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# Characterization of Forest Fires to Support Monitoring and Management of Mount Kenya Forest

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Historical analysis of wildfire frequency, intensity, size, season, and type helps to determine the fire regime and the impacts of human activity in a region. Information about the temporal and spatial distribution of forest fires can help guide the formulation of integrated fire management

policies. Mt Kenya Forest provides ecosystem services that sustain the livelihoods of local communities. However, forest fires have negatively affected sustainability of these services. This study describes recent fire patterns in the Mt Kenya forest. Field observations recorded by the Kenya Forest Service from 1980 to 2015 are analyzed. In addition, trends in fire occurrence over time and in relation to vegetation type are described. Key findings

evidence a fire-prone period in February and March and a decrease of total burned area during the study period. Bush and grassland were the most fire-prone vegetation, and the fire regime varied in each forest station. Further, field observations were compared with satellite data. Some discrepancies between the field and satellite fire data were observed, especially for larger fires. These findings confirm the importance of monitoring efforts by the Kenya Forest Service to inform wildfire management. Recommendations are made on ways to improve fire monitoring and fire suppression efforts.

**Keywords:** Fire regime; remote sensing; Moderate Resolution Imaging Spectroradiometer (MODIS); burned area; vegetation; fire management; Africa.

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## Introduction

Fire is a key factor shaping the landscape and influencing vegetation structure (Dempewolf 2007) and composition (Detsch et al 2016). Fire frequency, distribution, and severity are fundamental drivers of ecosystem dynamics (Tansey et al 2004), and although many ecosystems are well adapted to recurring fire events, human activities and climate change have modified traditional fire regimes. In Kenya, the human impact on fire regimes became more intense after the introduction of industrial plantations in 1930 (Colombaroli et al 2016). In contrast to other regions, where fire occurrence has recently decreased (Detsch et al 2016), in Kenya the annual fire frequency slightly increased in the last century, a consequence of a growing human population with increasing per capita food consumption that is driving agriculture expansion and affecting natural ecosystems (Grau et al 2008; Nyongesa 2015). The communities living around Mt Kenya depend on its forest for fuelwood, grazing, fishing, and nontimber forest products (Nyongesa and Vacik 2019). Pastoralists from neighboring counties also bring their livestock to Mt Kenya to pasture during the dry season, increasing the pressure on resources (KWS 2010).

Wildfire causes in Africa are mainly related to human activities (Wass 2000; Lambrechts et al 2002; Detsch et al 2016); natural ignition, such as by lightning or friction between dry leaves, is extremely rare (Poletti 2016). At Mt Kenya, fires in bushland and forest are common because community members use fire to burn charcoal, harvest honey, hunt in the forest, prepare farmland, break impenetrable bushland, and control weeds, pests, and parasites (Nyongesa and Vacik 2018). Among local people, lack of awareness of the need to evaluate and balance the relative risks posed by fires against the beneficial ecological and economic effects is common (Poletti 2016; Nyongesa and Vacik 2018).

In these mountainous and frequently inaccessible areas, many fires occur in the dry seasons (Dempewolf 2007). Firefighting efforts are often hampered by lack of information, equipment, and training (KFS 2010). Although strong efforts have been made to understand wildfire patterns in African savannah ecosystems (Meyer et al 2005; Govender et al 2006), few similar studies have been done for the mountains of East Africa (Buytaert et al 2011). Resources used to reconstruct a fire regime include field fire records, paleoecological evidence, and satellite images (Eastaugh and

Vacik 2012; Colombaroli et al 2016; Dioszegi 2018). Solid information about forest fire characteristics could help guide the development of fire policies and management principles in Kenyan mountain forests.

The Mt Kenya forest is an indispensable natural resource, providing ecosystem services, income from tourism, and job opportunities for local communities and other Kenyans. Despite its importance and long fire history, studies of Mt Kenya forest fire ecology are scant (KFS 2010). This study of the fire regime of the Mt Kenya forest aimed to characterize fire location and period and the type(s) of vegetation most affected by fire. Its main goals were to (1) collate and analyze field-based fire records collected by the Kenya Forest Service (KFS) from 1980 to 2015, (2) detect any trend in fire occurrence by time, location, and in relation to vegetation type, (3) compare the field-based records with satellite-based data, and (4) develop recommendations for more effective forest fire management.

## Material and methods

### Study area

Mt Kenya (0.15083° S and 37.3075° E) is located in the central highlands of Kenya and spreads over 5 counties: Embu, Kirinyaga, Meru, Nyeri, and Tharaka Nithi. The mountain, covering an area of more than 200,000 ha, hosts almost 15% of Kenya's native forest (Emerton 1999; UNESCO 2013). The 5199 m high mountain provides drinking water and hydroelectric power to a great part of the country (Enjebo and Öborn 2012). The Mt Kenya forest plays an essential role for the Kenyan people, especially for those who live close to it. It is a source of income for more than 200,000 people who live within 1.5 km of its edge (Emerton 1999) and depend on it for firewood, charcoal, food, water, herbal medicine, and income from tourism. Mt Kenya's importance is globally recognized; it was designated as a United Nations Educational Scientific and Cultural Organization (UNESCO) Natural World Heritage Site in 1997 (Gichuhi et al 2014).

Mt Kenya has climatic patterns typical of boreal forests (Downing et al 2016). Its rare afro-alpine ecosystem (UNESCO 2013) occurs only in a few elevated areas on the continent (KWS 2010). The forest, at 2000–3500 m elevation, is mainly characterized by *Olea capensis* L., *Juniperus procera* H., and *Podocarpus* spp (Niemelä and Pellikka 2004; Gichuhi et al 2014) and has high biodiversity (Bussmann 1994). Due to its equatorial location, there is little or no difference between northern and southern aspects (Young and Peacock 1992), but orographic precipitation characterizes the region's humid eastern and southern areas (2500 mm precipitation per year), while the northern area is dry (less than 1000 mm per year) (Lange et al 1997; Gichuhi et al 2014). Heavy rains occur from the middle of March to the beginning of June ("long rains" period) and from the middle of October to December ("short rains" period) (Henne et al 2008). The East African climate has changed in the last decades, and more intense rain and drought periods are forecast for the future (Hulme et al 2001). Fire, climate, and vegetation are closely connected (Satendra and Kaushik 2014), and an alteration in rain patterns may influence the vegetation composition and fire regime.

The mountain is divided into 2 main administrative areas (Figure 1). The Kenya Wildlife Service (KWS) is responsible

for Mt Kenya National Park (69,406 ha), the innermost area. KFS manages the 20 forest stations that make up the Mt Kenya Forest Reserve (213,083 ha) (KFS 2010; Gichuhi et al 2014). Each forest station is a management unit area of Mount Kenya Forest. It has a well-defined administrative boundary and is managed by a forest manager employed by KFS. KFS and KWS work together to document and fight fires (Nyongesa and Vacik 2018). Mt Kenya community forest associations were formed in 2009 to involve communities in managing forest and wildlife resources and to help regulate human activities according to the agreed user rights (KFS 2017). Participatory forest management includes regular maintenance of fire breaks, forest protection by community scouts, regulated grazing to control grass growth, and community involvement in silviculture (Republic of Kenya 2005, 2016).

The current forest distribution is defined by geographic, climatic, and anthropogenic characteristics (Satendra and Kaushik 2014) with many local microclimates due to the irregular topography (Buytaert et al 2011). Fire is the major hazard for Mt Kenya vegetation (IUCN 2013), altering its structure and composition (Poletti 2016). Some plant species are fire-intolerant; others, like *Juniperus procera* H. and *Hagenia abyssinica* Bruce (Lange et al 1997; Njeri et al 2018), require fire to germinate, establish, or reproduce (Adie and Lawes 2009; Butz 2009).

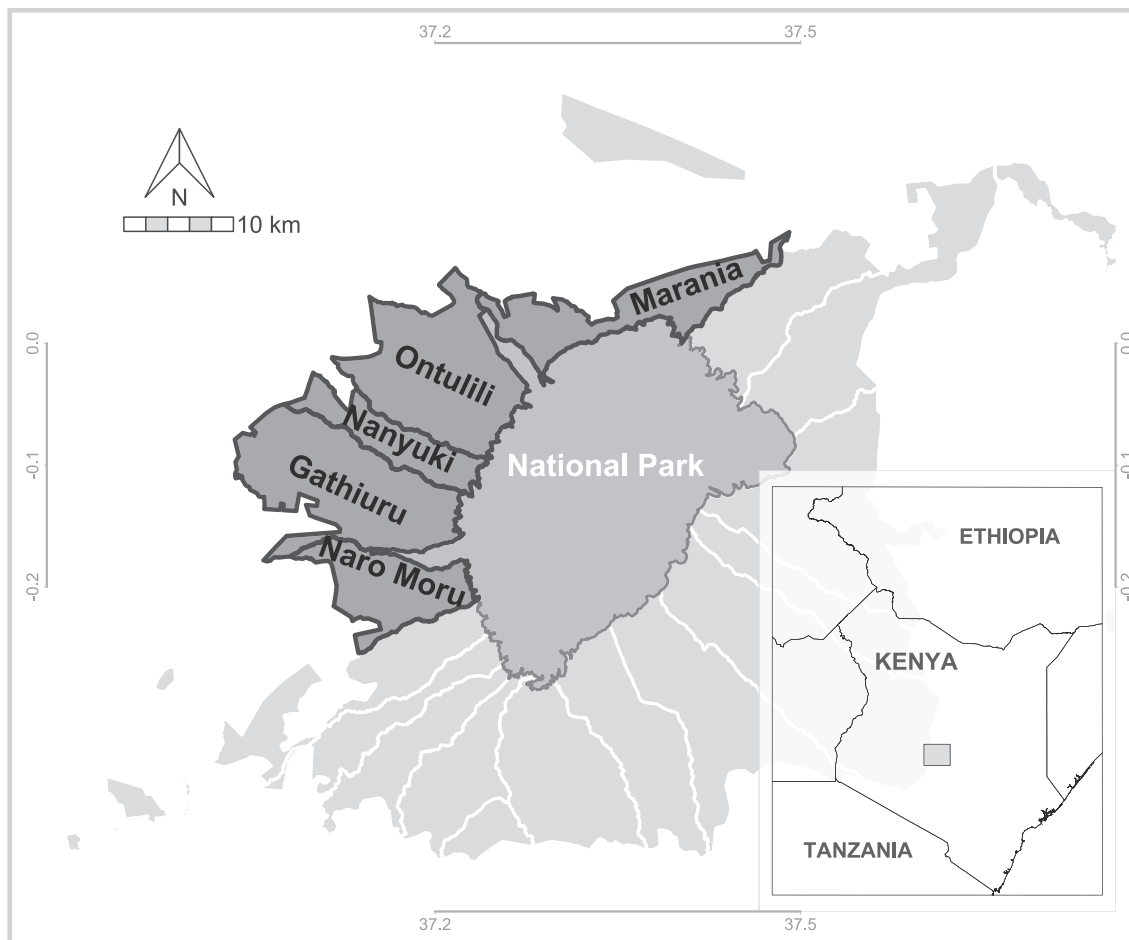
The most fire-prone areas are those spanning the lower western forest to the northeast, where the fire risk is strongly increased by lack of rainfall during the dry seasons (KWS 2010). Our study area, 5 fire-prone forest stations (Marania, Ontulili, Nanyuki, Gathiuru, and Naro Moru; Figure 1) extending over 53,726 ha, was selected based on the availability of field fire records.

### Fire records

KFS station managers document wildfire size, date, causes, and firefighting actions, estimating burned area directly in the field or, if the burned site is not easily accessible, through aerial imagery. Fires that start in the forest reserve can spread to the national park and vice versa, so some fire records kept by KFS cover fires that occur on the moorland in the national park (Nyongesa and Vacik 2018). The moorland was excluded from our study because it is not forested and grows at higher elevations (Lange et al 1997) outside the Mt Kenya forest boundaries. In March 2016, all KFS documents related to fire events that occurred from 1980 to 2015 were digitized and converted to an Excel spreadsheet (Poletti 2016).

The Kenyan Forestry Research Institute provided Esri shapefiles of forest station boundary maps and Mt Kenya vegetation composition. The Moderate Resolution Imaging Spectroradiometer (MODIS) provided the burned area fire product MCD45A1, which provides information about the confidence in detecting burned versus nonburned areas (Boschetti et al 2009; Giglio et al 2015; Sharma et al 2015). The MCD45A1 product combines data from 2 satellites (Aqua and Terra) and returns monthly estimates of burned areas; it has a spatial resolution of around 500 m. In this study, MODIS MCD45A1 product polygons were used to select burned areas within the studied forest stations, along with another MODIS product, MCD14DL Collection 5, which provides detected fire occurrences on a monthly basis.

**FIGURE 1** Location of the study area on Mt Kenya. Mount Kenya Forest Stations: light gray with white borders; National Park: darker grey; forest stations (study area): darker gray with black borders. (Map by Dioszegi Gergo)



Ignition sites (Dioszegi 2018) were displayed to visualize the spatial extent of burned areas and ignition sites.

Field data were cleaned (unreliable records were removed) and analyzed to verify any anomalies in the recording system. The field dataset was split into 2 periods, 1980–1999 and 2000–2015. These intervals contain similar numbers of fire events, and the latter period coincides with the years for which satellite-based burned area product was available.

The hypothesis assumed that if there were no differences between the field data observation in the different periods (1980–1999 and 2000–2015), the field dataset could be considered consistent through the years. Conversely, the presence of differences between the periods might suggest some change in the data collection method. The comparison focused on the relation between burned area and fire frequency (Eastaugh and Vacik 2012). It was assumed that (1) small fires tend to appear more often than large fires and tend to be underreported, especially in older data sources, thus affecting dataset consistency; (2) fire size and frequency relationships can be described by power law distributions that show no significant changes over time (Malamud et al 2005); and (3) such power laws refer to the upper tail of the distributions. For power law fitting, a minimum burned area ( $K_{min}$ ) threshold was calculated, under which burned area records were excluded. The consistency between the 2 periods was verified by comparing their scaling parameters

(gamma, from power law fitting) and distributions (via nonparametric tests).

The analyses were performed in the R computational environment (R Core Team 2018). For the fit of power law distributions,  $K_{min}$  was determined as proposed by Clauset et al (2009), whose R function returned the gamma parameters of both periods; this operation also required the R VGAMdata package. Then, the presence of differences was assessed with nonparametric tests as burned area size is not normally distributed. Similarly to Eastaugh and Vacik (2012), we performed the Kolmogorov-Smirnov test (K-S) (Unsworth et al 1999; Sekhon 2011). K-S (R matching package) returned the significance of the maximum absolute distance (D) between 2 cumulative curves, in this case between the burned area distributions of the 2 periods. Since K-S describes a part of distributions only (the interval with the maximum D), we also used the Kruskal-Wallis test (K-W) (Ostertagová et al 2014; Dinno 2015). K-W (R stats package) gives a critical value below which 2 ranked distributions can be considered as taken from the same population. To get more insights, we also performed K-S and K-W tests on paired subsets of data from the 2 periods according to determined threshold sizes ( $\geq 20$  ha,  $\geq 5$  ha but  $< 20$  ha, and  $\geq 0.5$  ha but  $< 5$  ha; the  $< 0.5$  ha class was excluded due to its small sample size).

After dataset evaluation, the study focused on characterizing the fire regime and identifying any fire trends



**TABLE 1** Goodness of fit of power law relationships for each study period.

	1980–1999	2000–2015	1980–2015
Number of fires	38	39	77
Gamma (best-fit power law exponent)	1.595	1.611	1.595

through the year and within different vegetation types. In this analysis, 2 new periods (1984–1999 and 2000–2015) were considered. Fire events before 1984 were excluded in order to provide 2 time periods of equal length (16 years), which was assumed to provide a better perception of similarities and differences in burned area size and fire occurrences.

To characterize the fire regime, we estimated the number of fire events, fire frequency, total burned area, fire rotation (amount of time the whole study area takes to be burned), mean burned area, and mean annual burned area (Downing et al 2017) for the whole period (1984–2015) and for the 2 subperiods (1984–1999 and 2000–2015). The monthly occurrence of fires during the 32 years and in the different vegetation types was also analyzed.

Following directions provided in the work of Dioszegi (2018), the field dataset was compared with the burned areas determined via satellite. First, a method called the absolute summed percentile (ASP) was created and applied for the comparative analysis. The ASP was calculated with the following formula:

$$ASP\% = \sum_{h,i=0}^n \left[ (x_h + y_i) / \sum_{abs} (x_h + y_i) \right] \times 100 \quad (1)$$

where  $x$  is satellite-based burned area size,  $h$  is its  $h$ -th iteration,  $y$  indicates field-based burned area sizes and  $i$  is their  $i$ -th iteration. Obtained values were binned into 6 increasing 3% classes, determined as  $\geq 15\%$ ,  $\geq 12\%$  but  $< 15\%$ ,  $\geq 9\%$  but  $< 12\%$ ,  $\geq 6\%$  but  $< 9\%$ ,  $\geq 3\%$  but  $< 6\%$ , and  $< 3\%$ . The generated ASP classes represent weighting. The higher an ASP class is, the more weight the class takes in the absolute sum  $[\sum (x_h + y_i)]$  of burned areas (ie the size of the burned area was detected more often or the burned area size was considerably higher for the given class). This made it possible to reveal the underlying structure of large (ie above 500 ha) burned areas detected by the different systems.

A second, quantitative comparison was conducted for 2000–2015 and visualized with a mirrored bar chart indicating yearly burned areas and fire seasonality as recorded by satellite and in the field. The spatial distribution of satellite-detected seasonal burned areas and ignition sites was plotted on map.

## Results

### Evaluating field fire records

The selected forest stations reported 153 fire events from 1980 to 2015. Of these, 5 occurred on the moorland, and 1 had to be omitted because of its unconventional documentation format. This study analyzed the remaining 147 fires: 73 in 1980–1999 and 74 in 2000–2015. Exclusively for the comparison of time periods through power law fitting, data were reduced according to the  $K_{min}$  value (20 ha) to 77 fires (38 in 1980–1999 and 39 in 2000–2015). The resulting gamma values are very similar for both periods (Table 1).

Differences in the K-S D-statistic values turned out to be insignificant ( $P > 0.05$ ), as can be seen in Table 2 and Figure 2. K-W observed values for the subsequent burned-area categories did not exceed their critical values. No significant differences between the fire area distributions of the 2 periods could be found from the K-S and K-W tests.

### Characterizing the fire regime

From 1984 to 2015, 130 fire events occurred in the analyzed forest stations, destroying 19,236 ha of forest (Table 3). The territory was affected on average by 4 fires per year and a fire rotation of 89 years was registered. Fewer fires (56) occurred from 1984 to 1999 than in the following period (74 in 2000–2015); on the other hand, the mean individual fire size and mean total burned area per year were higher in the first period (177 ha and 620 ha per year, respectively) than in the second period (126 ha and 582 ha per year, respectively).

Throughout the study period, fires occurred primarily in the first 3 months of each year (Figure 3), burning 16,386 ha (more than 85% of the total burned area) in February and March alone. After 2000, a few big fires occurred later in the year as well. Burned area was the greatest (5580 ha) in March from 1984 to 1999 and in February (5111 ha) from 2000. A notable area (967 ha) burned in January only in the first

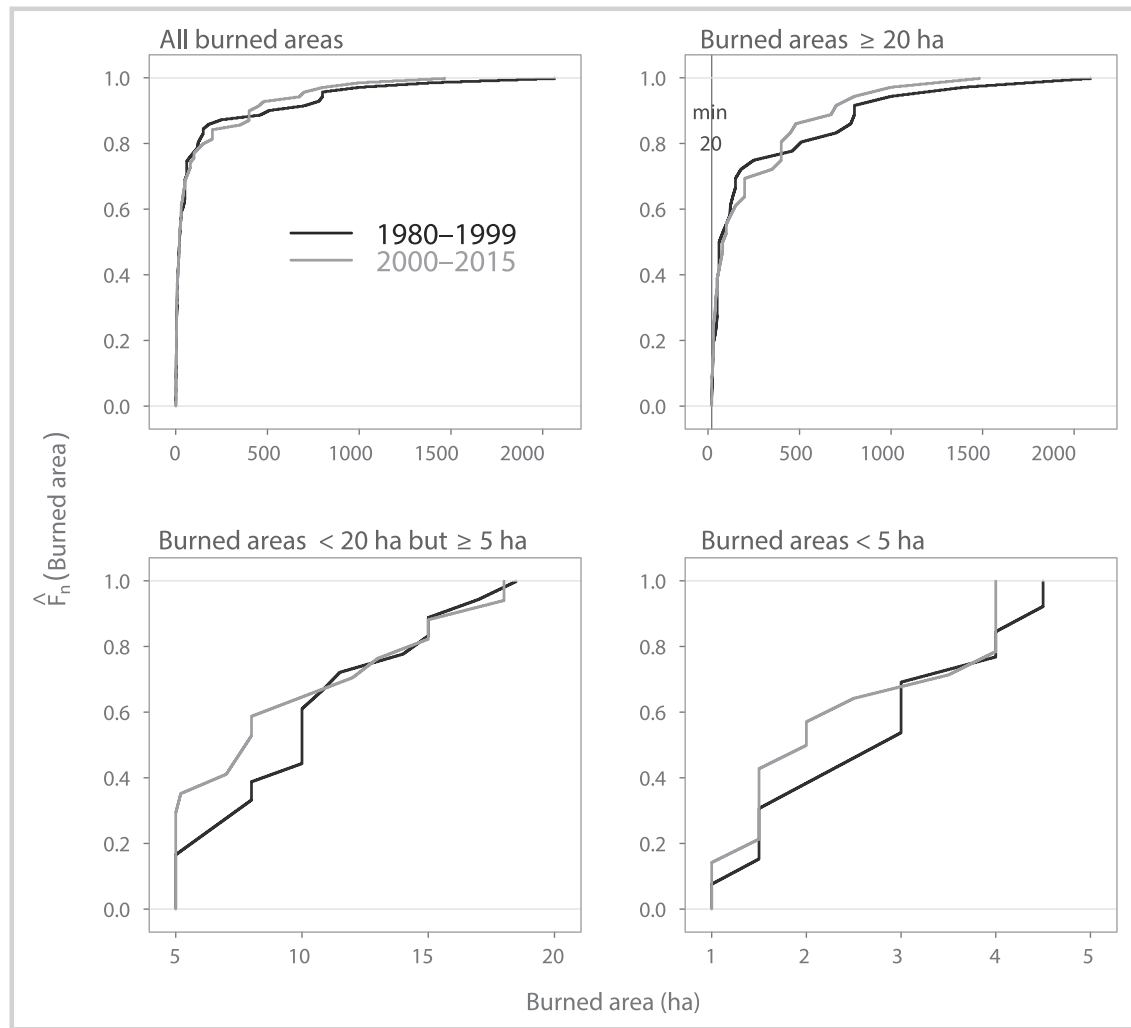
**TABLE 2** Results of K-S and K-W conducted on burned area size as detected in the 2 study periods. Because of the small number of cases, we excluded areas  $< 0.5$  ha from the analysis.

	All fires	Fires by extent of burned area		
		$\geq 20$ ha	$< 20$ but $\geq 5$ ha	$< 5$ but $\geq 0.5$ ha
Number of fires, 1980–1999	73	38	19	18
Number of fires, 2000–2015	74	39	18	16
K-S D-statistic value <sup>a</sup>	0.052	0.097	0.190	0.188
D-statistic P-value	1.000	0.993	0.892	0.956
K-W observed value	1.347	1.117	2.596	1.741
K-W critical value <sup>b</sup>	18.092	13.135	9.171	8.299

<sup>a</sup>) This represents the maximum absolute distance (D) between the burned areas' distributions in the 2 time periods.

<sup>b</sup>) This represents the value below which 2 ranked distributions can be considered as taken from the same population.

**FIGURE 2** Results of K-S: a comparative analysis of empirical cumulative distribution function curves of burned areas for 1980–1999 and 2000–2015 for the subset burned area classes indicated above the concerned panel. The calculated minimum burnt area threshold, 20 ha, is shown in the top right panel.



period, and in July and September (709 ha and 497 ha, respectively) only in the second. The 2 periods had similar trends in fire occurrence, showing a notable difference only in the most fire-prone month, February, with 23 fires detected in the first period and 33 in the second. Other fire-prone months were March (with 31 events across both study periods), January (with 11), and September (with 13). In the earliest years, March was also the month with the highest

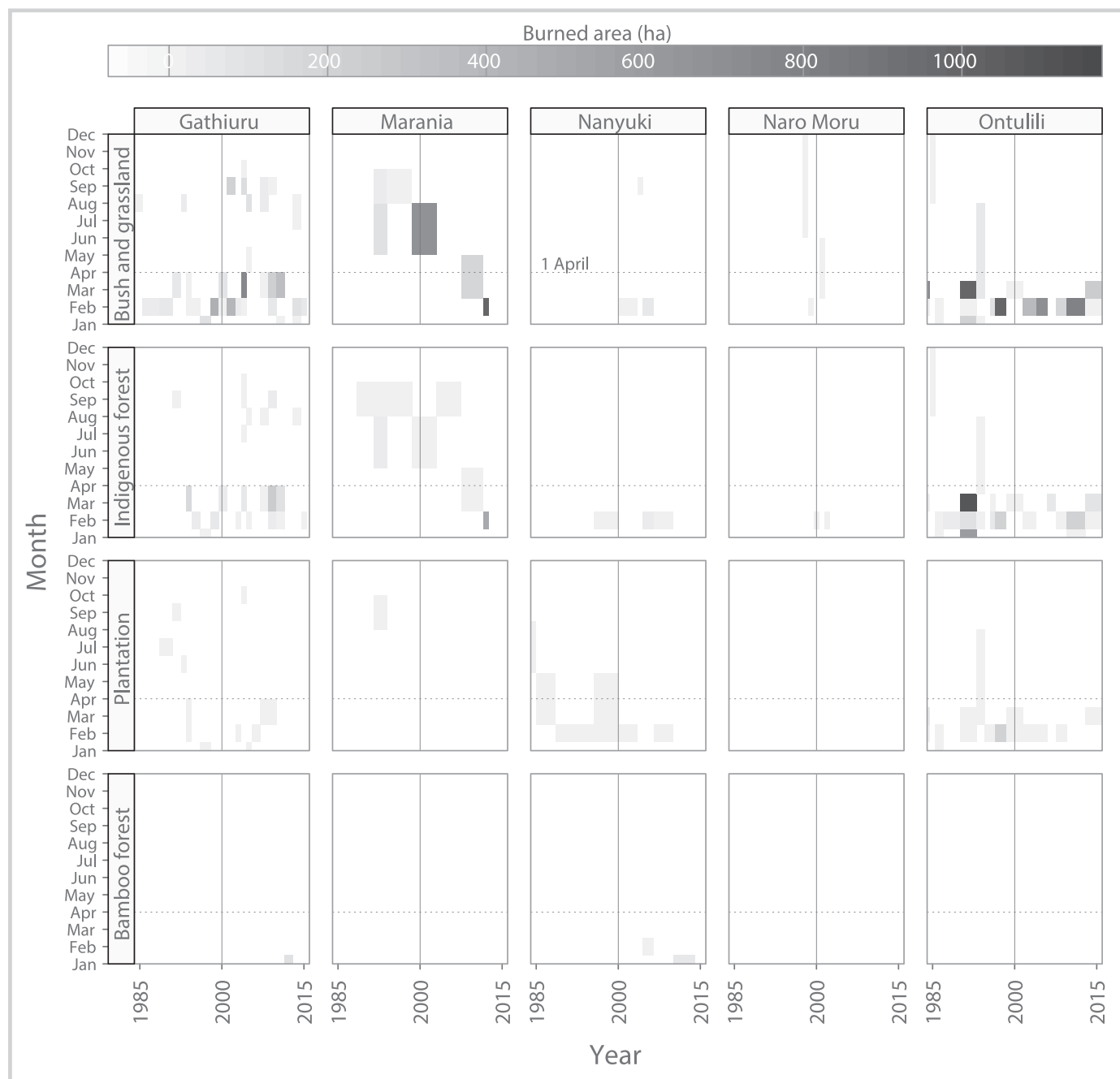
mean annual burned area (350 ha/year), but this seemed to move to February (320 ha/year) in the second period.

Bush and grassland were the most fire-prone vegetation types (Figure 3), mentioned in more than 65% of the fire reports. These areas experienced fire regularly throughout the study period, with little or no difference between the 2 subperiods. Over the 32 years of the study period, Mt Kenya Forest lost 14,000 ha of bush and grassland (6600 ha in 1984–

**TABLE 3** Fire statistics for Mt Kenya.

Index	1984–1999	2000–2015	1984–2015
Number of years	16	16	32
Number of fires	56	74	130
Number of fires per year	3.5	4.6	4.1
Total burned area (ha)	9924.15	9312.45	19,236.60
Fire rotation (y)	87	92	89
Mean individual fire size (ha)	177.22	125.84	147.97
Mean burned area (ha/year)	620.26	582.03	601.14

**FIGURE 3** Characterization of Mt Kenya forest fires, 1984–2015. Dotted horizontal lines indicate April 1, considered the end of the main fire season; solid vertical lines separate 1984–1999 from 2000–2015. Burned areas by month, year, forest station, and vegetation type. Rectangle width indicates the occurrence of fire during the months, while shading indicates the size of burned areas.



1999 and 7400 ha in 2000–2015). Burned area as a proportion of total burned area increased from 34% to 38%.

The areas covered by Gathiuru and Ontulili forest stations revealed similar fire behavior, with the majority of events detected from January to March. By contrast, Marania experienced fires mainly from July to September, especially from 1984 to 2000. The 3 forest stations were affected especially in indigenous forest and in bush and grasslands; on the other hand, Nanyuki was affected almost exclusively in the plantation (Figure 3).

Figure 3 summarizes the major fire trends in the study area. The most fire-prone season was February/March, and fires occurred predominantly in bush and grassland. The

most affected forest stations were Gathiuru, Ontulili, and Marania.

In the first period, fires affected plantations (55% of fires) more frequently than indigenous forest (48% of fires); but in the second period, more than 60% of fires occurred in indigenous forest and fewer than 25% on plantations. On plantations, fire destroyed more than 400 ha (2% of total burned area) in the first period but less than 90 ha (0.5%) in the second period. A similar trend occurred in the indigenous forest, where the burned area decreased from 2884 ha (15%) in the first period to 1673 ha (8.7%) in the second period. Fires occurred in bamboo forest only in the second period, with a loss of 155 ha (Table 4).

**TABLE 4** Burned area by vegetation type and study period.

Vegetation type	Burned area size (ha)		Burned area % of total burned area 1984–2015	
	1984–1999	2000–2015	1984–1999	2000–2015
Bush and grassland	6627	7396	34.5	38.4
Indigenous forest	2884	1674	15.0	8.7
Plantation	413	87	2.1	0.5
Bamboo forest	0	155	0.0	0.8

### Comparison of field and satellite fire data

Comparison of the 2 datasets was possible only for the second study period because satellite data were not available for the earlier period. For 2000–2015, the field data showed a burned area of 9312 ha, while satellite data showed 8439 ha (Table 5). With a spatial resolution of about 500 m, the satellites can only detect burned areas bigger than 24 ha. For this reason, 304 ha of the burned area recorded in the field (the sum of all recorded burned areas smaller than 24 ha) were not detectable by the satellite sensor, reducing the difference between the 2 datasets to 569 ha. Greater differences between the 2 datasets existed in some forest stations. For example, for Marania, the forest station with the highest percentage of burned area, the field documents indicated that 30% of the area was burned, while satellite data indicated more than 70%. In terms of total burned area, the field data indicated that Gathiuru had the most at more than 3400 ha, while satellite data indicated that Marania had the most at 5500 ha (Table 5). Gathiuru had the most fire events according to the field data, and Marania had the most according to the satellite data.

More in-depth comparison revealed additional differences between the 2 datasets. The amount of burned area detected by at least 1 of the 2 systems was 14,356 ha, of which 3394 ha (24%) was registered by both systems in the same month within the same forest station; 5045 ha (35%) was recorded in a defined month and forest station only by the satellites; 5917 ha (41%) was recorded only by the field documents, of which only 304 ha (2% of the total) was not detectable by the satellites due to restricted detection capability (only areas >24 ha were detectable).

The slightly diverging  $R^2$  trend lines in Figure 4 indicate different large burned area detection for less and more

weighted classes of ASP. This weighting follows a logical principle: more frequently occurring large burned areas and larger burned areas mean larger fires, more devastation, more firefighting effort, and accordingly higher costs. Large less-weighted burned areas (ASP classes <3% and 3%–6%) were detected similarly in both datasets. No ASP value fell into the 9%–12% class; more frequent large burned areas and extremely large burned areas (12%–15% and ≥15%) were detected by field observations than by satellites.

The majority of burned areas registered by the satellites from April to December were detected in Marania, while in Gathiuru and Ontulili fires occurred mainly from January to March. Ignition sites revealed that the difference of fire occurrence between the high dry season and the rest of the year is common in all the considered forest stations (Figure 5).

Satellite data revealed a slight increase in fire frequency and burned area size after 2008, while field data showed only fluctuation of burned area size from 2000 to 2015. Both datasets recorded a high number of fires and large burned areas in 2002, 2005, 2011, and 2012. In 2008, fires that burned a large area were detected only by satellite, while in 2004, burned areas were detected only in field data. Both data sources were able to detect distinct seasonality, with greater fire activity from January to March than from April to December (Figure 5).

### Discussion

The K-S and K-W did not show any significant anomaly during the study period for any size class, suggesting a certain consistency of the dataset. Discrepancies were detected only considering small fires. The gaps in the lower tail of the distribution might be the result of underreporting of small fires in older records, as the curve representing the earlier period tended to be the lowest (Figure 2C, D), but no clear evidence of the differences has emerged. The field records had similar data in the 2 study periods, suggesting stability in the fire detection and fire recording system from 1980 to 2015.

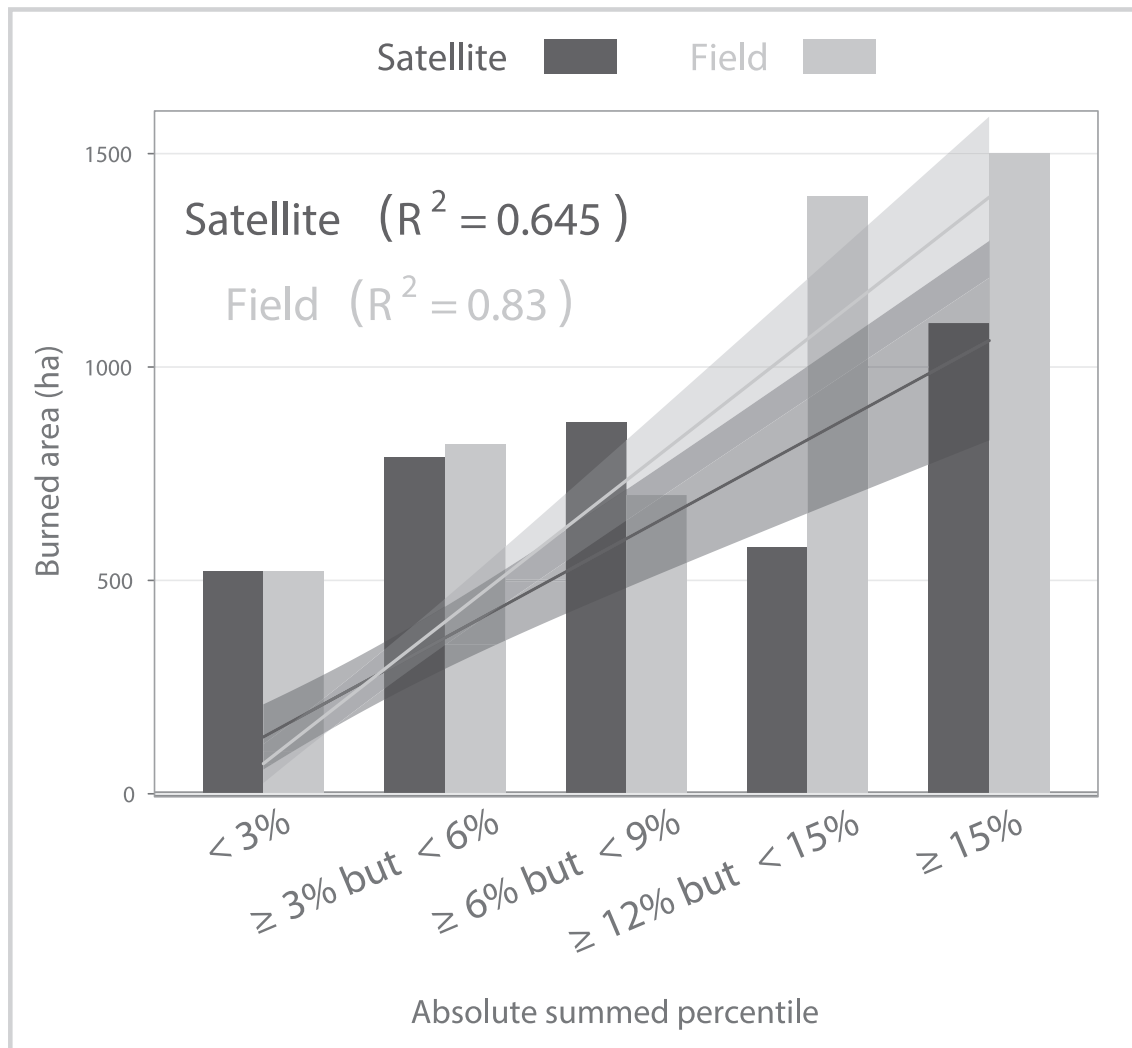
The mean fire size detected in our research (147.97 ha) is more than those detected in Kenya as a whole (around 100 ha) (Nyongesa 2015). Forest fires occur mainly from January to March and from July to September, during the dry seasons (Karanja 2016), but we observed differences in seasonal patterns in the 2 study periods, with the period of peak fire activity moving from March (1984–1999) to February (2000–2015). High fire occurrence from July to September was recorded in the study area only since 2000; in the same time

**TABLE 5** Forest stations' total size and amount of burned area from 2000 to 2015.

Forest station	Size (ha)	Burned area (ha)	
		Field data	Satellite data
Gathiuru	16,368	3483	692
Marania	7857	2385	5551
Nanyuki	5805	242	148
Naro Moru	7871	28	2
Ontulili	15,825	3174	2046
Total	53,726	9312	8439



**FIGURE 4** ASP comparative analysis results performed on satellite data and field data. No ASP value fell into the 9%–12% range. Lines are shown to help in visualizing the underlying behavior of ASP classes with respect to detection of large burned areas.



period, fire activity dropped in January. Our research found a clear fire season only in February–March in Mt Kenya Forest, but large fires were recorded during the second dry season (July–September) as well. Other researchers (Downing et al 2017) have found a shift from 2 fire seasons to a single season in Mt Kenya National Park as well, but this area is almost totally covered by moorland, a highly flammable vegetation present only at the high altitude of Mt Kenya. On the other hand, by local residents of Gathiuru forest station still perceive the second dry season (July–September) as a “relevant fire season,” and Dioszegi (2018) described it as a “fire-sensitive” period.

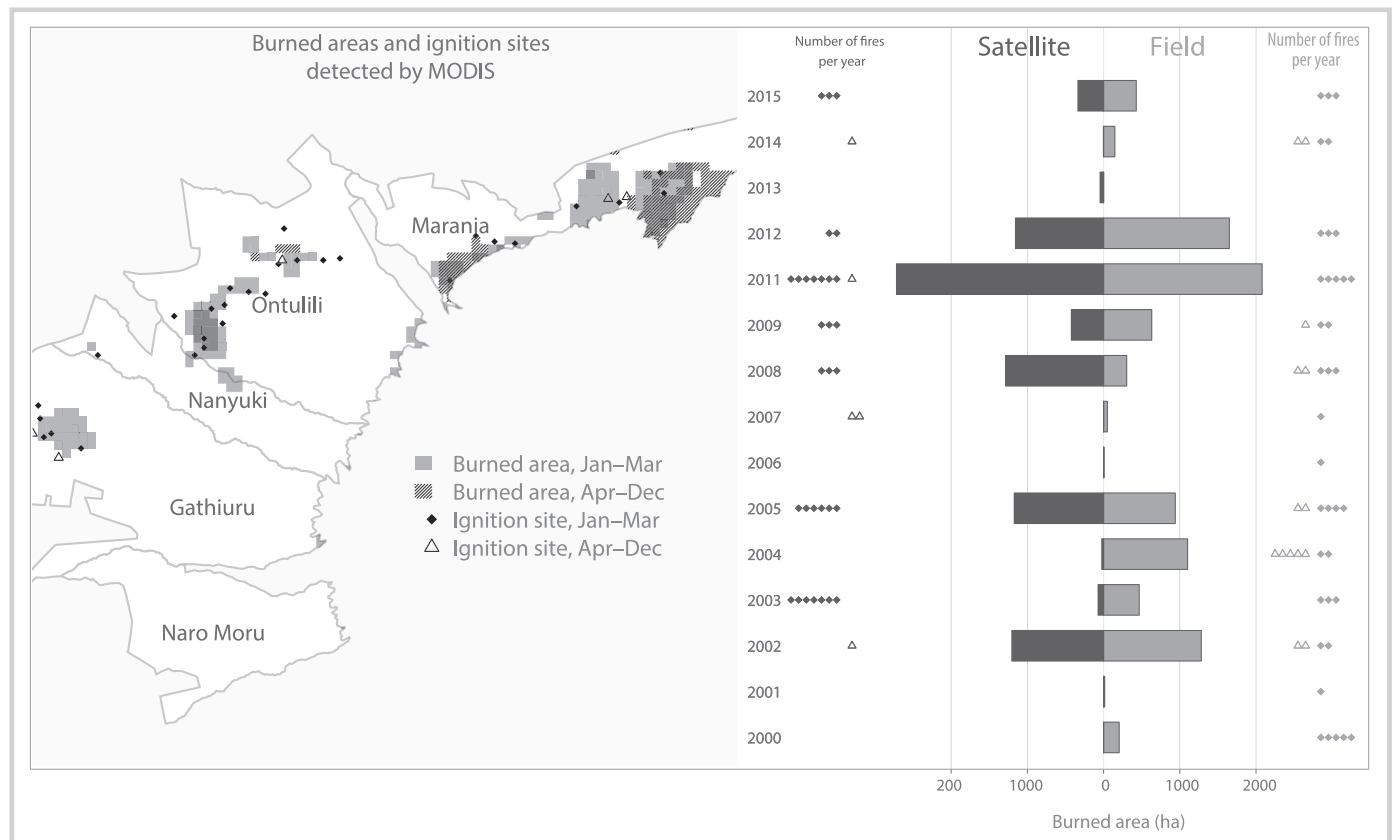
The correlation between climate change, wildfires, and vegetation composition is commonly accepted (Wooller et al 2002; Levin et al 2016). This correlation could carry the changing meteorologic patterns to the fire regime and, consequently, to the vegetation structure and composition (Poletti 2016; Downing et al 2017). Fire can alter forest in different ways depending on frequency and intensity. It reduces the amount of trees and their dimensions; moreover, it can favor the growth of species not, or less, preset in the natural forest not affected by fire (Poletti 2016). At the same time, fire composition can influence fire behavior (Kane et al

2014). Fire ignition and spread are strictly related to vegetation flammability (Nelson et al 2012). In Mt Kenya, fires occur more frequently in grasslands (Dioszegi 2018), in which, due to their high flammability, fires ignite easily and are difficult to extinguish (Downing et al 2017). Grasses and shrubs usually grow very rapidly during the rainy season and dry up during the dry season, increasing fine fuel accumulation and continuity (Archibald et al 2010). Moreover, before the rainy season begins, pastoralists set fires in the grassland to keep it open and to facilitate the growth of new grass for feeding livestock, thereby increasing fire ignition in this vegetation type (Nyongesa and Vacik 2018).

Field fire records showed the largest burned area in Marania forest station, while the highest fire occurrence was detected in Gathiuru. Except for Gathiuru and Ontulili, each forest station evidenced different periods of fire occurrence and vegetation affected (Figures 3 and 5). This might be related to land-use practices in each single forest station, highlighting the variability of fire behavior in a relatively small area like our study area.

A similar number of fires occurred in indigenous forests as in bush and grassland, but the burned area was smaller

**FIGURE 5** Comparative burned area documentation. Map represents burned areas and ignition sites (as classified by Dioszegi 2018) for satellite data only. The bar chart on the right compares burned areas between satellite and field data for 2000–2015. Black dots and white triangles evidence the seasonality of fire occurrence in both map and bar chart. The year 2010 is omitted because no records were available in any datasets. (Maps by Dioszegi Gergo, based on MODIS MCD14DL Collection 5 data [Dioszegi 2018])



throughout the study period and decreased in 2000–2015. This might be related to indigenous forests' higher value for local people but also to the increased participation by community forest associations in forest fire management. Plantations are more prone to fire spread than indigenous forest due to their structure and the high flammability of most plantation species (Karanja 2016). However, in Mt Kenya Forest, plantations are often more easily reached by firefighters and therefore more effectively protected. Their higher economic value could be a motivation to provide additional protection.

The lack of fire ignition site coordinates in field data does not permit a deeper comparison between the 2 datasets, which showed some discrepancies. The field and satellite fire records provide a good description of the fire regime in the region, evidencing fire-prone areas, vegetation, and periods. The field data are considered to be the most detailed fire documentation for Mt Kenya Forest as they contain a range of information in addition to what we analyzed in our study. Moreover, they do not have spatial detection limitations for small fires. The comparison of the 2 study periods of field data suggests that they are consistent over time. On the other hand, the lack of a proper storage system and human failures can influence the reliability of the dataset (Poletti 2016).

Satellite data are not always available (Dempewolf 2007; Detsch et al 2016). The satellite sensor may fail to detect some ignition sites and burned areas when they occur under clouds (Archibald et al 2010; Karanja 2016) or, in the case of small fires, under a closed canopy (Roy et al 2008; Tsela et al

2010). Satellites cannot detect fires smaller than 24 ha at all. MODIS was designed to produce low commission errors (Roy and Boschetti 2009; Bastarrika et al 2011), and its product, MCD45A1, contains information about the reliability of its data (Boschetti et al 2009). Its accuracy in afro-alpine ecosystems has not been thoroughly assessed. However, tests in other regions and ecosystems have indicated that it tends to underestimate burned area size (Roy et al 2005; Csizar et al 2006; Anaya and Chuvieco 2012; De Klerk et al 2012; Levin and Heimowitz 2012; Núñez-Casillas et al 2013; Ruiz et al 2014; De Araújo and Ferreira 2015; Libonati et al 2015; Fornacca et al 2017). Our study found sufficient discrepancy between burned areas and ignition sites to create uncertainty about its accuracy. The satellite system detected fire occurrences and burned areas in 2 different periods, developing 2 different datasets from these observations, 1 for fire occurrence and 1 for burned areas. The changes in cloud and/or canopy cover can alter satellite sensor efficiency. For this reason, some fires may have been detected but not registered in burned areas and vice versa.

Only about 24% of the burned areas were recorded in both satellite and field datasets. According to the ASP results, satellite and field fire records were similar for infrequently occurring large fires (ASP <3% and 3%–6%). The slightly diverging  $R^2$  lines indicate differentiation, with frequently occurring large fires and extremely large fires more often documented by the field system. This can be explained partly by satellite underestimation of burned area and partly by the consistency of the field recording system.

## Conclusion and recommendations

Fire conditions in the Mt Kenya Forest are continually changing, and it is difficult to forecast future conditions (Downing et al 2017). The field fire recording system did not change from 1980 to 2015, ensuring the consistency of the only wildfire data available before 2000. Thanks to this documentation, it can be stated that the Mt Kenya fire regime is similar to that of the country as a whole (Nyongesa 2015), with a higher number of forest fires and a lower total burned area in the last period.

Fire occurrence and spreads are related to the prevailing weather conditions, type of vegetation, intensity of local residents' activities that cause fires in the Mt Kenya Forest (Poletti 2016; Nyongesa and Vacik 2018; Nyongesa and Vacik 2019). Rain is the main natural factor that controls fires on Mt Kenya. Seasonal precipitation separates the year in 2 different fire seasons, which often coincide with dry seasons even if the most fire-prone months changed in the last years. Additionally, orographic precipitation, more frequent on the southeastern side of the mountain, limit the fire-prone areas to the western and northeastern side (KWS 2010), especially in the short dry season (Poletti 2016). Vegetation is another determinant factor of fire occurrence; total burned area and number of fires differ in each vegetation class. The study provides evidence of when fires occurred more frequently, where the largest burned areas were, which vegetation type was most affected, and how these patterns changed during the study period. Such fire regime data are essential to update and improve fire management (Satendra and Kaushik 2014), create forest fire maps, coordinate forest management activities, and raise public awareness of forest fire issues.

Fire prevention is more efficient than fighting fire. The adoption of an effective fire-prevention system depends strongly on stakeholders who directly benefit from forest services (Smith et al 2016). Fire awareness and management did not have high priority in the last century, but the recent involvement of community forest associations in forest management has contributed to monitoring of fires and reducing their damage (Nyongesa and Vacik 2018). Total burned area decreased in 2000–2015, evidence of improved forest management, monitoring, and firefighting efficiency.

The variability of fire behavior in each vegetation class and forest station suggests the need for forest fire management that is as specific as possible for each area. Different topographic and climatic conditions require different forest fire management tactics (Smith et al 2016). In a fragmented region like the Mt Kenya Forest, with many inaccessible areas, it is crucial to improve communication between local communities using radio, Internet, and text messaging to spread information about forest fire issues. The need for equipment, trained personnel, and road maintenance is also commonly accepted (Karanja 2016; Nyongesa and Vacik 2018). Stronger cooperation and coordination between stakeholders are essential to achieving fire management goals (Menya and K'Akumu 2016). Agreements between different interest groups at the local and national levels can be the starting point for problem solving (Satendra and Kaushik 2014). Coordination between KFS and KWS can definitely improve the efficiency of planning and implementing fire management, but only if local residents are involved as well (Dioszegi 2018; Nyongesa

and Vacik 2019). The reduction of fire occurrence and burned area size recorded in the plantation suggests, on the one hand, that in the last years, the size of burned areas was also related to the (economic) value attributed by local residents to the vegetation and, on other hand, that local involvement in warning and monitoring systems can greatly improve their effects (Smith et al 2016).

The comparison between field and satellite fire records revealed a gap between the 2 systems. Field data are mainly used to improve information about small fires not easily detectable by satellites, but we found that they are useful for large fires as well (Figure 4). Field and spatial data can correct each other (Levin et al 2016). Remote sensing is important to forest fire research, management, and monitoring, but it needs strong ground validation (Sonti 2015). The combination of advanced satellite detection systems and well-equipped human personnel, with fire towers and reliable communication and road systems, would improve fire detection systems (Dioszegi 2018). This, combined with improvements to the field recording system, would make satellite and field data much more comparable and useful and allow better understanding and prediction of fire spatial patterns (Levin et al 2016). More compatibility between these systems would also enable better comparative analysis of fire and climate trends.

The following improvements to Mt Kenya forest fire management are recommended:

- Disseminate reliable information about fire conditions with a well-organized communication system to increase local public awareness of fire prevention and firefighting strategies.
- Train community forest association members and other members of forest-adjacent communities in forest fire management, monitoring, and suppression.
- Encourage participation by local communities in the development of fire management plans to sensitize them about the impacts of fires in different vegetation types.
- Improve field records by adding fire ignition-site coordinates and creating a clear fire map.
- Combine the use of field fire documentation and satellite technology to further enhance the fire detection system.

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