue pine individual growth and stand stability.

Several studies have proofed the relation between ENSO and monsoon failures or weaker monsoons (Tenzin et al., 2018; Cook et al., 2010; Shrestha et al., 2000; Thompson et al., 2000). This relation makes it possible to predict beforehand years of favorable fire conditions. Combining this knowledge with the outcomes of this study, i.e. the most susceptible areas to suffer wildfires, it is possible to optimize fuel treatment for fire prevention and plan fire management strategies accordingly.

The hazard map created for this study can be used to adapt further city development and sprawl of houses into the forests, and to avoid developing on those areas that have higher chances of suffering high intensity fires.

5 CONCLUSION

This study is among the first to characterize the sensitivity of wildfire behavior to climate change of Himalayan blue pine ecosystems. It brings novel insights on the effect that extreme fire weather will have in the wildland-urban interface of blue pine forests of Bhutan.

Fuels, weather and topography are the three cornerstones of fire behavior and growth. We analyzed fire behavior and growth in blue pine ecosystems of two different valleys. The difference in forest structure between the two valleys is reflected on the wildfire simulation outputs. If a fire catches, it will burn with higher intensity and spread faster in Thimphu than in Jakar. However, due to fuel characteristics in Jakar, given an ignition, a fire is more likely to catch in these forests.

Based on climate change projections in the Himalayas, we created scenarios that symbolize monsoon failure and warmer temperatures and simulated the effect that extreme weather will have on blue pine ecosystems. The outcomes of this study indicate a two-fold increase in fire hazard due to climate change, consistently agreeing with our hypothesis. We produced a fire hazard map where the more susceptible areas to wildfire are revealed. Future fire management strategies could make use of this hazard map to optimize the allocation of resources and plan suburban development accordingly.

FlamMap is a versatile simulation model that could be applied for several purposes. For future research on fire in blue pine ecosystems, different fuel treatment scenarios could be run in FlamMap to analyze how the landscape responds to wildfire, for example, simulating fire breaks in areas where fire hazard is high.

All ecosystems will eventually adapt to climate change and its consequences. Climate change will alter natural disturbances regimes, whose alteration will likewise play a key role in determining towards which direction each ecosystem will adapt. Rural and urban population needs to adjust their subsistence livelihoods to this changing world, and that can cost some efforts. In regions where climate change is expected to have greater impacts, such as mountainous regions like the Himalayas, it is important to be able to foresee beforehand and as accurately as possible which ecosystem changes are to be expected, so that rural livelihoods highly dependent on natural resources are not threatened. In this context, and at a local scale, this study contributes to a better understanding of how climate change may affect fire behavior and growth in blue pine ecosystems in the Himalayas and thus how fire management strategies can be allocated to hinder the loss of rural livelihoods.

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7 APPENDIX

7.1 Stand structural parameters

Figure 1. Stand structural parameters of Thimphu and Jakar

7.2 FlamMap outputs, comparison between Thimphu and Jakar per scenario

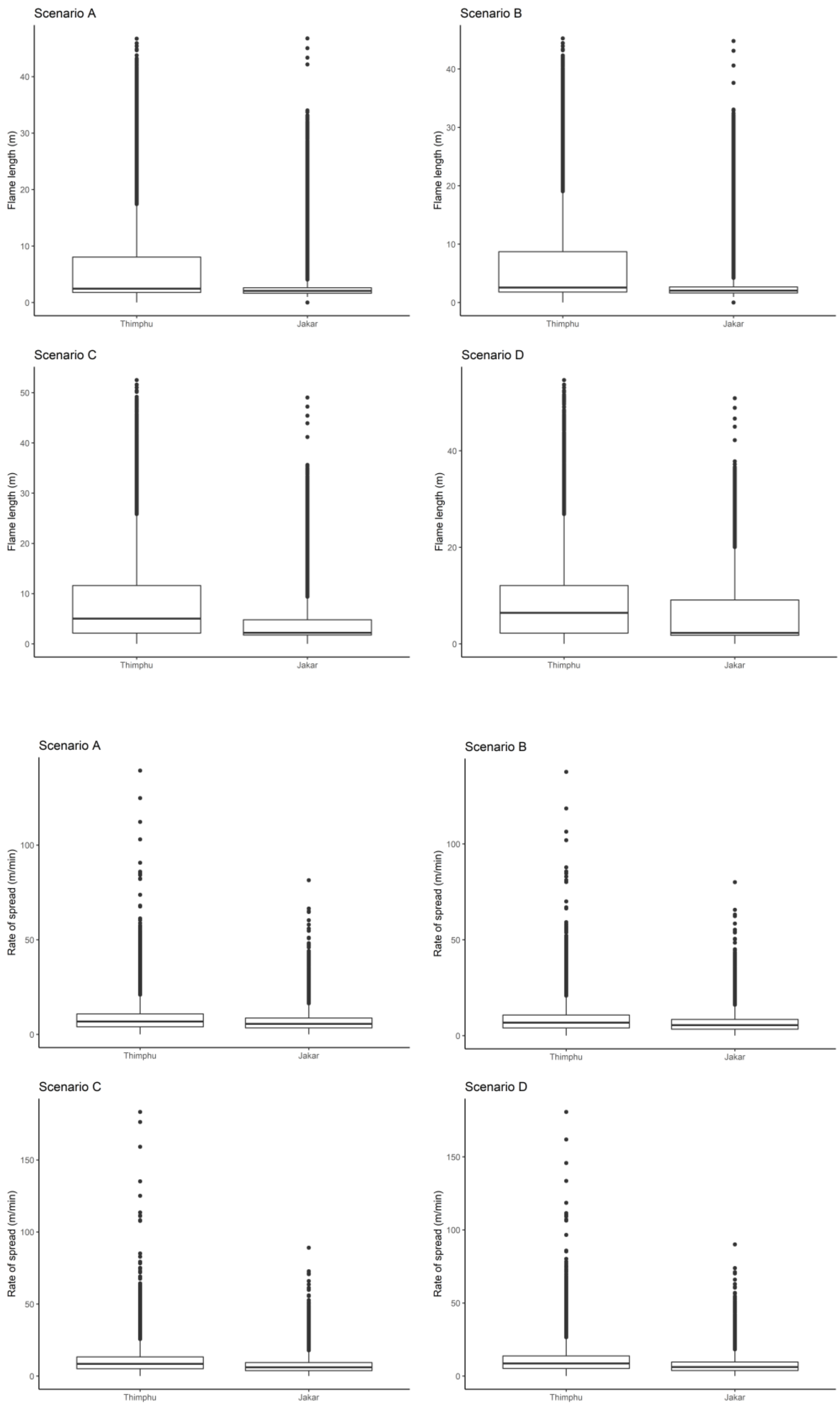

Figure 2 (a). FlamMap output values per fire behaviour and growth indicator and valley.

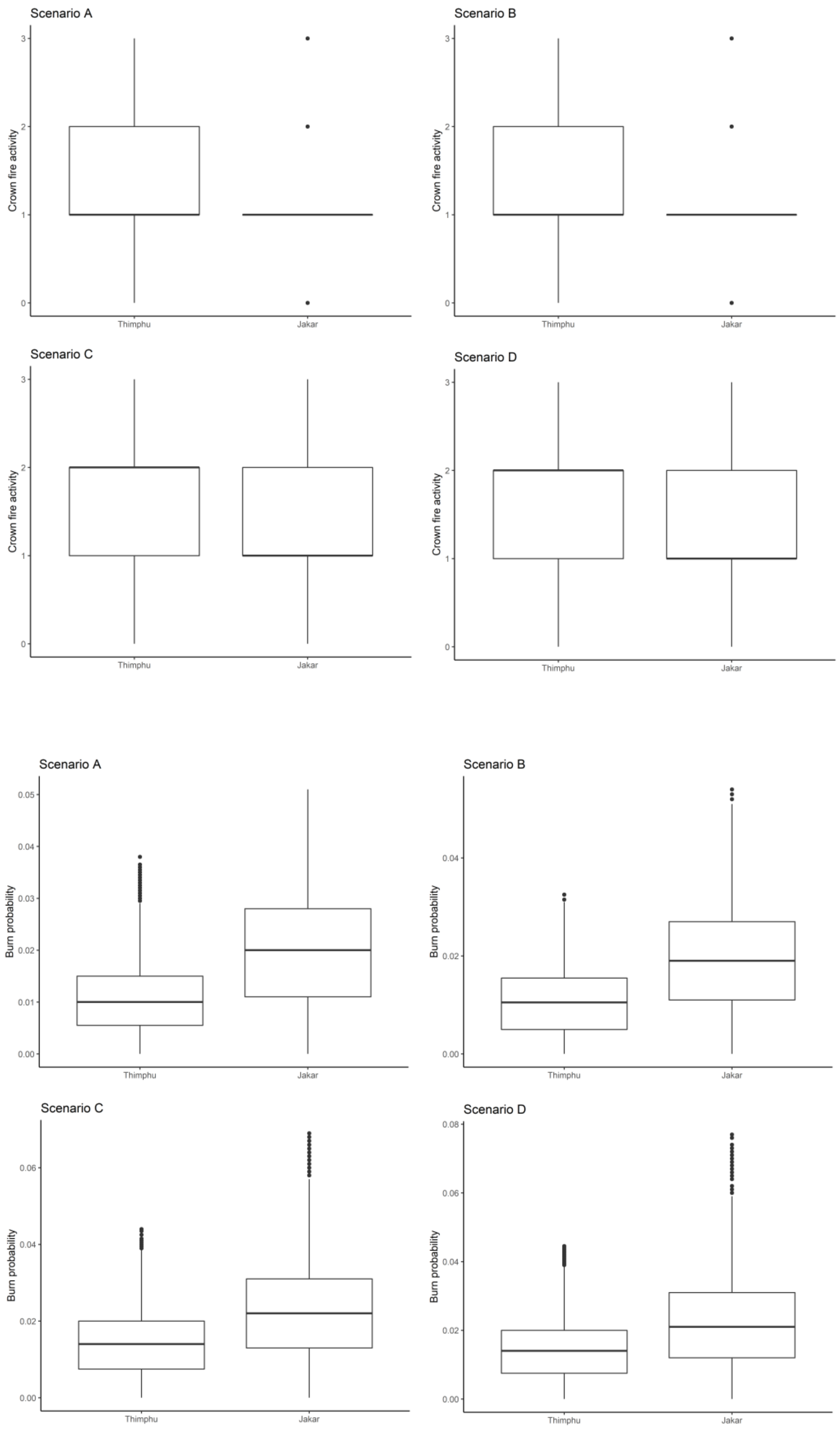

Figure 2 (b). FlamMap output values per fire behaviour and growth indicator and valley.

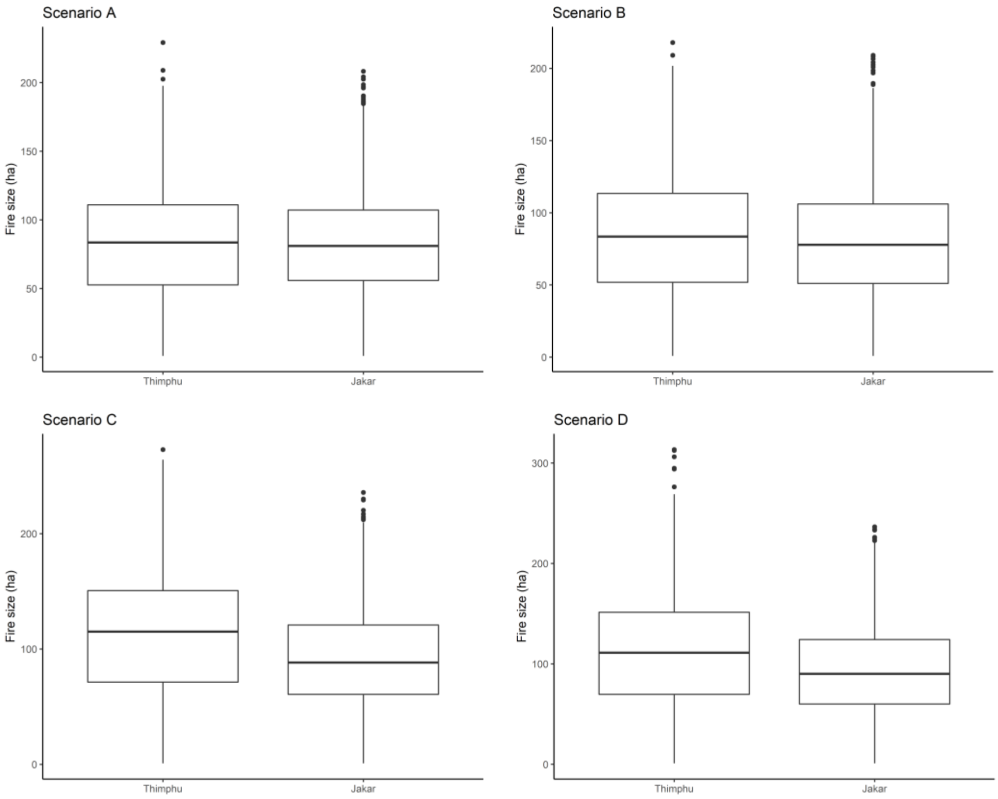

Figure 2 (c). FlamMap output values per fire behaviour and growth indicator and valley.