Combining remote sensing data and ground observations to identify fire patterns and develop an Integrated Fire Management framework for Mount Kenya Forest and National Park.

A PHD THESIS

By

MSc. Kevin Wafula Nyongesa

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Supervisor: ao. Univ. Prof. DI Dr. Harald Vacik
Institute of Silviculture
Department of Forest and Soil Sciences

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Dedicated

To

GOD

&

My beloved parents, fiancée, brothers and sisters

&

Österreichische Austauschdienst-Gesellschaft (OeAD)

Preface

The core part of this thesis consists of four peer reviewed manuscripts submitted and partly published in four scientific journals, which are part of the appendix chapter of this thesis. The timeline and status of the publication process of all manuscripts is given at the end of this thesis. The initial text describes the research concept and the major findings of the work. A detailed description of the research methodology and findings can be found in the respective papers.

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The Author

Abstract

This study investigated how the changing climate, vegetation dynamics, human activities, and forest management influence the occurrence of fires in Mount Kenya Forest and National Park (MKFNP). Qualitative information was obtained through questionnaires, focus group discussions and the documentation of forest and wildlife station fire data and management plans. Quantitative data were collected for the precipitation from weather stations as well as satellite data for estimating fire occurrence, burnt area and vegetation condition in MKFNP. Analysis was done to determine the wildfire frequency, spatio-temporal variability, intensity, size, seasonality, fire regime and the impacts of human activities in MKFNP.

The findings show that the fire season in MKFNP is from December to March and July to September. Bush and grassland in the Ericaceous zone in the National Park are the most fire-prone vegetation. Human activities are the major causes of fire ignitions but low precipitation and a low VCI (drought) contribute to a higher number of fire ignitions and a larger burnt area in MKFNP. The multi-criteria analysis using the Analytic Hierarchy Process (AHP) indicated that a management strategy focusing on community interests provided the best option to address the current challenges in all forest stations independently of their fire danger levels. The effectiveness of the developed Integrated Fire Management (IFM) framework depends on the active participation, formulation and implementation of the IFM activities by the main stakeholder groups so that they can prevent damaging fires and maintain desirable fire regimes in MKFNP. Community interests, biodiversity conservation and water catchment protection efforts should be considered by land scape managers in order to reduce fire danger and increase the benefits obtained by different stakeholders in MKFNP.

Zusammenfassung

Diese Studie untersuchte, wie die Klima- und Vegetationsdynamik, menschliche Aktivitäten und die Waldbewirtschaftung das Auftreten von Bränden im Mount Kenya Forest und National Park (MKFNP) beeinflussen. Qualitative Informationen wurden durch Fragebögen, Fokusgruppen-Diskussionen und die Managementpläne der Forst- und Wildstationen gewonnen. Es wurden quantitative Daten über den Niederschlag von Wetterstationen sowie Satellitendaten zur Abschätzung des Brandverhaltens, der Brandfläche und des Vegetationszustands gesammelt. Die Analyse wurde durchgeführt, um Häufigkeit, räumlich-zeitliche Variabilität, Intensität, Größe, Saisonabhängigkeit, Brandverhalten sowie die Auswirkungen menschlicher Aktivitäten zu bestimmen.

Die Ergebnisse zeigen, dass die Brandsaison im MKFNP von Dez. bis März und von Jul. bis Sept. ist. Busch- und Grasland in der Heidekraut Zone im Nationalpark ist die feuergefährdetste Vegetation. Menschlichen Aktivitäten sind die Hauptursache von Bränden, aber geringe Niederschläge und ein niedriger VCI infolge von Dürre tragen zu häufigeren Brandfällen und einer größeren Brandfläche bei. Die multi-kriterielle Analyse ergab unter Verwendung des Analytic Hierarchy Process (AHP), dass eine Managementstrategie, die sich auf die Interessen der Gemeinschaft konzentriert, die beste Option ist, um die aktuellen Herausforderungen in allen Forststationen unabhängig von ihrer Brandgefährdung anzugehen. Die Wirksamkeit des entwickelten integralen Waldbrandmanagements (IFM) hängt von der aktiven Beteiligung, Formulierung und Umsetzung der IFM Aktivitäten durch die Interessengruppen ab, so dass sie Feuerschäden verhindern und gewünschtes Brandverhalten im MKFNP aufrechterhalten können. Die Naturraummanager sollten die Interessen der Gemeinschaft, den Erhalt der biologischen Vielfalt und den Schutz der Wassereinzugsgebiete berücksichtigen, um die Brandgefahr zu verringern und den Nutzen für die verschiedenen Interessengruppen vom MKFNP zu erhöhen.

Keywords: Fire regime; remote sensing; Moderate Resolution Imaging Spectroradiometer (MODIS); burned area; vegetation; fire management, Fire occurrence; spatio-temporal; National Park; NDVI; VCI; precipitation; time series; forest; burned area; Mount Kenya; multi-criteria analysis (MCA); objectives and criteria (O&C); fire danger; benefits; forest managers; wildlife managers; management strategies (MS); community forest associations (CFAs); stakeholders; analytic hierarchy process (AHP); human activities; participation; firewood; charcoal; grazing; water; honey; farming.

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1. Introduction

1.1 Problem statement

Anthropogenic fires have been common throughout the world since the discovery of fire (Laris and Wardell, 2006) and almost every landscape has a complex history of human land use and natural disturbances (Aragon and Morales, 2003). The distinction between 'natural' and 'cultural' landscapes is not always obvious (Erickson et al., 2002) because different communities around the world have been using fire as a tool in land management for many centuries to manipulate vegetation composition, structure, and fuel loads on farmlands, rangelands and other wildland ecosystems (Nyongesa, 2015). Several studies have been done on the evolution of human-driven fire regimes in Africa (Sally et al., 2012) and the traditional ecological knowledge based fires (Seijo et al., 2015). Communities in Kenya have traditionally used fire as a tool in land management for many centuries. Perennial grassland fires are common in many parts of the country because each year during the dry season, communities set grasslands on fire to keep them open and to facilitate the growth of new grass for livestock, especially before the rain begins. Some farmers use fire to prepare farmlands; break impenetrable bushlands; control weeds, pests and parasites; and try to keep wildlife away from homes. Bushland and forest fires are common because some community members use fire to burn charcoal, harvest wild honey, and hunt and roast game meat in forests and national parks (KFS, 2010, KWS, 2010). As a result, Kenya has been experiencing ground fires, surface fires and crown fires in grasslands, farmlands, bushlands, forests and national parks (KFS, 2010, KWS, 2010).

It is important to understand the past and current fire patterns in Kenya's forests and national parks. The analysis of the fire history of a specific area for a given period by describing frequency, intensity, size, season, type, and extent of fires can help to determinate the fire regime (Flatley, 2012). Remote sensing is a valuable approach to reconstruct fire history, locate fire hot spots, map the burnt areas and monitor current fires (Flatley, 2012). The human activities, changing climate, vegetation dynamics and forest management influence the occurrence of fires (Dube, 2009). Despite compelling evidence on the role of climate change in influencing fire regimes through changes to temperature, rainfall, humidity, wind, and the amount of carbon dioxide in the atmosphere, humans are most often the leading cause of fire ignition in Kenya (Poletti, 2016). Human caused fire ignitions in forests and national parks of Kenya are more likely to increase in the future because climate change may affect fire season length and severity (Nyongesa, 2015, Timothy et al., 2017). Other studies have shown that frequent fires caused by increased human activities in forest and national parks may lead to grasses invading forest land resulting in vegetation type-conversion in Kenya (Wangari, 2016, Timothy et al., 2017). On the other hand, most of the natural fires in forests and national parks of Kenya are generally started by lightning (Nyongesa, 2015). However, fires caused by lightning are recorded by the KFS and KWS under unknown causes, making it difficult to estimate their social, economic, cultural and ecological effects (Poletti, 2016). Several studies have shown that fire occurrence has influenced the vegetation in Kenya's landscape (Wangari, 2016) and some plant species in require fire to germinate, establish or to reproduce (Butz, 2009).

Accurate and timely information on the vegetation condition and distribution based on remote sensing data is one of the key elements for understanding how changes in precipitation patterns (e.g. drought periods) and disturbances like fires can affect land use and land cover (Klisch and Atzberger, 2016). The most commonly used satellite data for the fire detection currently are the Moderate Resolution Imaging Spectroradiometer (MODIS) TERRA and AQUA with a 250 m spatial resolution and Suomi NPP (National Polar-orbiting Partnership) Visible Infrared Imaging Radiometer Suite (VIIRS), the former has the spatial resolution of 1 km and the later has 375 m (Klisch and Atzberger, 2016). Time series of the Normalized Difference Vegetation Index (NDVI) and the Vegetation Condition Index (VCI) are widely used to identify vegetation anomalies as a result of drought (Gebrehinot, 2016, Klisch and Atzberger, 2016). The NDVI and VCI values are usually lower during droughts compared to the normal growing conditions in the same region and growing season (Klisch and Atzberger, 2016). Timely detection of droughts and forest fires can play a crucial role in assisting the KFS and KWS managers, CFAs and other stakeholders to control the ignition and spreading of fires. Satellite data can be useful in detecting fires in near real time as compared to conventional methods such as fire watch towers or patrolling that are currently applied in Kenya.

Managing of Kenya's forests and national parks to fulfill multiple stakeholder interests presents complex decision-making challenges to the KFS and KWS managers, CFAs and other organizations on how to reduce fire danger and increase the benefits obtained by various stakeholder groups (KFS, 2010, KWS, 2010). There is need for the KFS and KWS managers, CFAs, researchers and other stakeholders to jointly develop, select and implement the best management strategy that will help to reduce fire danger and increase the benefits obtained by various stakeholder groups. This is because Kenya's fast growing population is increasing the pressure on the available forest resources (KFS, 2010, KWS, 2010). Human activities in forests and national parks have increased tremendously over the past decades due to the growing demand for good quality water, firewood, timber, poles, grazing of livestock, wild fruits, honey, charcoal, land for the cultivation of crops, income from ecotourism, herbal medicine among others (KFS, 2010, KWS, 2010). As a result, all five key forested water towers (Mt. Kenya, Mt. Elgon, The Cherangani Hills, The Mau Forest Complex, and The Aberdares) have experienced human encroachment, land use change, wildfires, and degradation and same applies to lowland and coastal forests in Kenya (Imo, 2012).

The existing bureaucracy in government ministries and departments do not support the collaboration on exchange of socio-economic data, meteorological data, fire records, wildlife inventory data and forest inventory data and as a result the KFS and KWS managers, CFAs, researchers and other stakeholders have at times made management decisions based on experience and not the relevant scientific findings. There are conflicts of interest between the various stakeholder groups (KFS, KWS, CFAs, saw millers, biodiversity conservation organizations, faith based organizations and researchers) on how to manage or use forest and wildlife resources in Kenya (GoK, 2005, KFS, 2010, KWS, 2010). The stakeholder groups in Kenya have suggested different management strategies that address only their needs and benefits from forests and national parks without taking proper consideration on how their activities may contribute to or compromise the interests of other user groups (KFS, 2010, KWS, 2010).

At the local level, the KFS and KWS managers have largely been addressing fire as a hazard rather than a tool for land management. The KFS and KWS have continued to practice fire suppression campaigns instead of using prescribed burning activities to manage fuel accumulation in forests and national parks of Kenya. This is mainly based on the belief that any disturbance, such as fire, disrupts the progress towards an equilibrium state. Total fire suppression leading to high fuel accumulation in combination with the changing climate and increasing human activities have resulted in catastrophic fires in forests and national parks affecting the socio-economy and environment in Kenya (Nyongesa, 2015). The catastrophic fires have been causing soil erosion, water pollution, bad air quality (smoke), loss of timber value, loss of livelihood, wildlife to escape onto peoples farms, death of wildlife, loss of wildlife breeding habitats, loss of human life, destruction of properties, loss of grazing grounds, destruction of tourist camps sites and loss of other ecosystem services (KFS, 2010, KWS, 2010). Limited funds from the government and donors to tackle fire management issues, the retrenchment of human resources within the KFS and KWS, the lack of well-trained firefighters and adequate firefighting equipment have seriously affected the capacity of KFS and KWS to effectively suppress and combat wildfires (KFS, 2010, KWS, 2010).

There is need for Kenya to develop and implement Integrated Fire Management (IFM) strategies. The KFS and KWS managers, CFAs and other stakeholders need to consider social, economic, cultural and ecological aspects when developing and implementing IFM so as to minimize the damage of catastrophic fires and maximize the benefits of prescribed fires by evaluating and balancing the associated risks (Aquilar and Montiel, 2011). Establishing and implementing IFM approaches in Kenya calls for understanding of the various uses of fire, along with the underlying perception and traditional ecological knowledge of the local people (Gadgil et al., 2000). The traditional use of fire in Kenya for supporting the livelihoods of the local people needs to be considered when developing and implementing IFM guidelines and policies (FAO, 2006). There is also a need to give special consideration to social and community values and engage the community in IFM planning and implementation. This will help communities and resource managers in Kenya to find cost-effective approaches to prevent damaging fires, as well as to maintain desirable fire regimes (Butz, 2009).

1.2 Fire Management in Mount Kenya Forest and National Park

Communities living around MKFNP use fire as a tool in land management and in on some occasions the fire goes out of control causing unintentional wildfires (KFS, 2010, KWS, 2010). Most of the fires in MKFNP are caused by humans but natural fires are caused by lightning (Poletti, 2016). The Mt. Kenya region has a very high population and human activities in MKFNP to obtain timber and non-timber forest products (NTFP) have increased over the past decades (KFS, 2010, KWS, 2010). According to the KFS and KWS, human-caused fire ignitions in MKFNP are more likely to increase in the future, because climate change may affect fire season length and severity (Nyongesa, 2015).

Conflicts have occurred between KFS, KWS, CFAs, and other stakeholders over the right to use forest resources in MKFNP (Kumssa et al., 2009). Conflicts do arise when some locals are not allocated land to practice farming (PELIS) because the need for farming is higher than land available or when locals are arrested by KFS staff, forest scouts, or CFA members for conducting illegal logging, grazing, collecting firewood, collecting honey, herbal medicine, burning charcoal and hunting in MKFNP (KFS, 2010, KWS, 2010). The culprits usually set the forest on fire as revenge (arson). Droughts have also cause conflicts over water resources and pasture in MKFNP. Conservation reports indicate that during years with prolonged dry spells, MKFNP will continue to experience the huge pressure of livestock from pastoral communities, thereby over stretching the available resources (KFS, 2010, KWS, 2010). This means that the pastoralists (Samburu and Maasai) will cause conflicts by continuing to graze in MKFNP without considering the local CFA grazers' user group agreements. The traditional setting of old dry grass on fire so that new grass grows when rains come by migrant pastoralists usually causes fires MKFNP (Nyongesa, 2015).

MKFNP is known to have a long fire history (Mary et al., 2019). More recent ecological research has shown that fire is an integral component in the function and biodiversity of many natural habitats in MKFNP, and that the organisms within these communities have adapted to withstand, and even to exploit, natural and anthropogenic fires (Wangari, 2016). The indigenous woody species mostly found in regularly burnt sites in MKFNP include *Juniperus procera* (Hochst. ex Endl.) and *Hagenia abyssinica* (Bruce) J.F.Gmel., while the herbaceous species include *Ferula communis* (Linnaeus), *Gomphocarpus stenophyllus* (Oliv.) and *Cardius keniensis* (Linnaeus) *Bambusa vulgaris* (Schrad Ex J.C. Wendl.) among others that usually regenerate after fire (Wangari, 2016). Native perennial grasses also regrow from root systems that are rarely damaged by fires that occur in MKFNP (Butz, 2009, Wangari, 2016). Fire is the only natural factor in MKFNP which supports the reproduction of the afro-alpine vegetation (chaparral). Older stands of chaparral dry up causing huge fuel accumulation over larger areas thus fire is necessary for the plants to remain vital (Downing et al., 2016, Downing et al., 2017).

The KFS managers have continuously established plantations of exotic tree species in MKFNP like cypress (Cupressus lusitanica Mill.), patula pines (Pinus patula Schiede Ex Schltdl. & Cham), radiata pines (Pinus radiata D. Don), blue gum (Eucalyptus saligna Smith), and rose gum (Eucalyptus grandis W. Hill Ex Maiden) for the pulp and timber industry which are likely increase fire hazard in the future (Wangari, 2016). Several studies show that exotic tree species contribute to changes in the patterns of anthropogenic ignitions, flammability of exotic species, forest ecosystem structure, and process and fuel loads (Butz, 2009). The Kenya Grass Fire Act, Cap 327, provides a regulation for planned burnings of bushes, shrubs, grass, crops, and stubble within protected areas to decrease the risk of catastrophic fires. However, the current banning of all fires from current land use practices by KFS and KWS might lead to an accumulation of fuel loads, which would play a major role in future wildfire outbreaks in MKFNP (Nyongesa, 2015, Poletti, 2016).

It is important to understand the past and current fire patterns in the MKFNP. Using remote sensing and ground observations to analyse the fire history in MKFNP will help KFS, KWS, CFAs, researchers and other stakeholders to determinate the fire regime, the number of fires, burnt area, fire hotspots, fire periods, droughts and the type(s) of vegetation most affected by fires (Flatley, 2012). There is need that the KFS, KWS, CFAs and other stakeholders obtain and use timely information from satellites on the number of fires, burnt area, fire hotspots, fire periods, precipitation (droughts periods) and the type(s) of vegetation most affected by fire in MKFNP. This information will enable KFS and KWS managers, CFAs, researchers and other stakeholders to understand how the increasing human activities and climate change may affect future fire patterns in MKFNP. The open sharing of this information will help improve fire monitoring and suppression activities in MKFNP.

The implementation of the Mount Kenya Forest Reserve management plan 2010–2019 by the KFS and the Mount Kenya Ecosystem management plan 2010–2020 by KWS has failed to address the current and future threats in MKFNP. The two different management plans present a complex decision-making challenge to the KFS, KWS, CFAs and other stakeholders on how they can work together to reduce fire danger and increase the benefits obtained by stakeholders from MKFNP (Nyongesa, 2015). Multi-Criteria Analysis (MCA) can help to solve such complex multi-criteria decision problems that include qualitative or quantitative aspects (Jalilova et al., 2012). Strong technical and theoretical support for MCA procedures exists, and they are designed to consider an intuitive and transparent participation of multiple experts and stakeholders. Considering stakeholder knowledge will contribute to the general acceptability of the results (Biswas et al., 2011). The Analytical Hierarchy Process (AHP) is a MCA tool that has been used widely by natural resource managers in complex decision-making situations.

The development and implementation of IFM strategies in MKFNP have to be in accordance with relevant international laws, taking into account all technological, economic, relevant biological, social, cultural and environmental expert knowledge (Myers, 2017). There is need to contribute to the development and implementation of sub-county, county and national policies and planning mechanisms for establishing or improving the legal, regulatory and institutional framework required for responsible IFM activities in MKFNP.

The overall objective of this PhD study is to improve wildfire management in MKFNP. This PhD thesis research seeks to compare human activities that cause fires in MKFNP; analyze how NDVI and VCI, weather data and socio-economic data can be used to improve fire management in MKFNP; determine the level of collaboration between the KFS, KWS, CFAs and other agencies in decision making on forest fire management in MKFNP; develop and apply an IFM framework in Gathiuru Forest. Combining remote sensing data and ground observations as shown in Figure 1 introduces a simple approach used in the formulation of the five PhD research objectives.

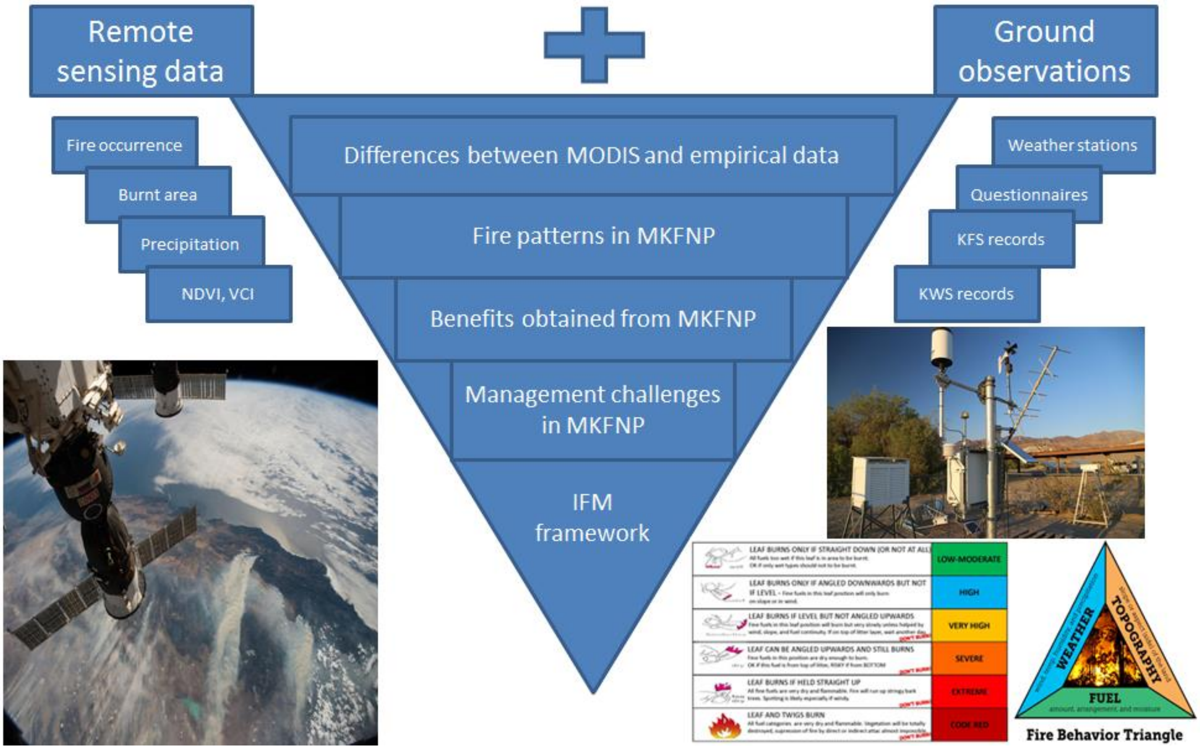

Figure 1: The approach used in the formulation of the PhD research objectives

The following five objectives, related research questions and hypothesis provide the research framework for the thesis:

Objective 1: To identify differences between empirical fire records and MODIS fire data in different forest stations in MKFNP.

Research question: Which data sources are available to describe the fire regime of MKFNP?

Hypothesis 1.1: There are typical trends in fire occurrence in relation to the dominant vegetation type.

Hypothesis 1.2: Differences in fire statistics can be identified using empirical fire records and fire data obtained by MODIS satellites.

Objective 2: To describe how the Normalized Difference Vegetation Index (NDVI) and the Vegetation Condition Index (VCI) obtained from remote sensing data can be used with weather and socio-economic data to develop fire danger maps
Research question: Can VCI data be used to explain the spatio-temporal patterns of fire occurrence in MKFNP?
Hypothesis 2.1: Fire ignition in MKFNP depends on socio-economic activities, weather and vegetation condition.
Hypothesis 2.2: Remote sensing data about the vegetation condition provides a solid estimate for the fire danger situation in MKFNP.

Objective 3: To evaluate how different stakeholder needs and benefits influence fire ignition in MKFNP.
Research question: What are the major causes of fires in MKFNP?
Hypothesis 3.1: Human activities are the leading cause for fire ignition in MKFNP.

Objective 4: To evaluate fire management plans regarding their effect on human welfare and maintenance of healthy ecosystems in MKFNP.
Research questions: Which evaluation criteria can be used to assess fire management plans? Which elements have to be considered in developing a fire management strategy?
Hypothesis 4.1: The involvement of various stakeholders from the KFS, KWS and CFAs contributes to the design and selection of appropriate fire management strategies.
Hypothesis 4.2: The AHP can be a useful tool to select the best management strategy that helps to reduce fire danger and increase the benefits obtained by various stakeholders.

Objective 5: To develop an Integrated Fire Management (IFM) framework.
Research question: Which factors and actors have to be considered for developing an IFM in MKFNP?
Hypothesis 5.1: The IFM framework can support communities and resource managers in finding effective and efficient approaches to prevent damaging fires, as well as to maintain desirable fire regimes in Kenya.

1.3 Structure of the thesis and publication framework

The introduction section of this PhD thesis covers the statement of the problem and general fire management practices in Kenya and MKFNP. The materials and methods section in this PhD thesis provides a detailed description of study site and highlights the steps used to obtained and analyze satellite and empirical data to determine the spatio-temporal occurrence of fires in MKFNP. It provides a detailed overview of the methods used in developing, evaluating and selecting the best management strategy in MKFNP and the procedures used developing and applying an IFM framework in Gathiuru Forest. Key findings are presented as tables, maps, graphs and qualitative statements in the results section. The discussion section of this PhD thesis highlights the key findings of this PhD study provides a comparison to finding of other similar scientific studies in Kenya, Africa or the rest of the world. The conclusion section provides personal statements on how the findings of this PhD study can help forest and wildlife managers, communities and other stakeholders to determinate fire regimes, to select the best management strategies and the need to develop and implement IFM in MKFNP, Kenya and the rest of the world.

The five objectives (Figure 2) considered in the thesis are addressed in four peer reviewed manuscripts, which are part of this thesis.

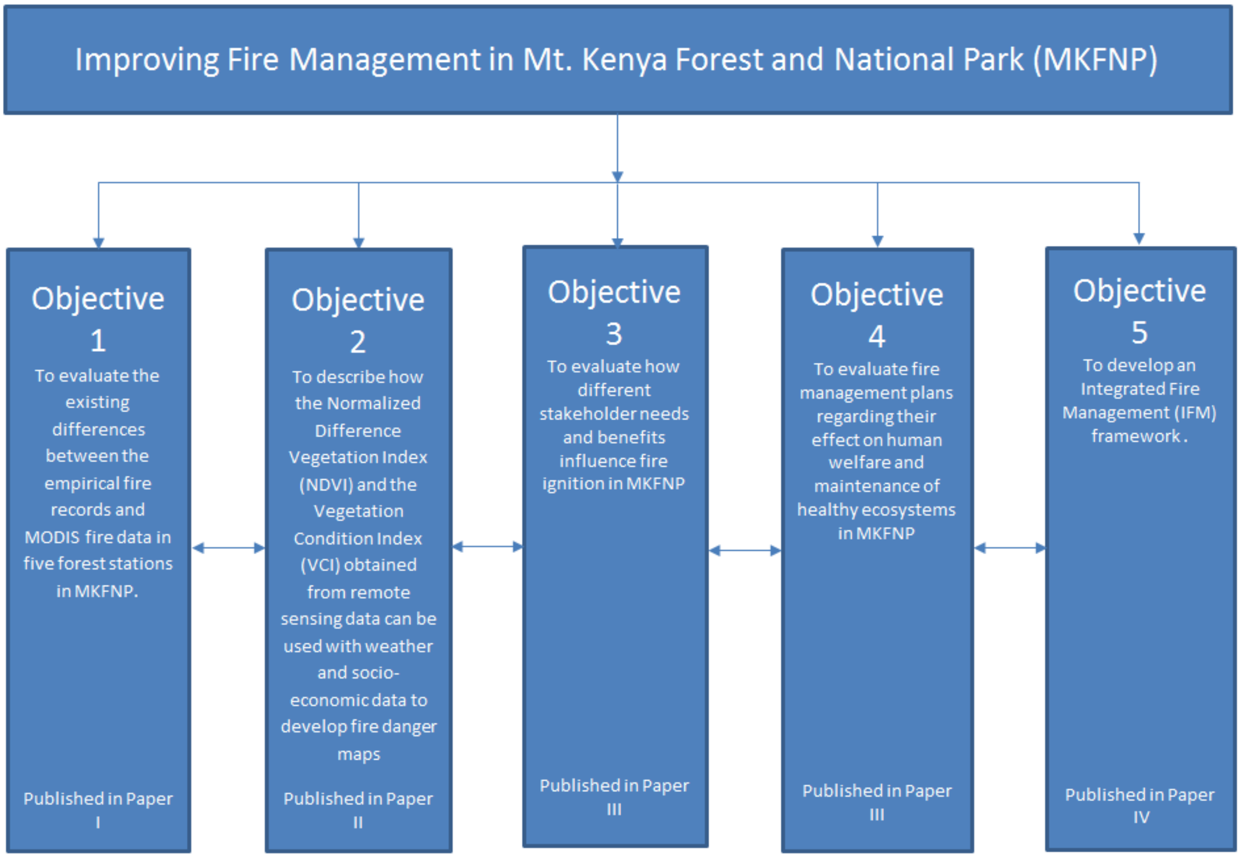

Figure 2: Research objectives and publication framework

To evaluate the existing differences between the empirical fire records and MODIS fire data in five forest stations in MKFNP were the objectives of manuscript 1. The objectives of manuscript 1 were as follows (i) to collate and investigate the historical fire records collected by the Kenya Forest Service (KFS) from 1980 to 2015; (ii) to detect any trend in fire occurrence throughout time or in relation to the vegetation type; (iii) to compare the historical empirical data with the remote sensing system detected data using geospatial analysis techniques **(Appendix 1).**

To describe how the Normalized Difference Vegetation Index (NDVI) and the Vegetation Condition Index (VCI) obtained from remote sensing data can be used with weather and socio-economic data to develop fire danger maps were the objectives of manuscript 2. The objectives of manuscript 2 were as follows (i) describe the human activities that cause fires and how they contribute to spatio-temporal patterns of fires in Mount Kenya Forest and National Park from 2003 to 2018; (ii) examine relationships between precipitation and the observed spatial-temporal patterns of fires from 2003 to 2018; (iii) perform a time series analysis of the NDVI and VCI to detect droughts and examine how they influence fire occurrences in Mount Kenya Forest and National Park from 2003 to 2018 **(Appendix 2).**

To evaluate how different stakeholder needs and benefits influence fire ignition in MKFNP and to evaluate fire management plans regarding their effect on human welfare and maintenance of healthy ecosystems in MKFNP were the objectives of manuscript 3. The objectives of manuscript 3 were as follows (i) to develop the Management Strategies (MS) which meet the demands for integrated fire management, (ii) to develop Objectives and Criteria (O&C) for the evaluation of the strategies with all stakeholder groups and (iii) to apply the AHP to propose the best management strategy that reduces fire risks and increases the benefits obtained by various stakeholders from MKFNP **(Appendix 3).**

To develop an Integrated Fire Management (IFM) framework were the objectives of manuscript 4. The objectives of manuscript 4 were as follows (i) to propose a framework for an integrated fire management approach, (ii) to apply the framework in a case study (Gathiuru Forest), and (iii) to propose fire management guidelines considering the challenges faced by the KFS and local CFA. Manuscript 4 highlights the importance of developing and using an IFM framework to support communities and resource managers in finding effective and efficient approaches to prevent damaging fires, as well as maintain desirable fire regimes, in Kenya **(Appendix 4).**

2. Materials and Methods

2.1 Description of the study site

Mount Kenya Forest and National Park (Figure 3) is located to the east of the Great Rift Valley, along Latitude 0’ 10’S and longitude 37’ 20’E. It bestrides the equator in the central highland zones of Kenya (UNESCO, 2013). The mountain is situated in two Forest Conservancies and five forest management zones namely Nyeri and Kirinyaga in Central Highlands Conservancy and Meru Central, Meru South and Embu in Eastern Conservancy (KFS, 2010). The whole MKFNP is divided into 23 forest stations. The national park covers 71,510 Ha and the forest reserve covers 213,082.64 Ha (KFS, 2010, KWS, 2010). Mt. Kenya was formed as a result of volcanic activity and it has a base diameter of approximately 120km. The Mountain highest peaks Batian (5,199 m) and Nelion (5,188 m) are covered in snow (UNESCO, 2013).

The altitudes with the highest rainfall are between 2,700 and 3,100m, while above 4,500m most precipitation falls as snow or hail. Frosts are common above 2500m above sea level (asl) (KFS, 2010). Rainfall pattern in MKFNP ecosystem is bimodal. It ranges from 900 mm in the north Leeward side) to 2,300 mm on the southeastern slopes (Windward side) of the mountain with maximum rains falling during months of March to June and October to November (Henne et al., 2008). The driest months are January and February and the windward side experiences the strongest effects of the trade wind system. The diurnal temperature range in January and February may be as high as 20 ^{0}C. The Eastern side (Windward side) of the MKFNP receives more precipitation and is less prone to fires than the Western side (leeward side) that experiences more fires throughout the year (Nyongesa, 2015). The climate varies with the altitude and temperatures MKFNP are cooler than throughout most of the country. The climate is subtropical or temperate. There is still a rainy season from March to May and from October to December when it is drizzly, cloudy and rainfall is moderate on the lower slopes and heavier higher up. The sunniest months are from December through March (Henne et al., 2008). The climate of MKFRNP region is largely determined by altitude. There are great differences in altitude within short distances, which determine a great variation in climate over relatively small distances. Average temperatures decrease by 0.6 ^{0} C for each 100m increase in altitude (Henne et al., 2008). An afro-alpine type of climate, typical of the tropical East African high mountains, characterizes the higher ranges of MKFNP (KFS, 2010, KWS, 2010).

Figure 3: Mount Kenya Forest and National Park

2.2 Determination of the spatio-temporal occurrence of fires in MKFNP

2.2.1 Evaluation of empirical fire records from KFS and KWS

The KFS and KWS station managers provided fire records showing the size, date, location, causes of fire, fire characteristics, and firefighting actions. The KFS and KWS estimated burnt area directly on the field or, if the burnt site is not easily accessible, through aerial imagery. Empirical fire data collection was carried out in March 2016, when all documents related to the fire events that occurred from 1980 to 2015 were digitalized and converted to an Excel spreadsheet (Poletti, 2016). The KFS and KWS fire records were used to identify the legal and illegal human activities that cause fires in MKFNP. The relative importance $(relImp)$ of human activities that cause fires was calculated as shown in equation (2).

$$relImp_{(\%)} = (\frac{w_{i \sim h}}{\sum w_{1 \sim h}}) \times 100 \qquad (2)$$

$relImp$ is the calculated relative importance as a percentage, h indicates a given human activity and i a belonging forest station iterated over 1 to 19 (since there are 19 forest stations), w is the weighted value of the outcomes from the KFS and KWS fire records (Nyongesa and Vacik, 2018).

2.2.2 Evaluation of satellite data on fire occurrence and burnt area in MKFNP

The data set of daily fire occurrences ranging from January 2003 to December 2018 was obtained from the Fire Information for Resource Management System (FIRMS) Archiving and Distributing MODIS Active Fire Data (NASA-FIRMS, 2019). The burnt area fire product MCD64A1 was obtained from the MODIS-FIRMS data. Besides information about the confidence of detection and the type of detected land cover, the main product of the algorithm is the differentiation between pixels with burnt and non-burnt areas. The MCD64A1 product combines data from two satellites (AQUA and TERRA) and returns estimated burnt areas monthly based, with a spatial resolution of around 500 m. In this study, MODIS MCD64A1 product polygons were utilized to select burnt areas within the study area. Another MODIS product, MCD14DL-Collection 6, that detected fire occurrences on a monthly basis, was also used in this study (NASA-FIRMS, 2019). MKFNP was then divided into three major land use types: the National Park (NP), Forest Stations (FS) and Farmlands (FL). Possible ignition spots in the NP, FS and FL were displayed to visualize the spatial extent of the burnt areas and ignition sites in MKFNP (Poletti, 2016).

2.2.3 Analysis of precipitation trends in MKFNP

Empirical monthly precipitation data from 2003 to 2018 was obtained from three metrological weather stations. Kalalu and Munyaka weather stations that are located at the foot and Naro Moru weather station that is located near the peak of Mount Kenya (CETRAD, 2019). Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) data v2.0 was used to generate the monthly precipitation at 0.05° spatial resolution (Dwomoh et al. 2019, CHIRPS, 2019). A comparison of the CHIRPS precipitation data and those obtained from the three weather stations in Mount Kenya region was done to determine any deviations in the accuracy of the CHIRPS precipitation data. CHIRPS precipitation data was used to explore the relationship between precipitation, fire occurrence and burnt area in MKFNP from 2003 to 2018.

2.2.4 Analysis of inter-annual variability of NDVI and VCI in MKFNP

MOD09Q1 and MYD09Q1 collection 6 surface reflectance products were obtained from NASA's Land Processes Distributed Active Archive Center (LP DAAC) (NASA-FIRMS, 2019). Normalized Difference Vegetation Index (NDVI) images have been calculated with 8 days temporal and 250 m spatial resolution. The NDVI data was filtered with BOKU's MODIS data processing chain (Klisch and Atzberger, 2016). The processing uses the Whittaker smoother, which fits a discrete series to discrete data and puts a penalty on the roughness of the smooth curve (Eilers, 2003). The smoothing takes into account the quality of the observations according to the MODIS VI Quality Assessment Science Data Set (QA SDS) and the compositing day for each pixel (Klisch and Atzberger, 2016). The resulting NDVI time series has a temporal resolution of 7 days spanning from 2003-2018. Monthly NDVI values were derived by averaging the 7-day images for each cell. A time series analysis of the NDVI was performed to explore the inter-annual variability from 2003 to 2018 using R scripts. The mean NDVI values were randomly stratified into three periods (2003 to 2008, 2009 to 2013 and 2014 to 2018) to evaluate any changes in land use. Monthly VCI values were calculated by applying the following equation (1) on the final NDVI data for each month on each cell.

$$\mathrm{VCI} = 100 \times \frac{\mathrm{NDVIi} - \mathrm{NDVImin}}{\mathrm{NDVImax} - \mathrm{NDVImin}}, \qquad (1)$$

So, for example for February: NDVIi would be the value for February 2006. NDVImin and NDVImax would be the minimum and maximum NDVI value observed for February from 2003 to 2018 for that cell. The numerator is the difference between the actual and the minimum values of the NDVI and is indicative of the meteorology and vegetation information of a specific period. The maximum and minimum values of the denominator reflect the best and worst conditions of vegetative growth and the difference between them reflects the condition of the local vegetation (Kogan, 1995). The VCI contains both real-time and historical information of the NDVI (Rimkus, 2017). The VCI ranges between 0 and 100 in which smaller VCI values below 35% indicate higher degrees of drought (Tagel, 2016). A time series analysis of the VCI was done to explore the relationship between drought and fire occurrences in MKFNP from 2003 to 2018. The relationship between the number of fires and burnt area and VCI in the NP, FS and FL was explored. Analysis was done to establish the relationships between number of fires, burnt area and the VCI in forest stations on the Northwest side that have a medium fire danger (Nanyuki), high fire danger (Ontulili) and those on the Southeast side that have a low fire danger (Chuka and Chogoria).

2.3 Developing, evaluating and selecting the best management strategy in MKFNP.

2.3.1 Selection of forest stations

It was not possible to visit all the 23 forest stations in MKFNP during the study period because it would have been too costly and time-consuming. Therefore seven forest stations were selected in MKFNP based on the description of the current management strategies, objectives, benefits obtained by stakeholders and the number of fire incidences recorded by KFS and KWS from 1980 to 2015. Three forest stations with a very high fire danger (Marania, Ontulili and Gathiuru) were selected because they had experienced 49, 71 and 63 fires incidences respectively. Two forest stations (Nanyuki and Naru Moru) with a high to moderate fire danger were selected because they had experienced 18 and 5 fire incidences respectively. Finally two forest stations (Hombe and Chehe) with a low fire danger were selected because they had experienced only one fire incidence each in the same period of time (Poletti, 2016). Basic information was also gathered on the current management programmes that are being implemented by the KFS and KWS in the seven selected forest stations in MKFNP.

2.3.2 Focus group discussions (FGDs)

There was a need to hold FGDs with various stakeholders living around, working in or with interests in MKFNP to address the issues affecting the current management practices. This is because a FGD is a productive and positive way to gather people together with similar backgrounds or experiences to discuss a specific topic of interest (Mishra, 2016). The facilitators comprised of scientific experts from Egerton University, University of Natural Resources and Life Sciences, Vienna (BOKU) and Kenya Forest Research Institute (KEFRI). The other FGDs participants were the KFS managers, KWS managers, the chief Ecosystem conservator, CFAs, NGOs, county water regional officers and other stakeholder groups participated in FGDs. FGDs were used to collect information from the different stakeholders on the needs and benefits that they obtain from MKFNP and how they influence the ignition of fires; the current management challenges; how the KFS, KWS, and CFAs were collaborating in the implementation of fire management plans, fire monitoring, fire prevention, fire-fighting, the reduction of hazardous fuels and maintenance of ecosystem health; and the need to come up with the best management strategy that will reduce fire danger and increase benefits obtained by different stakeholders from MKFNP.

2.3.3 Development and qualitative evaluation of management strategies

FGDs were held at the regional level by a team of scientific experts who were facilitators and other FGD participants to discuss the existing management programmes and the challenges resource managers were facing in making management decisions on how to reduce fire danger and increase the benefits obtained by the different stakeholders in MKFNP. After discussing the challenges in natural resource management, the strategies were outlined, describing how to overcome the main problems, ensure stakeholder participation, as well as minimize the perceived future threats. The regional FGDs described and developed nine management strategies with the help of the facilitators in detail for further evaluation. The FGDs participants then discussed the strengths and weaknesses of the nine management strategies. They all shared different views as to which management strategy would best fulfill the different interests of all the stakeholders, overcome the main problems, ensure participation in decision making, as well as minimize the perceived future threats. After intensive discussions, the team of scientific experts who were facilitators and other FGD participants qualitatively evaluated and finally selected seven management strategies based on the different stakeholder interests and ability to reduce fire danger in MKFNP. Management strategy one (MS1) was to achieve national climate change mitigation interests (MS1). Management strategy two was to achieve counties' water catchment protection interests (MS2). Management strategy three was to achieve education and research interests (MS3). Management strategy four was to achieve all stakeholders interests (MS4). Management strategy five was to achieve biodiversity conservation interests (MS5). Management strategy six was to achieve timber production interests (MS6) and management strategy seven was to achieve community interests (MS7). Based on their input, the seven management strategies were assessed qualitatively with the help of experts. They qualitatively evaluated how each management strategy would reduce the fire danger in MKFNP according to the following statements: "to a very great extent", "to a great extent", "to some extent", "to a little extent", "to a very little extent" or "to no extent" as shown in table 1.

Table 1: Evaluation of the seven management strategies and their Integrated Fire Management (IFM) activities qualitatively with regard to objectives and criteria

IFM Activities Management Activities	Targets	MS1	MS2	MS3	MS4	MS5	MS6	MS7
1. Increase stakeholder participation in IFM decision making;	1.1-Government departments and ministries,	+++++	++++	++++	+++++	+++	+++	++
	1.2-Communities,	++	+	+	+++++	+++++	+	+++++
	1.3-International agencies,	+++++	+++	+++	+++++	++++	+	+++
	1.4-NGOs,	+++	+	+	+++++	+++++	+	+++++
	1.5-Conservationists	+++	+	+++	+++++	+++++	+	+++++
2. Reduce fire hazards and danger (particularly in and around communities and other high value areas)	2.1-Clean up dry litter accumulations	+++	++++	0	++++	+++++	+++	+
	2.2-Close fire prone areas in dry season	+++++	+++++	0	+++++	+++	++++	+
	2.3-Handle inflammable materials safely	+++++	+++++	0	+++++	+++	++++	+
	2.4-Establish firebreaks and forest roads	+++++	+++++	0	+++++	+++	+++++	+
	2.5-Provide adequate equipment	+++++	+++++	0	+++++	+++	+++	+
	2.6-Train fire crews	+++++	+++++	+++++	+++++	+++	++++	+
	2.7-Establish less fire prone vegetation	+++++	+	+	+++	+++	++	+
3. Carefully use prescribed burning where the benefits are clearly defined;	3.1-Establish fire lines	+++++	++++	+++	+++++	+++	+++	+
	3.2-Monitor fuel and weather conditions	+++++	++++	++++	+++++	++++	+++	+
	3.3-Controlled burning of agricultural lands	+	+	+	++++	++++	+	+++++
	3.4-Controlled burning of grassing grounds	+	+	+	++++	+++++	+	+++++
	3.5-Controlled burning of timber slash	+	+	+	++++	+	+	+
4. Monitor & manage fire on communities land and forests;	4.1-Construct look out towers	+++++	+++	0	+++++	+++	+++	+
	4.2-Deploy fire monitoring crew/ scouts	+++++	++++	0	+++++	++++	+++	+++
	4.3-Establish access to water sources	+++++	+++++	0	+++++	+++	+++	+
	4.4-Evacuate people	+++++	+++++	0	+++++	+	+++	+
5. Integrate fire management programs that control invasive plant species;	5.1-Prevention	+++++	++++	+	++++	+++++	+++	+
	5.2-Chemical control	++	++	+	++	++++	+	+
	5.3-Manual control	+++++	++++	+	+++++	+++++	+++	+++
	5.4-Cultural control/ competition	+++	+++	+	++++	+++++	+++	+
	5.5-Biological control	+++	+++	+	+++	+++++	+	+
6. Minimize outbreaks of non-ecological	6.1-Protection plans	+++	+++	+	+++++	+++++	+++	+
	6.2-Protection maps	++++	++++	+	+++++	+++++	+++	+
	6.3-Prevention of erosion	++++	+++++	0	+++++	++++	+++	++

fires in hydrophobic soils;	6.4-Prevention of loss of organic-rich soils	+++++	++++	0	++++	++++	+++	++
7. Incorporate land use & forest managers, CFAs and policy actors in IFM	7.1-Land use planning	+++++	+++	+	+++++	++++	+++	++
	7.2-Forest resource management planning	++++	+	++	+++++	++++	++++	+
	7.3-Community participation in IFM	+	+	+	+++++	+++	+	+++++
	7.4-Laws, policy, institutional framework	+++++	+++++	++	+++++	++++	++++	+
8. Develop a high level of public awareness and support for IFM;	8.1-Public meetings and social groups	+++++	++++	+	+++++	++++	+++	+++++
	8.2-Posters & sign boards	+++++	+++++	++	+++++	++++	+++	+++
	8.3-Radio	+++++	++++	+	+++++	++++	+++	+++
	8.4-TV	+++++	++++	++	+++++	++++	+++	+++
	8.5-Newspapers	+++++	++++	+++	+++++	+++	+++	+
	8.6-Internet	++++	+++	+++++	+++++	+++	+++	++
9. Incorporate traditional fire use and management practices when developing and implementing of IFM strategies;	9.1-Clearing land for PELIS	+++	0	0	+++++	0	++++	+++++
	9.2-Replenishing nutrients on farms	+	0	+	+++++	0	+	+++++
	9.3-Killing woody species in rangelands	+	+	0	+++++	+	+	+++++
	9.4-Encouraging grass growth	+	+	0	+++	++++	+	+++++
	9.5-Increasing wild seed production	+	+	0	+++	++++	+	+++++
	9.6-Honey collection	+	+++	0	++++	++	+	+++++
	9.7-Hunting	+	+++	0	+++	+++++	+	+++++
10. Reducing IFM costs	10.1-Staff salaries	+++	+++	+	++	+++++	+++	++++
	10.2-Equipment purchase	+++	+	0	+++	+++++	++	++
	10.3-Repair and maintenance	+++	+	0	+++	+++++	+++	++
	10.4-Fuel costs	+++	+	0	+++	+++++	++	+++

+++++ to a very great extent, ++++ to a great extent, +++ to some extent, ++ to a little extent, + to a very little extent, 0 to no extent.

2.3.4 Application of the AHP in the selection of the best management strategy in MKFNP

The O&C set was developed based on the information and experiences provided by scientific experts who were facilitators and other FGD participants on issues affecting community livelihoods, agriculture, water, forestry and wildlife management in MKFRNP. Based on the inputs from the seven representatives and stakeholders as well as different international and national examples relevant objectives were identified. Then criteria were defined to decompose the objectives. The regional FGDs selected 12 objectives and 28 criteria for further discussion and evaluation with participants at the local level in the forest stations. In all local level FGDs the participants qualitatively evaluated the O&C based the local forest station fire danger (very high fire risk, high fire risk, moderate fire risk, and low fire risk). The O&C that were less preferred or redundant were excluded from the set. At the end, a final set of 8 objectives and 21 criteria was proposed for the evaluation of the management strategies. The 8 management objectives adopted were as follows: wood production, energy, biodiversity, social values, income, agriculture, non-timber forest products, protection and climate change mitigation. The 21 criteria adopted were as follows: timber, poles, firewood, charcoal, maintaining wildlife species diversity, tree species and ground vegetation diversity, key habitat protection, religious and cultural sites, education and research, employment in the forestry sector, tourism, livestock grazing, farming of crops (PELIS), foraging of wild fruits, honey collection, fishing, hunting of game for meat, medicinal plants and spices, soil erosion and landslides, water quality and quantity and carbon sequestration.

With the AHP, pairwise comparisons are made among a defined set of alternative options with regard to an evaluation hierarchy, to provide a cardinal ranking of the alternatives (Saaty, 2008). The technique allows the consistency of the decision makers' evaluations to be checked, thus reducing a potential bias in the elicitation process. Since some of the criteria are always contrasting, the best option is not the one which optimizes each single criterion, rather the one which achieves the most suitable trade-off among the different criteria (Saaty, 2008). In this study, the pairwise comparisons were not carried out at the field level, due to their complexity, as other studies have described problems related to their time-consuming nature (jalilova et al., 2012). The AHP was applied by a team of experts to select the best management strategy that helps to reduce fire danger and increase the benefits obtained in MKFNP to fulfill multi-stakeholder interests. A team of experts used the AHP to calculate weights for all objectives and criteria of the defined evaluation hierarchy (O&C) based on the preferences that were expressed by the FGDs participants. The higher the weight, the more important the corresponding criterion was.

Finally, the AHP allowed combining the preferences of the seven management strategies with the criteria weights and thus determining a global priority for each strategy. The mean values for each criterion in the seven forest stations were calculated by the experts based on the scores provided by the participants in the FGDs. The mean values of the scores derived from the FGDs' participants had to be transferred to pairwise comparisons. The scores provided for the objectives and criteria were used to calculate the preferences of the objectives and criteria in the AHP, assuming that the objectives and criteria with a highest score are of higher importance. The qualitative assessment, which provided for the evaluation of the performance of the management strategies, was used to derive the preferences for the seven options. The options were ordered according to the qualitative assessment and the preference values were calculated for each strategy for each criterion in the hierarchy using the Expert Choice Software. This helped to identify the best performing management strategies and potential trade-offs with regard to different preferences.

2.4 Development and application of an IFM framework in Gathiuru Forest

2.4.1 Questionnaires

In this study, questionnaires were designed and a pilot test was conducted to refine the questions. The questionnaire included: Yes or No responses, with some questions that allowed responses on a Likert type of scale ranging from a very great extent (5) to no extent at all (1) and no response (0); and others where participants were required to express their personal opinions verbally. The questionnaires were used to interview 16 respondents from Gathiuru Forest Station (one KFS manager, one ranger, two CFA leaders, and 12 CFA members) between October 2015 and December 2016. Questionnaires were used to collect information from the different stakeholders irrespective of their level of education or gender on their involvement in IFM activities, concerns about fires based on the damage it has caused to communities and the environment, and the type of equipment they use to fight fires in Gathiuru Forest. Questionnaires were also used to collect information on socio-economic activities, motivation, potential, and constraints (problems) affecting forest managers, rangers, CFA members, and other stakeholders' participation in IFM activities in Gathiuru Forest and the surrounding villages. The questionnaires were used to obtain information on respondents' awareness about the existence of IFM plans in Gathiuru Forest and the surrounding villages. The channels of communication preferred by forest managers, CFA members and other stakeholders to receive and give information on fires outbreaks and the IFM activities that help to minimize the damage caused by these fires in Gathiuru Forest and the surrounding villages were assessed using questionnaires. Questionnaires were used to get information on how often and who provides training of CFA members, rangers and forest scouts on fire monitoring and suppression as part of the IFM activities in Gathiuru Forest and the surrounding villages. Data entry of respondents' views collected from the questionnaires and processing by a ranking procedure was done. Analysis was conducted by using SPSS Statistics software from IBM Company that is located in New York, USA.

2.4.2 Ranking of the benefits obtained by CFAs and their concerns about fires

Focus group participants were actively involved in the importance ranking of their needs and benefits obtained from Gathiuru Forest. Participants were instructed by the moderators to come up with a list of the needs and benefits that they obtained from Gathiuru Forest and another list showing the concerns about fires in Gathiuru Forest. They voted by putting X or √ autonomously, without being influenced by members of their user groups. The same procedure that was used to vote for the needs and benefits was repeated for the concerns about fires in Gathiuru forest. A final tally was done to establish the total number of votes for each ranking. In the case where there was a tie in the first tally (TALLY I) of the ranking, a second round of voting was done (TALLY II) to determine the final rank of the benefits and concerns.

2.4.3 Stakeholder participation in the design of an IFM framework for Gathiuru Forest

The scientific experts from Egerton University, University of Natural Resources and Life Sciences, Vienna (BOKU) and Kenya Forest Research Institute (KEFRI) explained to the stakeholders (resource managers from KFS and KWS, the chief Ecosystem conservator, CFA members, NGOs, county water regional officers and other groups) how to develop an IFM framework. The scientific experts then explained to the stakeholders the procedure they used to calculate relative importance ($relImp$) of human activities that cause fires in MKFNP. The scientific experts and the stakeholders then jointly identified factors influencing fire ignition as it relates human needs and land use activities and the role of external drivers in influencing fire danger. They also jointly evaluated the positive and negative effects of fires and the benefits and risks of different management activities considering human needs and land use activities in MKFNP. The scientific experts then gave instructions to the stakeholders to autonomously identify the best IFM activities in MKFNP, without being influenced by other members. Finally the scientific experts and the stakeholders jointly proposed and applied IFM framework in a case study in Gathiuru Forest so as to help communities and natural resource managers to address both damaging and beneficial fires within the context of the natural environments and socio-economic systems in which they occur, by evaluating and balancing the relative risks posed by fires with the beneficial ecological and economic effects they may cause in a given conservation area, landscape or region.

3. Results

3.1. Human activities in MKFRNP

According to the KFS and KWS records, the type of human activities that cause fires vary between forest stations in MKFNP. Arson is the leading cause of fire in Gathiuru, Nanyuki, Naro-Moru, Ontulili and Ragati forest stations. Honey collection is the leading cause of fire Chogoria, Irangi, and Ngare ndare forest stations. Grazers are the leading cause of fire in Meru/Imenti and Mucheene forest stations (Figure 4).

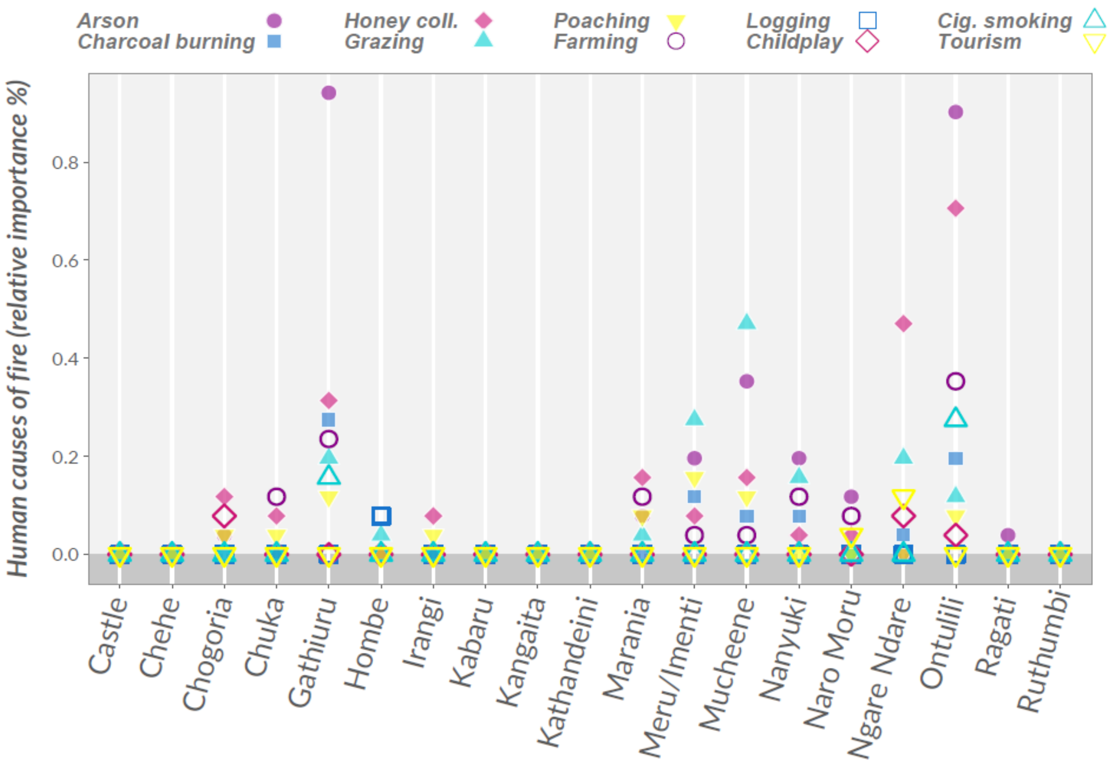

Figure 4: The type of human activities expressed in relative importance on a scale ranging from 0 to1 to show how they cause fires in Mount Kenya Forest and National Park.

At the forest station level results from analysis of data obtained using questionnaires shows that perception of local people on the leading causes of fires in Gathiuru Forest is different from what the records show. The CFAs are aware that charcoal burning is the leading cause of fires, followed by honey collectors, cattle grazers and cigarette smokers. Arson and hunting are the least causers of fire in Gathiuru forest (Figure 5).

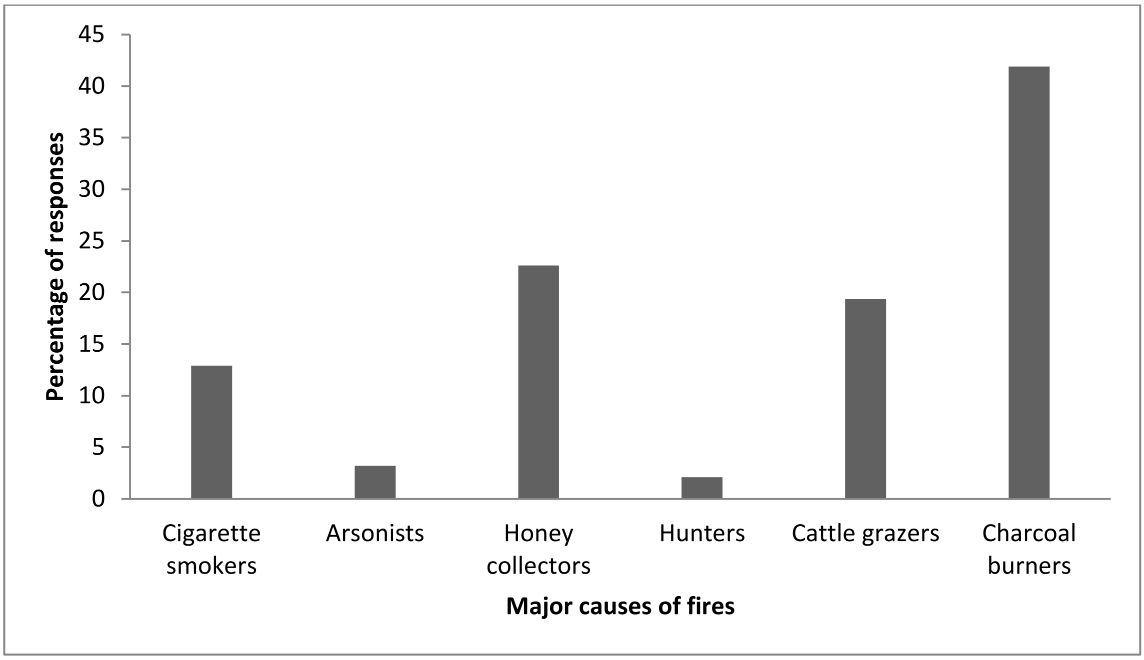

Figure 5: Major causes of fires in Gathiuru Forest as indicated by questionnaire respondents (N = 16).

3.2 Spatial distribution of fire occurrence, burnt area and precipitation in MKFNP

Results show that most of the fire ignitions took place in the Northwestern slopes because it is drier and prone to fires as compared to the Southwestern slopes. Most of the fires occurred in the National Park (NP) and it had the largest burnt area as compared to Forest Stations (FS) and Farmlands (FL) (Figure 6). The results show that from 2003 to 2018 the NP has experienced 530 fire ignitions and 581.8 Km^2 of burnt area, followed by FS that has experienced 358 fire ignitions and 275.3 km^2 of burnt area and the FL which has experienced 269 fire ignitions and 102.5 km^2 of burnt area (Figure 6). The December to March season (red color) has on average a high number of fire ignitions and burnt area compared to the other seasons and there are some differences observed between the land use types during the different seasons (Figure 6). FS have a high number of fires and large burnt area during the July to September seasons (light blue) as compared to the NP and FL (Figure 6). However the NP has a high number of fires and large burnt area during the December to March season as compared to FS and FL (Figure 6).

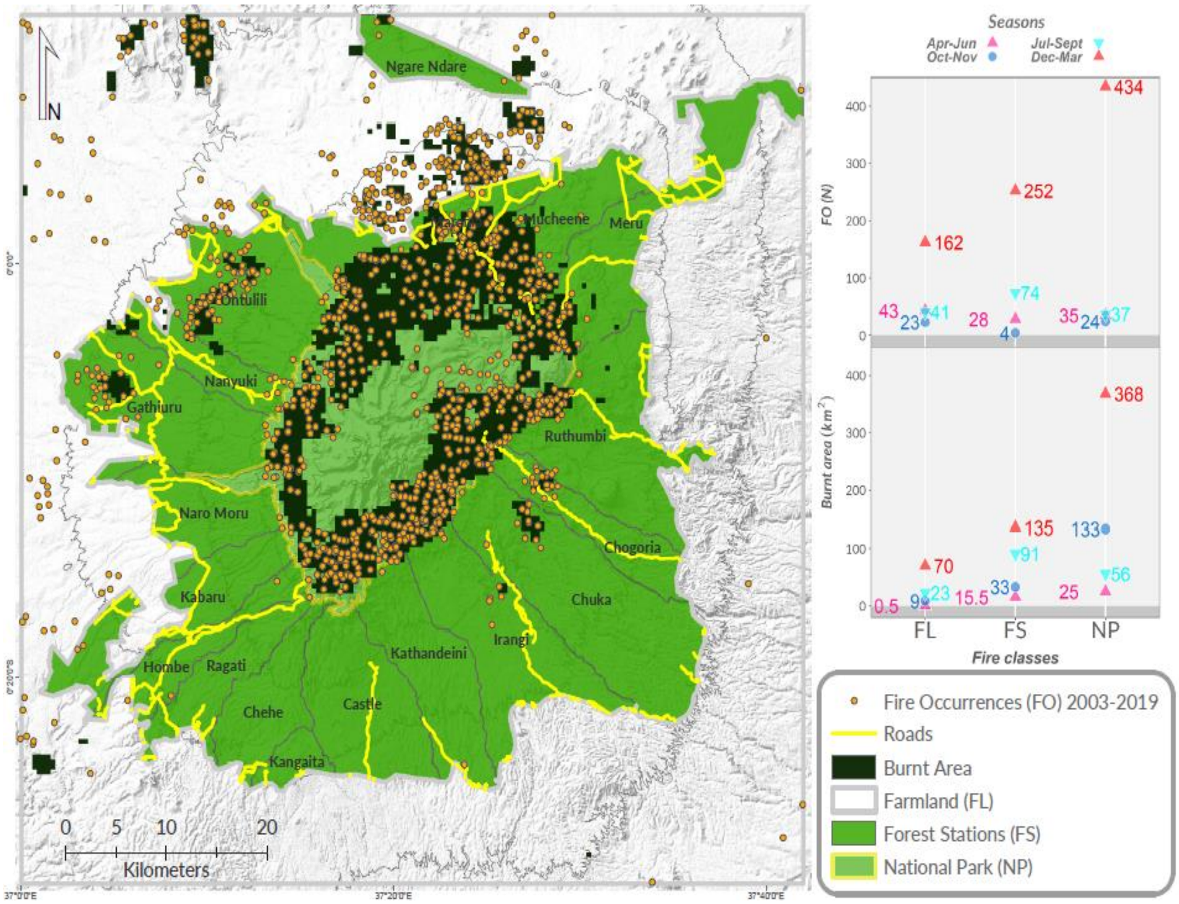

Figure 6: The spatial distribution of the number of fires and burnt areas according to the land use types (NP, FS and FL) and seasons in Mount Kenya Forest and National Park from 2003 to 2019.

A comparison of the CHIRPS precipitation data and those obtained from the Kalalu, Munyaka and Naro Moru weather stations show that there are few deviations in the accuracy of the CHIRPS precipitation data. The spatially explicit estimation of the precipitation data based on the CHIRPS approach seems to be generally a good fit for the study area as it confirms that the North West side is drier than the South East side of MKFNP (Figure 7). Analysis of the CHIRPS precipitation datasets shows that Castle forest station, Ruthumbi forest station and Meru forest station have received the highest amount of precipitation from 2003 to 2018. The lower slopes of Marania forest station, Ontulili forest station, Nanyuki forest station, Gathiuru forest station and Naru-Moru forest station have received the least amount of precipitation from 2003 to 2018. Ngare Ndare forest station has received the least amount of precipitation when compared to other forest stations in MKFNP (Figure 7).

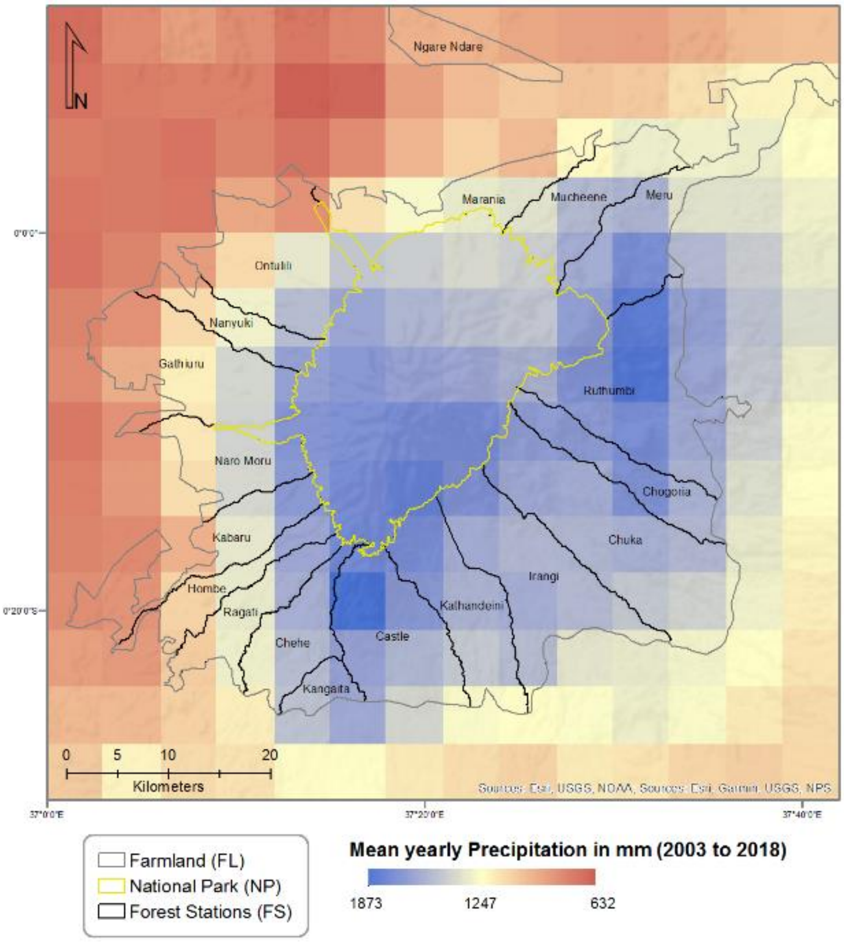

Figure 7: A map of the spatial pattern of precipitation in Mount Kenya Forest and National Park from 2003 to 2018

3.3 Comparison of empirical fires records and MODIS fire data

The empirical dataset from the forest stations from 2000 to 2015 revealed a total burnt area of 9.312 ha, while the total amount of burnt area collected during the same period reported in the MODIS data set is 8.439 ha (Table 2). The spatial resolution of MODIS (about 500m) permits to detect burnt areas with a size bigger than 24 ha only and, for this reason 304.45 ha of the burnt area recorded by the scanned documents (the sum of all burnt areas smaller than 24 ha) could not be detected by the MODIS sensor. The difference between the detected burnt areas of the two datasets decreases therefore from 873 ha to 569 ha. However, comparing the amount of burnt area recorded in each forest station, it was found that large differences could be observed.

According to empirical data from the fire records, Marania forest station had the highest ratio of burnt area/territory of 30%. However, MODIS data from 2000 to 2015 shows that the ratio of burnt area/territory was more than 70%. As the two data sources provided different values, the forest station that registered the largest burnt area, regarding the MODIS data set was Marania with 5.500 ha of burnt area, however according to the empirical data set it was Gathiuru with more than 3.400 ha burnt from 2000 to 2015 (Table 2). Gathiuru and Marania revealed the highest numbers of recorded fire events in the empirical fire records and MODIS dataset respectively.

Table 2: Amount of burnt area (ha) recorded by Kenyan Forest Service (empirical data) and remote sensing (MODIS) in the studied forest stations

Forest stations		Burnt area detected by	
Name	Size	*Empirical data*	*MODIS*
Gathiuru	16.368	3.483	692
Marania	7.857	2.385	5.551
Nanyuki	5.805	242	148
Naro Moru	7.871	28	2
Ontulili	15.825	3.174	2.046
TOTAL	53.726	9.312	8.439

MODIS data revealed a slight increase of fire frequency and burnt area size in the years after 2008, while historic data showed only fluctuation of burnt area size from 2000 to 2015. Both datasets recorded high amount of fire and large burnt areas in 2002, 2005, 2011 and 2012. In 2008 fires that burnt a large area were detected only by MODIS, while in 2004 only historic data recorded burnt areas (Figure 8). The mirrored bar chart highlights dual seasonality from January to March and from April to December in both datasets. Difference in period and location occurrence between satellite Ignition Site (inset map) and burnt area (main map) are evident (Figure 8).

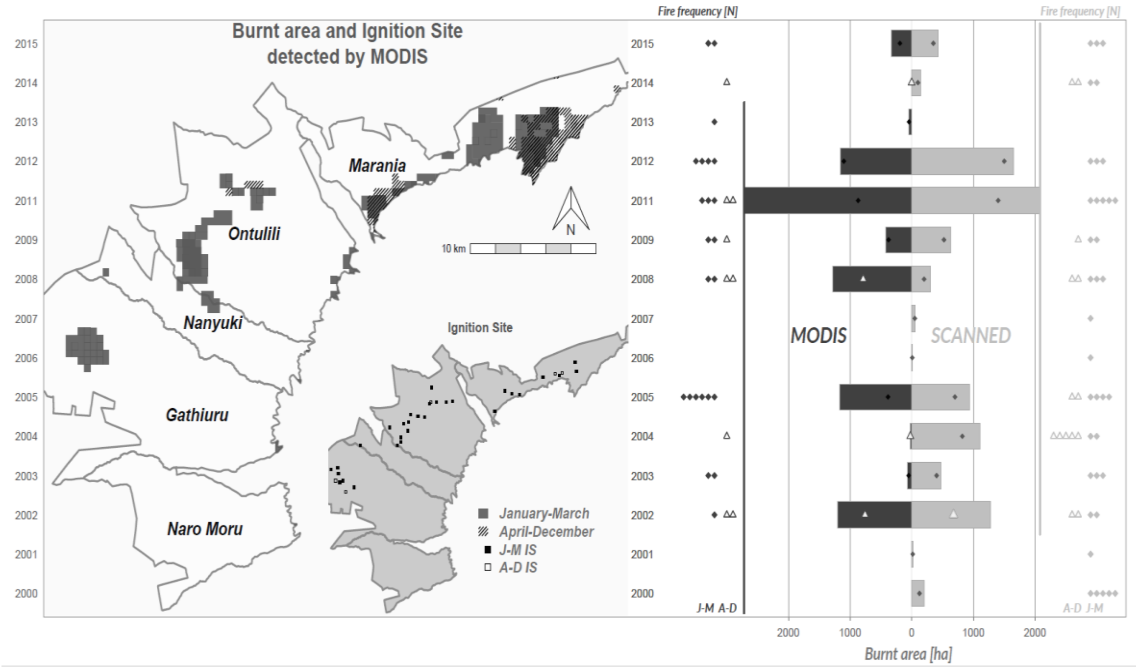

Figure 8: The ignition sites and burnt area in the recorded and MODIS datasets from 2000 to 2015 in Naro Moru, Gathiuru, Nanyuki, Ontulili and Marania forest station.

3.4 Spatio-temporal variability of the VCI

The VCI contains both real-time and historical information of the NDVI. The VCI ranges between 0 and 100 in which smaller VCI values below 35% indicate higher degrees of drought. A time series analysis of the VCI was done to explore the relationship between drought and fire occurrences in Mount Kenya Forest and National Park from 2003 to 2018. This study explored the relationship between the number of fires and burnt area and VCI in the NP, FS and FL.

Results show that the VCI differs in space in NP, FS and FL. Selecting the month of February as an example it can be seen, that there is a huge spatial variation of the VCI values in the NP, FS and FL (Figure 9). In the year 2006, a large area of the NP, FS and FL had a brown to red color indicating a VCI of 0 to 20%. A large area was therefore affected by drought and only a small area did not experience a severe drought. On the other hand results show that in 2016 a large area of the NP, FS and FL around MKFNP had a light green to dark green color indicating a VCI of 70 to 100 % on the VCI scale. This means that in 2016 a large area was not affected by drought (Figure 9).

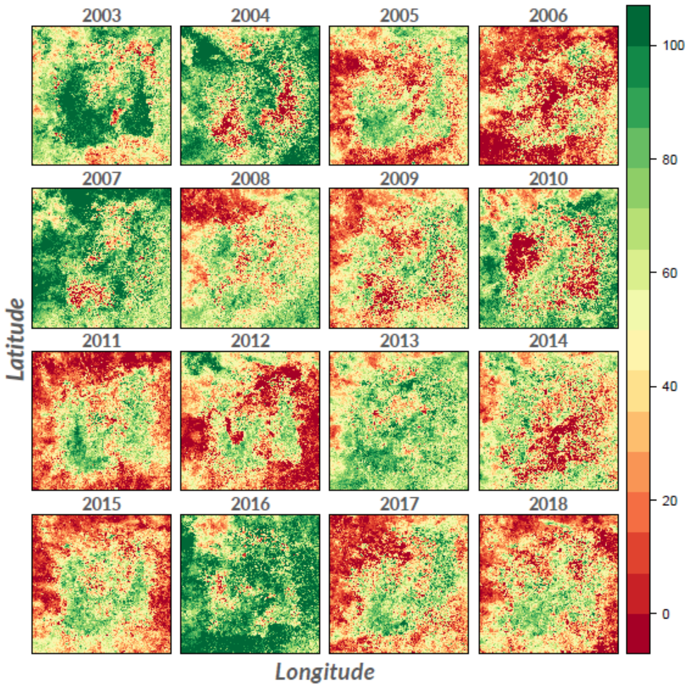

Figure 9: Spatial variability of the VCI in the month of February in the National Park, Forest Stations and Farmlands around Mount Kenya Forest and National Park from 2003 to 2018

Results show that there are large variations in the VCI values in the month of February between the years. The "drought" in Figure 10 indicates the threshold for experiencing a drought (VCI<35%). In the year 2006, the month of February had the lowest average monthly VCI value and in 2016, the highest VCI value was slightly above 82%.

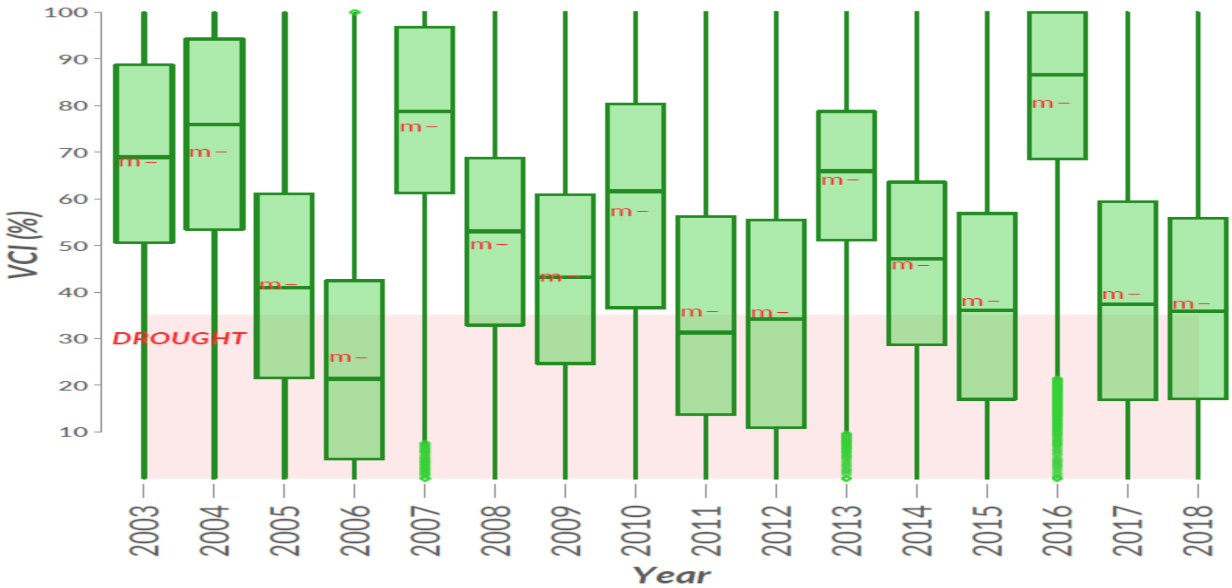

Figure 10: Temporal variability of the VCI in Mount Kenya Forest and National Park where m- indicates the mean VCI in the month of February from 2003 to 2018

3.5 Relationship between number of fires, burnt area and VCI in MKFNP

Correlations between number of fires, burnt area and VCI reveal that there are minor differences between the NP, FS and FL. Results also show that the increase of VCI causes a slight decline in the number of fires and burnt area in FS and NP. However increase of VCI does not have any effect on the number of fires and burnt area in FL. Slightly higher correlations between the number of fires, burnt area and VCI are visible for FS with higher R^2 and lower p-value than for NP and FL (Figure 11).

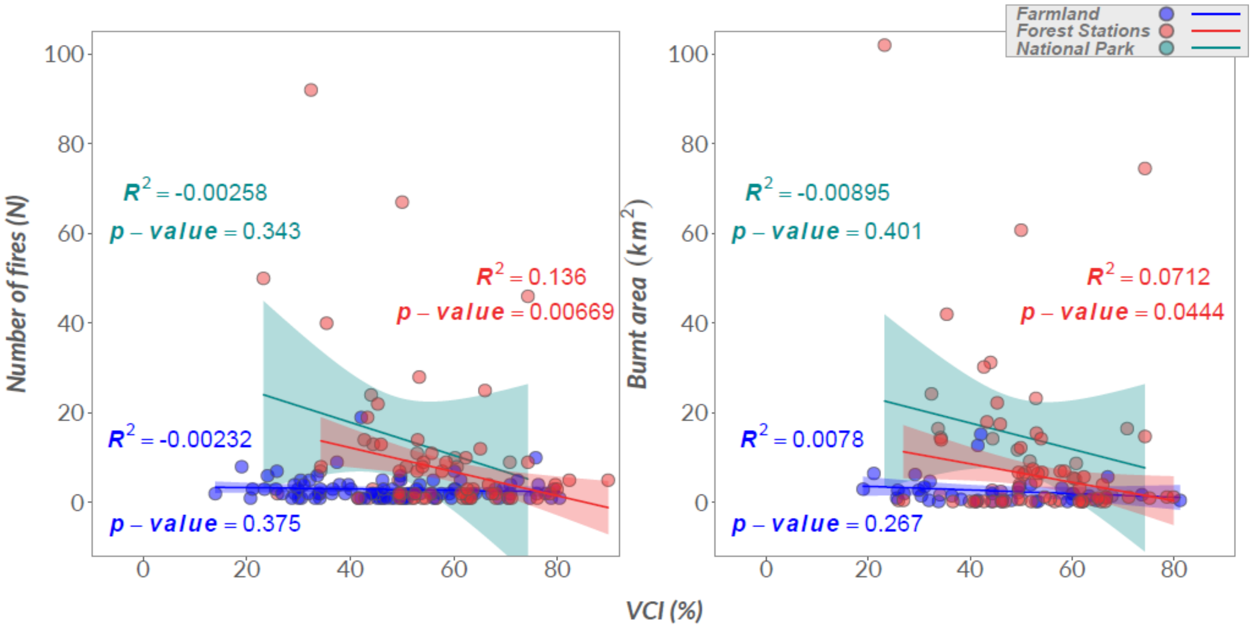

Figure 11: The effect of increasing VCI on the number of fires and burnt area in National Park (NP), Forest Stations (FS) and Farmlands (FL) around Mount Kenya Forest and National Park from 2003 to 2018

This study analyzed relationships between number of fires, burnt area and the VCI in forest stations on the Northwest side that have a medium fire danger (Nanyuki), high fire danger (Ontulili) and those on the Southeast side that have a low fire danger (Chuka and Chogoria). Correlations between number of fires, burnt area and VCI show that there are only minor differences between forest stations on the Northwest side that have a medium fire danger (Nanyuki), high fire danger (Ontulili) and those on the Southeast side that have a low fire danger (Chuka and Chogoria). It also shows that there are some similarities in the effects of VCI on the number of fires and burnt area in forest stations that have a medium to high fire danger and those that have a low fire danger.

3.6 Preferences of management objectives for different fire danger classes in MKFNP

FGD participants suggested eight management objectives that were as follows: wood production, energy, biodiversity, social values, income, agriculture, non-timber forest products, protection and climate change mitigation. Results of the FGD participants ranking of the eight management objectives according to the fire danger categories (reference scenario, very high fire risk, high fire risk, moderate fire risk and low fire risk) show that although all the seven forest stations had a different fire danger, all the FGDs participants ranked the biodiversity conservation objective first in all four scenarios, agriculture was ranked second for forest stations with a very high and moderate fire danger, climate change amelioration was ranked second for forest stations with a high and a low fire danger (Figure 12). In the "reference" scenarios of all the eight objectives were equally weighted (1/8 = 0.125).

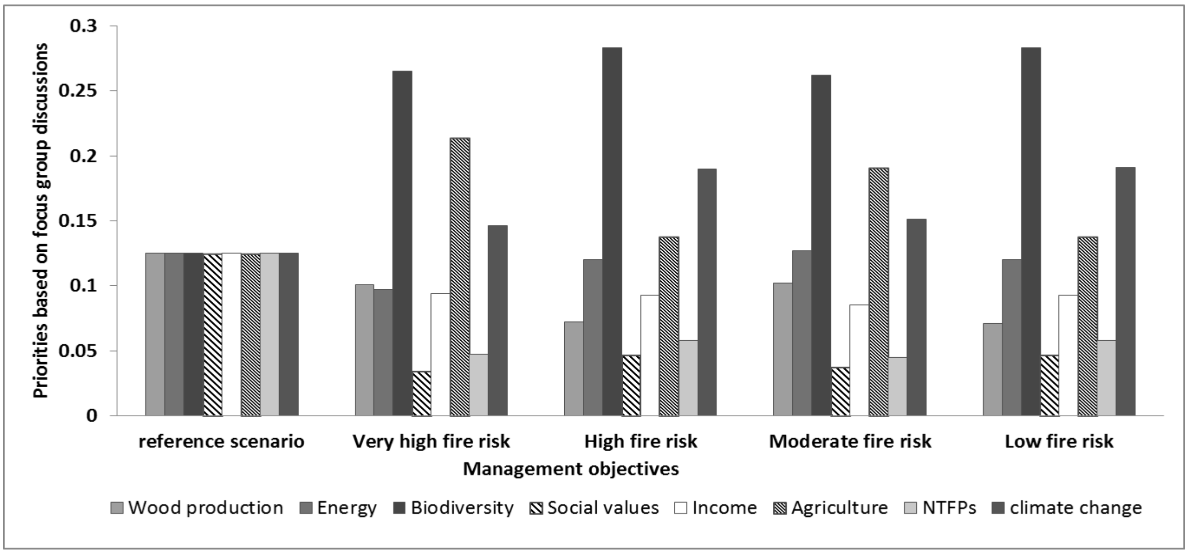

Figure 12: Priorities of management objectives according to the fire danger categories

3.7 Priorities of the management strategies in MKFNP

FGD participants suggested seven management strategies that were as follows: management strategy one (MS1) was to achieve national climate change mitigation interests (MS1); management strategy two was to achieve counties' water catchment protection interests (MS2); management strategy three was to achieve education and research interests (MS3); management strategy four was to achieve all stakeholders interests (MS4); management strategy five was to achieve biodiversity conservation interests (MS5); management strategy six was to achieve timber production interests (MS6); and management strategy seven was to achieve community interests (MS7). Based on the ranking of the priorities of the management objectives by the FGD participants, results of the application of AHP to compare the seven management strategies according to the fire danger categories (reference scenario, very high fire risk, high fire risk, moderate fire risk and low fire risk) and select the best management strategy show that although all the seven forest stations had a different fire danger, all the FGDs participants rated MS7 (community interests) first based on the weights given to all objectives and criteria. Only in the reference scenario (with equal weights for all objectives) was the MS5 (biodiversity conservation) ranked first. The second and third ranked strategy for the four different fire danger categories were MS5 (biodiversity conservation) and MS4 (all stakeholders interests) respectively. The MS3 (education and research) was classified as the least preferred strategy in each case (Figure 13).

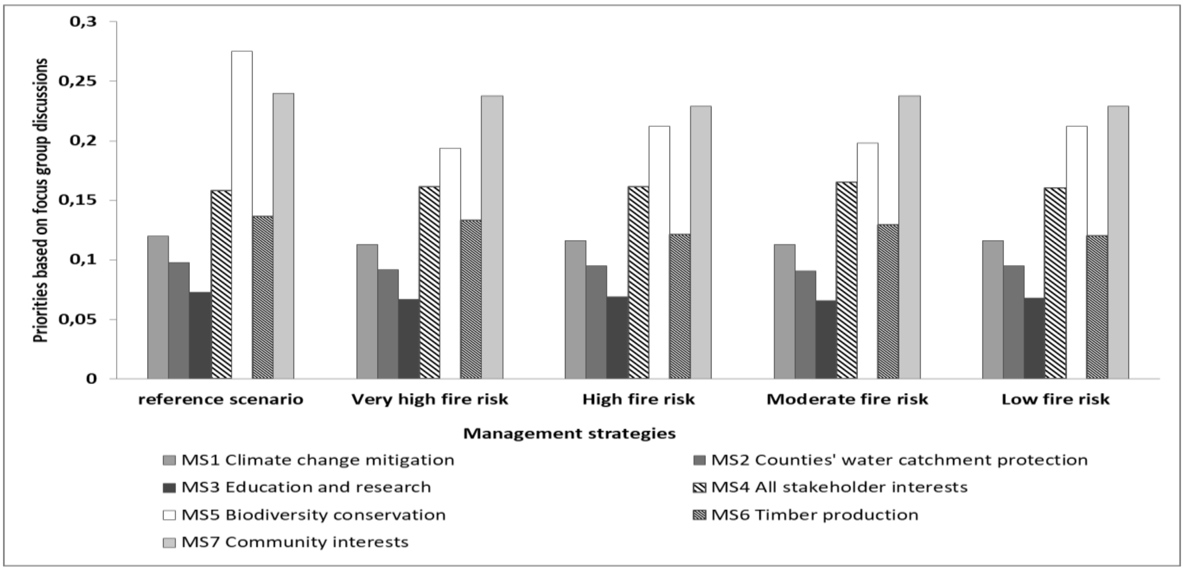

Figure 13: Priorities of the seven management strategies for the reference scenario and the four fire danger categories

3.8 Community benefits and concerns about fires in Gathiuru Forest

Management strategy (MS7) that helps achieve community interests is more preferred in Gathiuru Forest. The common human needs accessed by the local communities in Gathiuru Forest include water use, timber, firewood, livestock grazing, cultivation of crops, collection of herbs for medicinal purposes, and generally contributing to a good life style. Results from focus group discussions show that there are considerable environmental and economic values that support the livelihood of the communities living around Gathiuru Forest. The forests offer diverse resources for consumptive use, and local people are allowed to access these products through a permit and licensing system. Figure 14 shows the voting and ranking of the benefits obtained by the CFA in Gathiuru Forest, where using the land as farmland (PELIS) is ranked as first and providing cultural/religious benefits is ranked last.

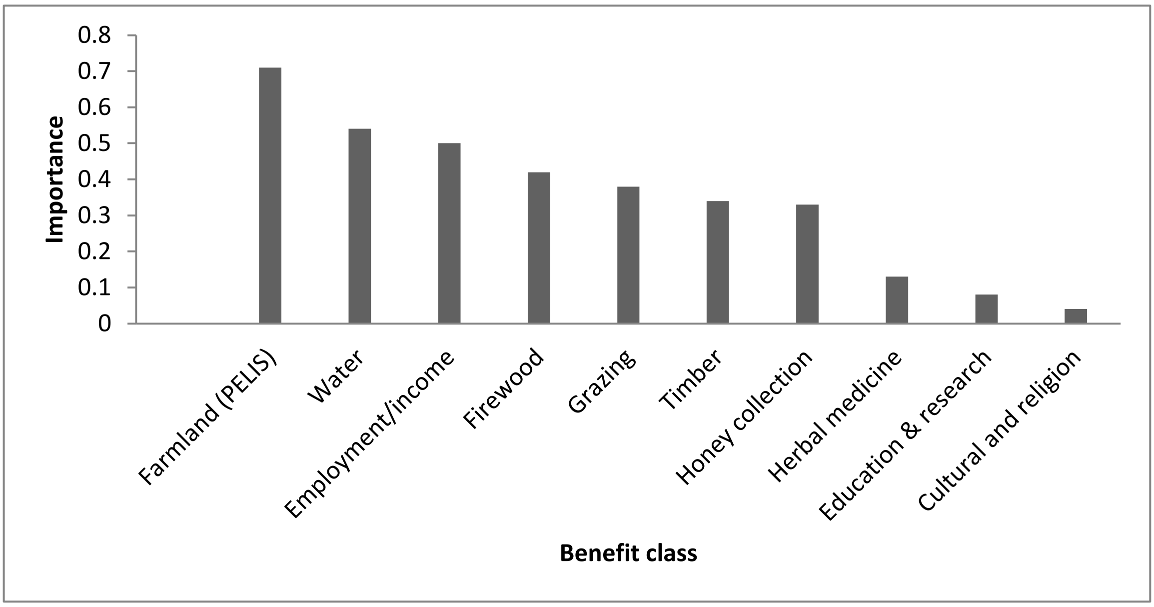

Figure 14: The ranking of benefits obtained from Gathiuru Forest (N = 24).

Fires can have several effects on the social, economic, and cultural aspects of the livelihood of local people. Focus group discussions indicated that the participants support the idea that when fire is used and managed properly through IFM, it has some positive effects for the communities and environment, but there are also concerns about the damages that can be caused by wanted and unwanted fires that are lit intentionally or unintentionally in Gathiuru Forest. Figure 15 shows the voting and ranking of the concerns related to the negative effects of fires by the CFA in Gathiuru Forest, where the loss of grazing grounds (pasture) is ranked as first and the loss of livestock is ranked last.

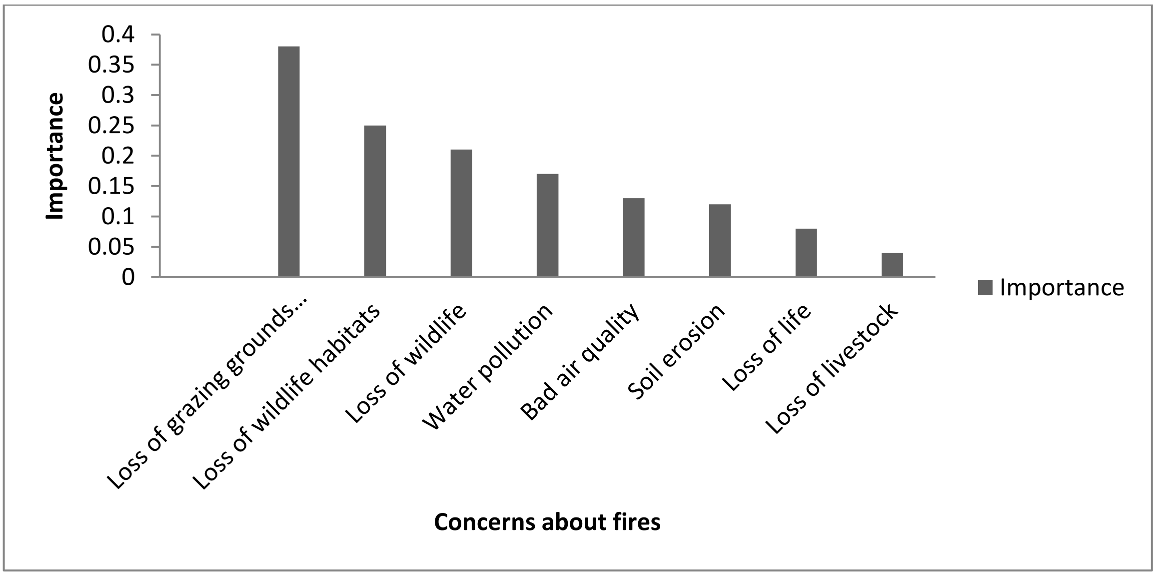

Figure 15: The votes & rank of concerns related to fire effects in Gathiuru Forest (N = 24).

3.9 Community participation in IFM in Gathiuru Forest

The KFS and KWS have to a great extent been involved in resolving conflicts between different user groups and the migrant pastoralists over the use of forest resources especially grazing grounds. The KFS and KWS have to some extent been by providing fire educational programmes and firefighting training programmes to forest managers, rangers, CFA members and forest scouts with the aim of improving their knowledge and skills in fire prevention and suppression in Gathiuru Forest. However, results indicate that the government of Kenya has to a small extent been providing firefighting equipment to be used in fire prevention and suppression in the Gathiuru Forest, as shown in Figure 16. This has greatly affected the ability of KFS, KWS and CFAs to implement some IFM activities like fighting the huge fires that have been occurring repeatedly in recent years.

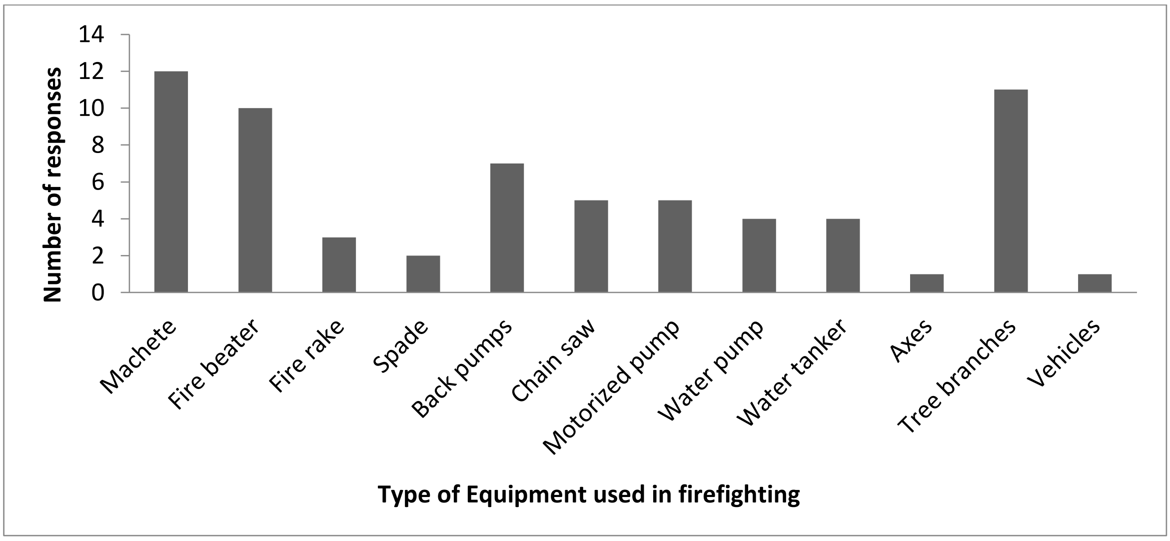

Figure 16: Type of equipment used to fight fires at Gathiuru Forest Station (N = 16).

3.10 Integrated Fire Management (IFM) framework

The scientific experts and other stakeholders (KFS, KWS, CFAs and NGOs) jointly developed an IFM framework (Figure 17). The jointly developed IFM framework that helps communities and natural resource managers to address both damaging and beneficial fires within the context of the natural environments and socio-economic systems in which they occur, by evaluating and balancing the relative risks posed by fires with the beneficial ecological and economic effects they may cause in a given conservation area, landscape, or region. It helps to identify factors influencing fire ignition as it relates human needs and land use activities. The roles of external drivers in influencing fire danger are estimated, and the positive and negative effects of fires are ascertained. It also helps in evaluating the benefits and risks of different management activities and developing fire management guidelines considering human needs and land use activities.

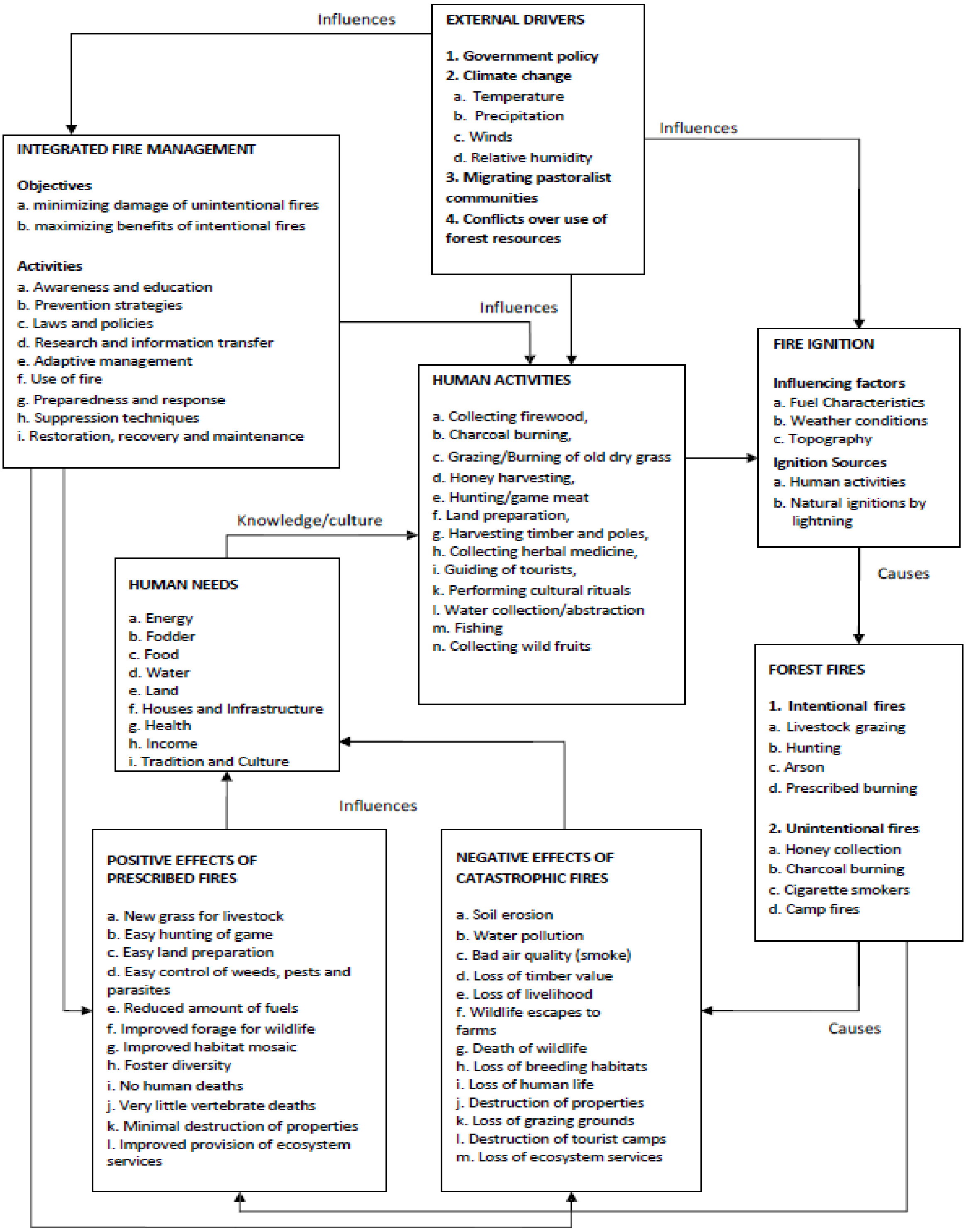

Figure 17: A proposed Integrated Fire Management (IFM) framework that helps communities and natural resource managers address both damaging and beneficial fires in Kenya.

4. Discussion

4.1 Impact of human activities on the spatio-temporal patterns of fire occurrence

The Kenya Forest Act 2005 provides a legal framework for the establishment of Community Forest Associations (CFAs) (KFS, 2010). This study found that human activities vary between forest stations in MKFNP. The CFAs benefit directly or indirectly from forest and wildlife resources. The CFAs are also involved in fire management activities (KFS, 2010, KWS, 2010). This is because communities living around MKFNP use fire as a tool in land management (Nyongesa, 2015). Perennial grassland fires are common in many parts of MKFNP (KFS, 2010, KWS, 2010). The months of December to March usually have a high number of fire occurrences and large burnt areas and may be attributed to the seasonal increase of human activities in these months (Timothy et al. 2017). The burning of old grass so that new grass can grow when the rain comes is a common practice done by migrant pastoralists who come to graze their livestock in MKFNP during the dry season (Nyongesa, 2015). Communities around MKFNP also use fire to prepare their farmlands and break impenetrable bushlands, control weeds, pests and parasites and try to keep wildlife away from homes (KFS, 2010, KWS, 2010).

However the decline in number of fires and burnt area in the months of July, August and September can be attributed to human activities changes like seasonal farming patterns (crops on field) and the migration of pastoralists (Maasai and Samburu) out of MKFNP in search of pasture and water for their livestock in the low plains (KFS, 2010, KWS, 2010, Nyongesa 2015). The KFS and KWS have however continued to practice fire suppression campaigns instead of using prescribed burning activities to manage fuel accumulation in MKFNP (Timothy et al. 2017). This has resulted to an increase in the number of catastrophic fires that have caused damage to the forests, socio-economy, and environment in Mount Kenya region (Poletti, 2016, Timothy et al. 2017). Based on the land use classes, this study established that most of the fire ignitions and burnt area was in the NP, followed by FS and then FL located in the leeward side (northwestern slopes) of MKFNP from 2003 to 2018 (Timothy et al. 2017, Mary et al. 2019).

According to the fire records and interviews conducted, it was found that the charcoal burners, honey collectors, cattle grazers, cigarette smokers, arsonists, and hunters are the main causes for fire ignition in MKFNP. However, other studies have shown that not all ignitions are directly linked to land use activities, for instance, fires due to arson and the careless disposal of smoked cigarettes are related to social behavior (Mathew, 2005). It is important to understand how, at the local level, communities utilize land resources with or without the use of fire and the social behavior that drives ignitions, and incorporate them into IFM approaches as a basis for addressing the risk of fires (Mistry et al., 2005, Myers, 2017).

In many studies, it was found that the growing human population and the increase in per capita food consumption are driving agriculture expansion and affecting natural ecosystems (Grau et al., 2008). According to the 2009 Kenya Population and Housing Census, many of the communities living around MKFNP are poor and do not have enough land for farming (Obare and Wangwe, 2017). Communities living around MKFNP also heavily depend on the forests for many ecosystem services and non-timber forest products. Most of the CFAs in MKFNP were formed from 2005-2012 to involve the community in Participatory Forestry Management and at the same time to help regulate human activities according to the agreed user rights in MKFNP. The user groups have the right to conduct their activities within MKFNP which includes timber production and running saw mills, grazing, firewood collection, beekeeping, collecting herbs, water abstraction, farming trout fish (*Oncorhynchus mykiss* Walbaum), providing hotel and cottage services as well as ecotourism and cultural exhibitions, conducting the PELIS system on farms, and acting as community scouts.

The signing of the user group's agreement has enabled the CFAs to source funding from other key sources, principally the Green Zones Development Support Project. Each of these user groups has been provided with an area for their business and in the case of a fire outbreak, the whole group will lose their user rights (KFS, 2017). The use of fire in MKFNP is forbidden by the forest station managers according to the PELIS guidelines. The CFA members involved in farming activities are not allowed to use fire for land preparation. This is not compatible with their traditional farming practices. However farmers still use fire illegally in MKFNP and at times, these fires get out of control causing larger unintentional fires. According to the farming (PELIS) rules and guidelines, the growing of beans (*Phaseolus vulgaris* Linnaeus), potatoes (*Solanum tuberosum* Linnaeus) and onions (*Allium cepa* Linnaeus) has been practiced in MKFNP from 2005 to 2019. For example, PELIS has helped to reduce poverty and to increase food security amongst Gathiuru CFA members involved in the production of high-quality potatoes with an estimated production of 7500 tons per year. From 2008 to 2017 total sales of food crops (potatoes) amounted to KSh 756 million ($7.56 million) and this enabled CFA members to stop depending on the forest resources and start other income generating activities.

Firewood is utilized in many parts of the world as a source of energy and is a major focus in the management of primary and secondary forests (FAO, 1997, Fuwape, 2011). According to the studies done by (CIFOR, 2016), the increased demand for fuelwood can lead to forest degradation, slow down regeneration, change tree species composition, cause a reduction of tree cover, increase fine fuel (grass) accumulation, and consequently change the rate of wildfire spread (Sassen et al., 2015). It was found that firewood collection also plays an important role for the CFA members as well. Firewood collection in MKFNP has been licensed and the fee for collecting firewood two or three times per week ranges from KSh 100 to 150. However, the some CFAs in MKFNP have bought energy saving cooking stoves (jikos) and distributed them among CFA women. This has helped to reduce the fire wood consumption and hence women do not need to go to the forest daily to collect firewood (KFS, 2017). There is also great potential for CFA members to use the pruned lower branches and thinned small diameter trees for charcoal or briquettes for domestic use or commercial purposes (income) as this may help prevent ladder fuel accumulation, thus partly mitigating fire risk.

Several studies have been done to assess the impacts of cattle grazing on forests fires, water quality, biodiversity, invasive species, soil fertility, regeneration, tree damages, and soil erosion (Stern, 2002). Cattle grazing and cutting of grass to feed livestock is allowed and has been licensed in MKFNP. Grazing and cutting grass helps to reduce the fuel load and at the same time minimizes the risk of rapid surface fires occurring. Cattle grazing reduces low ground fuels, which decreases wildfire intensity and the length of flames, thereby reducing the risk of higher fuels (such as branches) catching fire (Savadogo et al. 2007). The CFAs are responsible for collecting grazing fees of Ksh. 100 per head of cattle. For example, agriculture officers have been involved in designing a carrying capacity for cattle grazing in Gathiuru Forest to help reduce the problem of over grazing. When the grass in the grazing area is gone, the cattle grazers are reallocated to another grazing area according to the carrying capacity. The CFA cattle grazers groups are not allowed to use fire for managing grasslands in MKFNP, but are responsible for monitoring and reporting to the forest and wildlife managers any illegal grazing activities and fire outbreaks so that the culprits are arrested and prosecuted. Nevertheless, there have been many cases of illegal grazing in MKFNP and fire outbreaks caused by illegal grazers (migrant pastoralists) who set grasslands on fire to keep them open and to facilitate the growth of new grass for livestock (KFS, 2017).

Studies of sacred forests and other sacred sites show that religious and spiritual beliefs can sometimes be the motivation for conservation and environmental protection. African indigenous religions view land and its resources as communal property that belongs not only to the living, but also to their ancestors and to future generations (Verschuuren, 2010). Mount Kenya is a holy mountain for the Kikuyu community. The term Kikuyu originates from the Mukuyu tree (*Ficus sycomorus* Linnaeus). According to the Kikuyu culture, three sacred trees make the community believe that they should conserve the forest: Mukuyu tree (*Ficus sycomorus* Linnaeus), Mugumo tree (*Ficus thonningii* Blume), and Mukurwe tree (*Albizia gummifera* J.F. Gmel.). Nobody in the community is allowed to cut down or set fire to these trees. This is similar to other places in Africa (Muriuki, 2011) and contributes to the efforts of conservation.

Ecotourism can be an incentive for conservation activities, and may provide socio-cultural benefits (Acquah, 2017) and income for local communities living around nature parks (Ogato, 2014, Vishwanatha and Chandrashera, 2014). Fires burning camp grounds and other tourist resorts, destroying the national park, and causing evacuations of tourists from fire-threatened recreation sites are a great concern (GFMC, 2017). The CFA ecotourism group views fire in MKFNP as a serious threat to ecotourism, but studies have shown that there are wild herbivores that benefit from plant regrowth after fires. Using prescribed fires in the landscape can help to maintain native flora and fauna that might attract tourists (Eby et al., 2014). The perception of risk and the knowledge about wildfire by tourists has to be considered, as some tourists are not aware of the potential danger of becoming trapped by wildfires or causing a fire due to the negligent handling of barbecue fires or cigarettes (GFMC, 2017). Some CFAs have been establishing hiking trails that are being used by tourists and also act as fire breaks (KFS, 2017).

Hunting of game-meat used to be a traditional practice of many communities in Kenya. The communities used fire as a hunting tool and to roast game meat for centuries. With the introduction of a ban on hunting in Kenya in 1977, the hunting practice was rendered illegal. However, poachers in MKFNP have continued to use fire as a hunting tool and to distract rangers from arresting them as the rangers try to put out an early fire outbreak, which allows the poachers to escape (KWS, 2010). The KWS, KFS, and CFAs are working together to ensure there is no more hunting of wildlife in MKFNP. Nowadays, the CFA members are educated on how to keep rabbits (*Oryctolagus cuniculus* Linnaeus), chicken (*Gallus gallus domesticus* Linnaeus), sheep (*Ovis aries* Linnaeus), goats (*Capra hircus,* Linnaeus), and cattle (*Bos Taurus*) for producing food and hence the need for game-meat is declining. The legal fine for those involved in illegal hunting has also been increased tremendously to discourage this bad practice (KFS, 2017).

Some CFA members are involved in bee keeping within MKFNP. Their practice has been registered and licensed to established apiaries within the forest and some have been trained by KWS on bee keeping, honey harvesting, and processing. The Ogiek tribe in the Great Rift Valley of Kenya is one of the honey hunter-gatherer peoples in East Africa and honey plays a central part in the Ogiek society, being used for food, beer brewing, and trade. Besides using beehives of hollow logs placed in tree branches, the traditional honey collectors in MKFNP illegally hunt for honey in tree hollows. They use fire to produce smoke and keep away the bees (*Apis mellifera* Linnaeus) before collecting honey and sometimes this causes fires in MKFNP during the dry season, especially when the honey collectors act carelessly (KFS, 2017).

4.2 Positive and negative social and environmental benefits of fires in MKFNP

Communities living around MKFNP have a long history of using fire as a land management tool. MKFNP has some fire-dependent species like *Juniperus procera, Bambusa vulgaris* (Schrad Ex J.C. Wendl.) and *Hagenia abyssinica* that usually regenerate after fire. Native perennial grasses also regrow from root systems that are rarely damaged by fires that occur in MKFNP. Fire is the only natural factor which also supports the reproduction of the subalpine forests as the grass layer of larger areas is cleared by occasional burning (Bussmann, 2001). Some scavenger animals like hyenas (*Crocuta Crocuta* Erxleben) and bird species like the black eagles (*Ictinaetus malaiensis* Temminck) have been seen to move to burned areas in MKFNP as the reduced vegetation allows them to catch prey easily (Gorte and Bracmort, 2012). Fire has influenced the vegetation in the landscape because some plant species require fire to germinate, establish, or to reproduce, and total fire suppression not only eliminates these species, but also affects the animals that depend upon them (Butz 2009, Wangari 2016). A regular occurrence of fires in MKFNP can reduce the amount of fuel build-up, thereby lowering the likelihood of a potentially large wildland fire (Timothy et al., 2017). Fire removes low-growing underbrush, clears dead or weaker trees, cleans the forest floor of debris, opens it up to sunlight, and reduces competition for nutrients and space, allowing established trees to grow stronger and healthier (Downing et al., 2017). The ashes that remain after a fire add nutrients that are often locked in older vegetation to the soil for trees and other vegetation. Fires can also provide a way of controlling insect pests by killing off the older or diseased trees and leaving the younger, healthier trees (Heydari et al., 2016). Burned trees provide habitats for nesting birds, homes for mammals, and a nutrient base for new plants. Overall, fire is a catalyst for promoting biological diversity and healthy ecosystems as it fosters new plant growth and wildlife populations often expand as a result

(Wade and Lundsford, 2018). However, the use of prescribed fires by KFS and KWS for fuel management is not practiced in MKFNP. These prevention measures would help to decrease the risk of catastrophic fires. However, the current banning of all fires from current land use practices might lead to an accumulation of fuel loads, which will have a major role in future outbreaks. For example, in the last 35 years, catastrophic fires have burned 4509.10 ha of Gathiuru Forest, destroying plant material and the litter layer. KFS records show that from 1980 to 2015, the total damage caused by catastrophic fires in Gathiuru Forest plantations for timber and pulpwood was $443,837 and the cost incurred while fighting these fires was $41,917 (Downing et al. 2017).

Plantations of exotic tree species have been established by the KFS for the pulp and timber industry in Kenya. Several studies have been done on how exotic tree species contribute to changes in the patterns of anthropogenic ignitions, flammability of exotic species, forest ecosystem structure, and process and fuel loads (Huffman, 2015). Fire also stimulates the release of large amounts of seeds from the serotinous cones of Pinus radiata and can create favorable conditions for germination and establishment (Moira and Glenda, 2007). The principal mechanisms of recovery in fire-resistant Eucalypt species are resprouting from epicormic strands (i.e., regeneration from meristem strips, usually extending from the inner to outer bark on aboveground branches and stems, which produce buds), and/or from basal buds (Filipe et al., 2013). Therefore unmanaged fires may contribute to an increase of exotic species in the natural environments of MKFNP.

Shrubs, forbs, grasses, trees, and the litter layer break up the intensity of severe rainstorms. The stabilization of the soil by the plant roots, stems, and leaves slows down the water drops and provides time to percolate into the soil profile (Dell'Angelo, 2016). The subsequent rains after fires have caused landslides, flash floods, and soil erosion in MKFNP (Moench and Furaso, 2012). The ash from burned sites caused water pollution affecting trout fish farming and heavy sedimentation has been recorded in the seven folk dams that rely on water from rivers in MKFNP (KFS, 2010). Other studies have also proved that surface water coming from burned areas causes serious water quality problems in streams, lakes, and reservoirs by introducing hazardous chemicals into the water bodies (Tecle and Neary, 2015).

Fires occurring in MKFNP have been causing smoke that is spread by wind several kilometers away. Wildfire smoke composition depends on many factors, including the types of vegetation burned and the pollutants in smoke can include deadly gases, e.g., carbon monoxide and many solid and liquid elements often known as particulates or particles (Nyongesa, 2015). Forest fires have been polluting the air, irritating the eyes, reducing the visibility of travelers, and causing difficulty in breathing to communities living around MKFNP and several kilometers further away.

Some wildlife has lost its life after huge catastrophic fires in MKFNP; especially slow moving, sick, or young birds/animals that cannot escape fire (Gorte and Bracmort, 2012). Fires cause a loss of their habitats and provoke them to escape to nearby farms, destroying crops and thus causing huge losses to CFA members who obtain their food and income from MKFNP. Tourism is also negatively affected after huge fires, as the scenery is destroyed and some wildlife are forced to migrate to other parts of MKFNP.

During years of extreme drought, migrant pastoralists usually come to graze in MKFNP, set fire to the old grass to facilitate the growth of new grass, and then move away in search of good pasture grounds. This practice has been causing huge fires and the loss of grazing grounds for the locals, who depend on the grasslands within MKFNP for grazing their livestock. Inter-community conflicts over water and pasture grounds between the locals (Kikuyu) and the pastoralists (Samburu and Maasai) are likely to increase (Kumssa et al., 2009).

The highest human fatalities from fighting fires occur in developing countries, with a figure of up to nearly 80% for the period between 1997 and 2006 (Dube, 2013). This is also one of the most serious concerns in MKFNP. Volunteer fire fighters suffer from the lack of proper firefighting equipment which can be a strong contributing factor in loss of life while fighting huge fires. Fires have also destroyed houses constructed by CFA members within MKFNP (KFS, 2017).

Loss of livestock has been reported after extreme shortages of pasture caused by drought and fires in the MKFNP. The poor nutritional status of the livestock does not allow the long distance movement of livestock for pasture and water. Wildfires suppress grass production for about two rainy seasons and it is recommended that pasture grounds must rest for at least one rainy season after a runaway fire, and for at least one rainy season before a prescribed burn. After huge fires, the leftover grass is grazed by wild animals, and may not be suitable for livestock grazing, and this makes weak livestock prone to death or the communities have to sell them at low prices (Waal, 2016).

4.3 The relationship between precipitation, NDVI, VCI, fire occurrences and burnt area in MKFNP

MODIS data are not always available (Detsch et al 2016). The MODIS 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 (Tsela et al 2010). MODIS cannot detect fires smaller than 24 ha at all. MODIS was designed to produce low commission errors (Bastarrika et al 2011), but its accuracy in afro-alpine ecosystems has not been thoroughly assessed. The MODIS product MCD45A1 contains information about fire occurrence than empirical fire records. However, tests in other regions and ecosystems have indicated that MODIS tends to underestimate burned area size (Fornacca et al 2017). This study found sufficient discrepancy between MODIS's detection of burned areas and ignition sites and this created uncertainty about its accuracy because some fires ignitions were detected but not registered in burned areas.

Other studies using ground stations and satellites to monitor weather conditions have shown that the windward side (southeastern slopes) of MKFNP receives more rainfall with approximately 2250 mm while the leeward side of the mountain (northwestern slopes) receives about 900 mm (Henne et al. 2008). The drier conditions on the leeward side of MKFNP make the area to be prone to more fires than the windward side (Poletti, 2016, Timothy et al. 2017, Mary et al. 2019). In comparison of the empirical data from the weather stations with the CHIRPS precipitation data it can be assumed, that the real weather conditions were even more severe, as the CHIRPS precipitation data underestimated the drought conditions to some extent. Even though several studies have shown that MKFNP fire seasons are usually defined as January-March and July-September (Poletti, 2016, Timothy et al. 2017, Mary et al. 2019), analysis of MODIS-FIRMS data from 2003 to 2018 showed that the month of December is also fire prone and needs to be included in the fire season of MKFNP.

A study by (Timothy et al. 2017) found out that the years 2007 and 2012 had the highest number of fire ignitions. This study also confirmed that, in the years 2006, 2008 and 2009 a high number of fires and large burnt areas were observed. Most of these fires took place in the months of December, January, February and March as compared to July, August and September except in the year 2008. Generally the human activities coupled with low precipitation, high temperatures and increased wind speed contribute to the high number of fire ignitions and burnt area in MKFNP (Nyongesa 2015, Poletti, 2016). It was found that an increase in precipitation had a slight negative effect on the monthly number of fires and burnt area detected by MODIS-FIRMS satellite during the dry and wet season in MKFNP. This is also in line with a study done by (Timothy et al. 2017) which focused on the fire occurrence on Mount Kenya and patterns of burning, who established that the number of fire ignitions and burnt area decreased as precipitation increased and vice versa.

Several studies have been conducted to monitor ecosystem dynamics using NDVI and climate variables to assess long term trends in dryland vegetation variability (Zewdie, 2017). A five-year analysis of NDVI (Gu, 2007) for grassland drought assessment over the central Great Plains of the United States found out that NDVI was low during the drought period. Other Studies have found out that the maximum and minimum values of the NDVI reflect the best and worst conditions of vegetative growth and the difference between them usually reflects the condition of the local vegetation (Dwomoh et al. 2019, Kogan, 1995, Kogan, 1997). This study indicated that the mean monthly NDVI from 2009 to 2013 was lower because of the two drought periods that occurred in 2009 and 2012 (Klisch and Atzberger, 2016).

Studies done by (Klisch and Atzberger, 2016, Measho et al. 2019) have classified drought levels in Kenya and Eritrea using a VCI above 35% to represents no drought conditions. This study used the same threshold of VCI values below 35% to indicate drought conditions in MKFNP. Similar studies by (Tagel and Maathuis, 2016) that used the VCI to monitor agricultural drought were able to found out the major historical agricultural droughts in Ethiopia and the geographical regions that were most exposed to recurrent cycle of drought events. Also the studies by (Klisch and Atzberger, 2015) used a three-monthly aggregated vegetation condition index (VCI3M) for classifying the rainy and dry season from 2003 to 2014 and for the development of a fully operational processing chain for mapping drought occurrence. In this context the extent and strength of the nationwide droughts are comparable to the findings of this study especially the monthly VCI values in February were below 35% indicating that MKFNP was also affected during the severe nationwide droughts (Klisch and Atzberger, 2016).

Fire as disturbance has been known to affect the VCI (Congalton and Green 2008, Klisch and Atzberger, 2016). As a result, if the burnt areas in MKFNP were large, they might have also caused a drop in the VCI after the fire events that occurred between 2003 and 2018 (Klisch and Atzberger, 2016). However this study found that there is no effect of VCI on the number of fires during the wet season as the increased precipitation makes the fuel moisture content very high and probability of fire ignitions in MKFNP to be very low (Timothy et al. 2017). However, results of this study show there is a slight relationship between VCI and number of fires in the dry season and the VCI has a similar effect on burnt area during the dry and wet seasons. This is because whenever the VCI value increases above 35% during the wet or dry season, it indicates that the fuel conditions are not favorable for large fires (Measho et al. 2019) and this result in the reduction in the number of fire ignitions and burnt area in MKFNP (Timothy et al. 2017).

Correlations between number of fires, burnt area and VCI reveal minor differences between the NP, FS and FL. This is related to the temporal and spatial differences in VCI values depending on the season and the land use types (Timothy et al. 2017, Measho et al. 2019). A study by (Downing et al., 2017) found out that the moorland in the MKFNP has had the highest number of fire occurrences from 2000 to 2015 in the area characterized by Ericaceous vegetation, which is an open community of bushes often discontinuous and merging into Afromontane shrub land. This study also found that the moorland that characterized by Ericaceous vegetation had the highest number of fire occurrences from 2003 to 2018. This is related to the fact that during the rainy season the ericaceous vegetation usually grows very fast and dries up quickly during the dry season resulting in a low VCI as compared to the other forest vegetation in MKFNP. As a result the ericaceous vegetation accumulates large amounts of fuel during the dry season and increases the risk of fire outbreaks (Timothy et al. 2017). This study found out that was a slightly higher correlation between the number of fires, burnt area and VCI in the FS that had a higher R^2 and lower p-value than for NP and FL. This study results also show that VCI has no effect on the number of fires and burnt area between forest stations on the Northwest side that have a medium to high fire danger and those on the Southeast side that have a low fire danger. This is because forests in MKFNP have a high VCI and spatially explicit heterogeneous vegetation that is less fire prone as compared to the moorland during the dry season. As a result forests regulate pick flows, intercept precipitation, improve the ground water recharge and steady the discharge during the season thus performing water catchment functions better than the moorland in MKFNP (Notter et al. 2007).

4.4 Use of Multi Criteria Analysis (MCA) in evaluation of management strategies in MKFNP

This study provides important insights into the application of a MCA approach to develop management strategies, objectives and criteria that can be used to identify, structure, monitor, evaluate and select the best management strategy that will help to reduce fire danger and increase the benefits obtained in MKFNP. Other studies have also shown that MCA is both an appropriate and useful approach for capturing diverse views, objectives and perspectives of different stakeholders involved in decision making (Saaty, 2008).

The careful selection of FGD participants during the study, helped to develop and evaluate the seven management strategies based on the identified objectives. A team of professional experts in the application of MCA techniques was selected and made responsible for supporting the process of comparing management strategies. The interaction between the facilitators, FGDs' participants, and experts was undertaken by having a high number of meetings within a short period of time (Khadka and Vacik, 2012). However, it was found out that the FGDs' participants were had difficulties in expressing their preferences with regard to the management strategies, and importance of objectives and criteria. Many of them were not familiar with the forestry and wildlife terms that were used in the qualitative evaluation, while others did not understand well how the scoring and ranking of the developed management strategies, objectives and criteria was to be done and this made the exercise challenging and time-consuming. The developed management strategies varied both in the temporal and spatial scale to meet the various stakeholder interests and this made it even more difficult for the participants to evaluate the strategies. Another observation was that some FGDs' participants only preferred objectives that required a shorter time to be achieved and therefore had strong interests in having them implemented. This indicates that the best management strategy that is applicable on the entire area of MKFNP has to help reduce the fire danger and consider both the short term and long-term interests of the different stakeholder groups for it to be accepted and implemented.

The facilitators used a mixture of a bottom-up and a top-down approaches during the regional and local FGDs. This allowed for keeping a consistent overall framework for the evaluation, while including inputs from the participants in a participatory way. The FGDs' participants were able to express their own preferred management strategies, objectives and criteria and appropriately address some of the challenges in the qualitative assessment. This helped to accurately structure the problem, increase transparency and improve the quality of the decision-making process by contributing to a participatory implementation (Jalilova et al. 2012). The use of MCA for evaluating the management strategies for implementation in MKFNP helped to address the stakeholder interests and provided a framework for evaluating trade-offs in a transparent and understandable way (Vacik and

Lexer, 2001). The application of the MCA allowed the team of experts to come up with solutions which resulted in higher level of overall stakeholder satisfaction (Jalilova et al. 2012).

Several studies have shown that the use of the AHP can impose several challenges, as it can be time-consuming when scores and ranking of the participants are transferred to pairwise comparisons (Hajkowicz and Higgins, 2008). AHP allows the use of both qualitative and quantitative information when comparing the performance of alternatives (Saaty, 2008). However, very often it is not possible to consider quantitative information in assessing management strategies with regard to the effectiveness to fire management or in improving the livelihood conditions. Therefore, transferring the qualitative ratings to pairwise comparisons is useful (Jalilova et al. 2012). The analysis with the AHP allowed for the sensitivity of each management strategy to be identified by varying the weights assigned to each objective.

Evaluation of the performance of management strategies in MKFNP showed that MS1 (national climate change mitigation interests), MS5 (biodiversity conservation interests) and MS6 (timber production interests) are long term management strategies. MS2 (counties' water catchment protection interests), MS3 (education and research interests), MS4 (all stakeholder interests) and MS7 (community interests) are short-term management strategies. However, the results indicate that MS5 and MS7 are almost equally preferred. This indicates that long and short-term aspects are considered as relevant by the various stakeholders. To achieve sustainable management of MKFNP, other programmes should offer a similar degree of importance for the improvement of community livelihoods (Swallow, 2009). Objectives such as wood production, biodiversity conservation, protection, and climate change amelioration require long-term management to provide positive outcomes and meet various stakeholder interests. However, energy, social values, income, agriculture and non-timber forest products require short-term management activities (Tumpach et al. 2018).

The current management strategies being implemented by resource managers have focused more on the conservation of biodiversity and have paid less attention to fulfilling other objectives such as wood production, energy, social values, non-timber forest products, protection and climate change amelioration (Uddin et al., 2019). The KFS and CFAs have been implementing the Mount Kenya Forest Reserve (MKFR) management plan 2010–2019 that considers sustainable management, including conservation and rational utilization of the forest resources for socio-economic development (KFS, 2010). On the other hand, the KWS has been implementing the Mount Kenya Ecosystem (MKE) management plan 2010–2020 that has Ecological Management programme that aims at addressing biodiversity restoration and protection, linking ecosystems, and carrying out applied research to understand how the ecosystem functions (KWS, 2010). Biodiversity conservation is seen as basis for the functionality of MKFNP ecosystem including fuel wood, soil fertility, water, timber, poles, wildlife, tree species, agriculture, non-timber forest products, protection, climate change amelioration, culture and scenery (Chapin et al., 2000). Since MS5 is effective in conserving biodiversity, reducing fire danger and increasing the benefits, it has the greatest likelihood of being socially, economically and politically acceptable. When MS5 is fully implemented in MKFNP, it is possible that many of the current management problems might be reduced. However, although the biodiversity conservation objective is ranked first by all the participants of the FGDs, the results of the analysis indicate that MS7 (community interests) is the most preferred management strategy followed by the MS5 (biodiversity conservation interests). This means that the resource managers will have to work closely with all stakeholders so that the selected management strategy addresses threats like poaching of wildlife and control of wildfires, which threatens all conservation targets and requires long-term monitoring as well (KFS, 2010, KWS, 2010).

Agriculture was ranked as the second most relevant objective and therefore it is obvious that MS7 (community interests) was more preferred by the FGDs' participants. This is in line with other studies that have shown that communities in developing countries are more concerned with socio-economic activities aimed at achieving their livelihood benefits such as employment, farming activities, firewood collection, water collection, grazing, honey collection, tourism, herbal medicine and hunting or timber production (Milder et al., 2012). During preference elicitation, the FGDs participants scored hunting low because it is prohibited by law to hunt in MKFNP. Some community members have been prosecuted for being involved in wildlife poaching, by getting imprisoned and or paying heavy fines (KWS, 2010). Most of the community members living around MKFNP prefer growing food crop, cash crop and keeping livestock and these are reasons why fishing was scored low by FGDs participants (Nyongesa, 2015). Fishing in MKFNP's rivers, dams and lakes is legal but only a few small-scale farmers around MKFNP have initiated fish farming projects for the growing market especially in the local hotel industry (KFS, 2010, KWS, 2010). The growing population and the increasing human demands pose a serious question as to how long this management strategy may address the growing stakeholder interests (Ongugo et al., 2007).

The findings of this study show that the decision-makers and policy actors need to consider biodiversity and community interests in the decision-making process. This will allow them to select and implement the best management strategy that reduces fire danger and increases the benefits obtained in MKFNP. They also need to consider that the changing climate and the increasing human activities are likely to contribute to increased fire outbreaks in future unless proper IFM practices are developed and implemented by the KFS, KWS managers and communities living around MKFNP.

4.5 Development and application of Integrated Fire Management (IFM) practices in Gathiuru Forest.

The scientific experts from Egerton University, University of Natural Resources and Life Sciences, Vienna (BOKU) and Kenya Forest Research Institute (KEFRI) and the other stakeholders (resource managers from KFS and KWS, the chief Ecosystem conservator, CFA members, NGOs, county water regional officers and other groups) jointly developed an IFM framework that helped to identify the role played government in IFM , human activities and other external drivers that have an influence on fire danger in Gathiuru Forest.

The government of Kenya has taken several steps to address some of the problems affecting the management of forests and national parks. In the year 2005, the government of Kenya established the Kenya Forest Act that allowed the registration CFA user groups and participation in management of forest and national parks. It also initiated a participatory forest and national park management program that involves collaboration between the KFS, Kenya Wildlife Service (KWS), the Kenya Defense Forces (KDF), the British Army, Community Forest Associations (CFAs) and other stakeholder groups to work together in forest fire prevention and suppression efforts. The government of Kenya has also been providing some incentives resource managers, rangers, firefighters, CFA members and forest scouts to motivate them so that they are more involved in fire prevention and suppression activities in Gathiuru Forest.

A lot of external drivers that have an influence on fire danger were identified during the development of the IFM framework. They include the changing climatic conditions, government policy and the role of migrating pastoralists. The meteorological factors that influence the fire weather indices include high temperatures along with dry, low humidity, and windy weather. Natural, cyclical weather occurrences, such as El Niño events, affect the likelihood of fires by influencing precipitation and the moisture content of plants, and lead to year-by-year variability. Changes in climate are likely to alter the two fire seasons in

Gathiuru Forest. According to the Kenyan government (GoK, 2013) projections, temperature and precipitation levels are likely to further alter in Kenya over the course of this century. However, despite compelling evidence on the role of climate in influencing fire ignitions, the majority of ignitions in Kenya are caused by humans, as noted in different parts of the world.

Droughts associated with climate change will cause annual flow reductions in most rivers, conflicts over water resources and pasture; and the complete disappearance of the Kilimanjaro, Ruwenzori, and Mount Kenya glaciers by 2015–2020 (Thompson, 2002). Conservation reports indicate that during years with prolonged dry spells, the forests and national parks of Kenya will continue to experience the huge pressure of livestock from pastoral communities, thereby over stretching the available resources (KFS, 2010). The setting of old dry grass on fire by migrant pastoralists also contributes to fires at Gathiuru Forest Station. This means that in all likelihood, the pastoralists (Samburu and Maasai) will continue to graze in Gathiuru Forest without considering the local CFA grazers' user group agreements and this result in inter-community conflicts. However, the government of Kenya through the county assemblies and ministry of environment and natural resources have adopted new mechanisms for addressing inter-community conflicts over the use of forest resources in Kenya by establishing good working collaboration between KFS, KWS, CFAs and other stakeholder groups (KFS, 2010, KWS, 2010).

In the year 2014, the parliament of Kenya passed the county governments' fire and disaster management bill that prepared the ground for the country to establish and implement IFM approaches in future. The Kenya forest policy also stipulates that there must be a forest fire protection unit within every forest station organizational structure. The Ecosystem conservator of the forests appointed at the headquarters helps forest managers to plan, organize, equip, train, and provide follow-up supervision of cost effective fire management at all levels with the KFS. They develop comprehensive nation-wide programs to create awareness about the need for fire protection and control and plan the implementation of risk and hazard reduction. In the field, the KFS Station Forest Managers organize and supervise the activities of the prevention and suppression of forest fires within their areas (GoK, 2005). At the regional level, the minister for the environment in each county provides firefighting staff, as well as technical and financial support to communities and forest station managers during fire incidences (GoK, 2005).

The Kenya forest policy also stipulates rules for the establishment of forest management zones to guide the different management strategies and future planning of particular areas to avoid conflicts among different users (GoK, 2005). The management zones reflect the priority of the different objectives, and generally provide a direction for daily management, as well as long-term decision making with respect to the land use patterns in the ecosystem. The developed IFM framework helps in implementing cost-effective approaches to prevent damaging fires and maintain desirable fire regimes in Gathiuru Forest. The IFM framework is scalable and can be applied in places with fire-dependent ecosystems, as well as in places with fire-sensitive ecosystems in Kenya. However, the fact that exotic tree species are still being established in Kenya's forest raises the concern that needs to be addressed when developing and implementing IFM approaches. Exotic tree species like *Pinus radiata* and Eucalyptus in Kenya's forests and national parks poses a serious threat of changing the fire regimes in the future and may also affect the regeneration of native tree species if proper IFM strategies are not established and fully implemented.

5. Conclusion

This study used the VCI to detect vegetation anomalies as a result of drought, taking into consideration the variability caused by seasonal change for each land use type (forests, national park and farmlands). The distribution of drought and fire impacts in MKFNP will be more remarkable by visualizing the difference in vegetation conditions between dry and years with an average precipitation. The hypothesis "There are typical trends in fire occurrence in relation to the dominant vegetation type" was found to be true. This study found that the moorland that characterized by Ericaceous vegetation had the highest number of fire occurrences from 2003 to 2018. This study found that forests in MKFNP usually have a high VCI and have spatially explicit heterogeneous vegetation that is less fire prone as compared to the moorland during the dry season. Based on findings of this study, the hypothesis "Differences in fire statistics can be identified using empirical fire records and fire data obtained by MODIS satellites" was found to be true. This study found sufficient discrepancy between MODIS's detection of burned areas and ignition sites and this created uncertainty about its accuracy because some fires ignitions were detected but not registered in burned areas. The hypothesis "Remote sensing data about the vegetation condition provides a solid estimate for the fire danger situation in MKFNP" was found to be true. This study found that whenever the VCI value increased above 35% during the wet or dry season, it indicated that the fuel conditions are not favorable for large fires (Measho et al. 2019) and this resulted in the reduction in the number of fire ignitions and burnt area in MKFNP (Timothy et al. 2017).

The hypothesis "Fire ignition in MKFNP depends on socio-economic activities, weather and vegetation condition" was found to be true. It was found out that besides human activities which are the major cause of fire ignitions, low precipitation and Vegetation Condition Index (VCI) contributes to a higher number of fire ignitions and a larger area burnt in MKFNP. The generated MODIS satellite fire alerts can be disseminated to the KFS and KWS for further planning and management of targeted suppression activities in Mount Kenya Forest (Mary et al., 2019). These findings will support the implementation of fire management strategies in areas where the land-cover types show heterogeneous mosaics, in regions where the network of existing meteorological stations does not cover certain remote areas, and in areas where landscape vulnerability to droughts and fire is vital to the livelihood of the communities living in that region. To improve findings of this study, future monitoring studies need to focus on the change of seasonal human activities, on the role of anthropogenic driven land-cover changes before and during the study period and on the climate variables (precipitation and temperature) in the determination process for vegetation anomalies as a result of drought and fires.

The hypothesis “The AHP can be a useful tool to select the best management strategy that helps to reduce fire danger and increase the benefits obtained by various stakeholders” was found to be true. This study found that applying AHP by experts and resource managers for assessing management strategies in MKFNP has the potential to reduce the information gap between decision-makers and other stakeholders at the local and national levels. The hypothesis “The involvement of various stakeholders from the KFS, KWS and CFAs contributes to the design and selection of appropriate fire management strategies” was found to be true. This study found that the KFS and KWS managers need to take into account how the involvement of the local communities in the decision-making process can be improved, with the main goal of stimulating the development of commonly accepted management strategies for MKFNP. However, the performance of the best management strategy might be different in other forests and national parks in Africa, where conditions are slightly different and where different views of stakeholders may be present. This study presents recommendations for further policy options that consider forest health, productivity and socio-economic values, as basic requirements for improving the livelihoods of the people. Resource managers can make better management decisions in the future to ensure that: rare and threatened species are protected, restored and monitored; habitats are protected, preserved and restored; ecosystem connectivity is established to increase resilience; and Mt. Kenya ecosystem functioning is understood (KFS, 2010, KWS, 2010). Further research needs to be carried out in other forest and national parks in Kenya, as different stakeholder interests, vegetation and wildlife species, and threats require adapted management strategies and a revised evaluation framework.

In the year 2014, the parliament of Kenya passed the county governments’ fire and disaster management bill that prepared the ground for the country to establish and implement IFM approaches in the future (Nyongesa, 2015). Even though the Kenya Grass Fire Act, Cap 327, provides a regulation for planned burnings of bushes, shrubs, grass, crops, and stubble within protected areas, the KFS and KWS have continued to practice fire suppression campaigns instead of using prescribed burning activities to manage fuel accumulation in MKFNP. This is mainly based on the belief that any disturbance, such as fire, disrupts the progress towards an equilibrium state. Total fire suppression and other human-caused environmental changes have resulted in huge and catastrophic wildfires in MKFNP (Poletti, 2016). The hypothesis “human activities are the leading cause for fire ignition in MKFNP” was found to be true. This study found that human activities were found to be the major cause of fire ignitions MKFNP irrespective of the season. The study developed an IFM framework to help resource managers, communities and other stakeholders address both damaging and beneficial fires. It also evaluated the various uses of fire, the underlying perceptions and the traditional ecological knowledge of the local people. The risks posed by fires were then balanced with the beneficial ecological and economic effects, which will thus support the development of effective fire management approaches. The hypothesis "The IFM framework can support communities and resource managers in finding effective and efficient approaches to prevent damaging fires, as well as to maintain desirable fire regimes in Kenya" was found to be true. This study found that effectiveness is dependent on the active participation, formulation, and implementation of the IFM activities by the main stakeholder groups (KFS, KWS and the CFAs). The developed IFM framework also emphasizes the need for the government of Kenya to finance, educate, train, equip, and motivate resource managers, rangers, CFA members, and forest scouts that are involved in fire prevention and suppression activities to achieve sustainable IFM strategies. Identifying potential stakeholders and their interests will help to mitigate conflicts over the use of forest resources in Kenya by following the traditional and legal arbitration mechanisms at the village, regional, and national level. It highlights the need to implement the relevant international, national, and county laws and policies for establishing or improving the legal, regulatory, and institutional framework required for responsible IFM activities in Kenya's forests.. The information from the proposed IFM framework may be used by resource managers, policymakers, and researchers to improve or advocate for sustainable land and resource management programmes that consider the fire history of the areas; the ecologically appropriate use and management of fire; and the suppression of unwanted, damaging fire in Kenya's forests, Africa and the rest of the world.

6. References

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7. Appendix: Articles

Timeline of publications

Contribution	Date of 1st Submission	Editor Statements (peer review)	Date of publication
Paper I	29th December 2018 Mountain Research and Development (MRD)	Accepted for publication on 4th November 2019	-
Paper II	11th October 2019 Multidisciplinary Digital Publishing Institute (MDPI) Journal of Remote Sensing	Resubmitted to journal with major revisions on 14th November 2019	-
Paper III	7th April 2019 Multidisciplinary Digital Publishing Institute (MDPI) Journal of Forests	Accepted for publication on 12th May 2019	Published on 17th May 2019
Paper IV	11th June 2018 Multidisciplinary Digital Publishing Institute (MDPI) Journal of Forests	Accepted for publication on 2nd August 2018	Published on 8th August 2018

7.1 Characterization of wildfires to support monitoring and management of Mount Kenya Forest

<<ARTICLE TYPE>> Mountain Research

<<TITLE>> Characterization of Forest Fires to Support Monitoring and Management of Mount Kenya Forest

Claudio Poletti[1], Gergo Dioszegi[2], Kevin Wafula Nyongesa[1,3], Harald Vacik[1], Marco Barbujani[4], and John Ngugi Kigomo[5]

** Corresponding author: claudio.poletti60@gmail.com*

[1] Institute of Silviculture, University of Natural Resources and Life Sciences, Vienna (BOKU); Peter-Jordan-Strasse 82, A-1190 Vienna, Austria

[2] Institute of Surveying, Remote Sensing and Land Information (IVFL), University of Natural Resources and Life Sciences, Vienna (BOKU); Peter-Jordan-Strasse 82, A-1190 Vienna, Austria

[3] Egerton University, PO Box 536, 20115, Egerton, Kenya

[4] Independent Researcher. 5 Via Nobile, 35020 Legnaro, Padova, Italy

[5] Kenya Forestry Research Institute, P.O Box 20412, Nairobi, Kenya

<<ABSTRACT>>

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 impacted on 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, trends in fire occurrence over time and in relation to vegetation type are described. Key findings evidence fire-prone period in February and March; total burned area decrease during the study period; bush and grassland as the most fire-prone vegetation; variability of fire regime in each forest station. Further, field observations are 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.*

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<<#1>> 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, 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, driving agriculture expansion and affecting natural ecosystems (Grau 2008; Nyongesa 2015). The communities living around Mt. Kenya depend on its forest for fuelwood, grazing, fishing, and non-timber 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 in evaluating and balancing the relative risks posed by fires with 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.

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 its 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 over time, location or in relation to vegetation type, (3) compare the field based records with satellite based data, and (4) develop recommendations for the development of more effective forest fire management.

<<#1>> Material and methods

<<#2>> 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, with 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 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 the 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 geographical, 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 from the lower western forest to the northeast, where the fire risk is strongly increased by lack of rainfall during the dry season (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.

<<#2>> 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 started 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, since 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 of Mt. Kenya vegetation composition. The Moderate Resolution Imaging Spectroradiometer (MODIS) provided the burned area fire product MCD45A1, which provides information about the confidence of detection and burned vs. non-burned 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, with 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 returns detected fire occurrences on a monthly basis. Ignition sites (Dioszegi 2018), were displayed to visualize the spatial extent of both 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 ones, and tend to be underreported, especially in older data sources, thus affecting dataset consistency; (2) fire size–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 different periods was verified by the comparison of their scaling parameters (gamma, from power law fitting) and their 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, since 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 (≥ 20 ha, ≥5 ha but <20 ha, and ≥0.5 ha but <5 ha; the <0.5 ha class was excluded due its small sample size).

After dataset evaluation, the study focused on characterizing the fire regime and identifying any fire trends 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 (the 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 set in the work of Dioszegi (2018), field data set was compared to the satellite burned areas. Firstly, a method, called the absolute summed percentile (ASP) was created and applied as the comparative analysis. The ASP was calculated with the following formula:

$$ASP_{\%}=\sum_{h,i=0}^{n} \quad [(x_h + y_i)/\sum_{abs} \quad (x_h + y_i)] * 100 \qquad (1)$$

where *x* is 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 six increasing 3% classes, determined as ≥15%, ≥ 12% but < 15, % ≥ 9% but < 12%, ≥ 6% ha but < 9%, ≥ 3% but < 6% and < 3%. In doing so, the generated ASP classes represent weighting. The higher an ASP class is, the more weight the class takes in the absolute sum (abs(xh+yi)) of burnt areas (ie the size of the burned area was detected more often or the burned area size was considerably higher of the given class). In this way it was possible to reveal the underlying structure of large (above 500 ha) burnt 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.

<<#1>> Results

<<#2>> Evaluation of 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 two periods could be gained from the K-S and K-W tests.

<<#2>> Characterization of 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 it registered a fire rotation of 89 years. From 1984–1999 occurred less fires (56) than in the following period (74 in 2000–2015), on the other side the mean individual fire size and the 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).

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 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 in the second period to February (320 ha/year).

Bush and grassland was the most fire-prone vegetation type (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 sub-periods. Over the 32 years of the study period, Mt. Kenya Forest lost 14,000 ha of bush and grassland (6600 ha in 1984–1999 and 7400 ha in 2000–2015). Burned area as a proportion of total burned area increased from 34% to 38%.

Gathiuru and Ontuili forest stations' territories revealed similar fire behavior, with the majority of events detected from January to March. On contrary Marania experienced fires mainly from July to September, especially from 1984 to 2000. The three 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).

Figures 3 summarize the major fire trends in the study area. The most fire-prone season is February/March, and fires occur 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).

<<#2>> 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 two 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 the 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 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 more 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. Ignitions 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).

<<#1>> Discussion

Kolmogorov-Smirnov test and Kruskal-Wallis test 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 size 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 tends to be the lowest (Figure 2C and 2D), 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 two 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 period, fire activity in January dropped. 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, an highly flammable vegetation present within the Mount Kenya Forest only at its highest altitude. On the other hand the second dry season (July-September) is still perceived by local residents of Gathiuru forest station 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 of meteorological 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/less preset in the natural forest not affected by fire (Poletti 2016). At the same time, forest 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, in order to keep it open and to facilitate the growth of new grass for feeding their livestock, 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. Excepting for Gathiuru and Ontulili, each forest station evidenced different periods of fire occurrence and vegetation affected (Figure 3 and 5). This might be related to the land use that takes place 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 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 two dataset, which evidenced 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, since they contain several information in addition to those analyzed in our study. Moreover they have not spatial detection limitation for small fires. The comparison of the 2 study periods of field data suggests they are consistent over time. On the other side, 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). Satellite 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 ts product MCD45A1 contains information about the reliability of its data (Boschetti et al 2009). but 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; Csiszar 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 detects fire occurrences and burnt areas in two different periods, developing two different datasets from these observation, one for fire occurrence and one for burned areas. The changes of clouds and/or canopy cover can alter satellite sensor efficiency. For this reason, some fires could 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 do indicate differentiation, with frequently occurring large fires and extremely large fires more often documented by the field system. This can be partly explained by satellite underestimation of burned area, and partly by the consistency of the field recording system.

<<#1>> Conclusion

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 an increase in the number of forest fires and a decrease in total burned area.

Fire occurrence and spreads are related to the prevailing weather conditions, to the type of vegetation and to the intensity of the local residents activities that cause fires in 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 precipitations separate the year in two different fire seasons, which often coincide with dry seasons even if the most fire prone-months changed in the last years. Additionally, orographic precipitations, more frequent in the southeastern side of the mountain, limit, especially in the short dry season (Poletto 2016), the fire-prone areas to the western and northeastern side (KWS 2010). The vegetation is another determinant factor of fire occurrence, recording total burned area and number of fires different in each vegetation class. The study evidences when fires have occurred more frequently, where the largest burned areas are, which vegetation type is most affected and how these patterns changed during the study period. Such fire regime data are essential to update and improve the 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 of an as specific as possible forest fire management for each territory. 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 burnt area size recorded in the plantation suggests that in the last years the size of burned areas is also related to the (economic) value that the local residents relate to the vegetation and that the 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 find 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 system 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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<<**CAPTIONS FOR FIGURES and TABLES**>>

FIGURE 1 Location of the study area on Mt. Kenya. Mount Kenya Forest Stations are light grey shaded and white bordered; National Park is displayed with darker grey; the five forest stations that compose the study area are highlighted with darkest grey and black border. (Map by Dioszegi Gergo)

FIGURE 2 Results of Kolmogorov-Smirnov test: 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.

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 months, years, forest stations, and vegetation types. Rectangle width indicates the occurrence of fire during the months, while shading indicates the size of burned areas.

FIGURE 4 Absolute summed percentile (ASP) comparative analysis results performed on satellite data and field data. No ASP value fell into the 6–9% range. Lines are shown to help in visualizing the underlying behavior of ASP classes with respect to detection of large burned areas.

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 burnt 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])

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

TABLE 2 Results of Kolmogorov-Smirnov (K-S) and Kruskal-Wallis (K-W) tests conducted on burned area size as detected in the 2 study periods.

Because of the small number of cases, we excluded areas of <0.5 ha from the analysis.

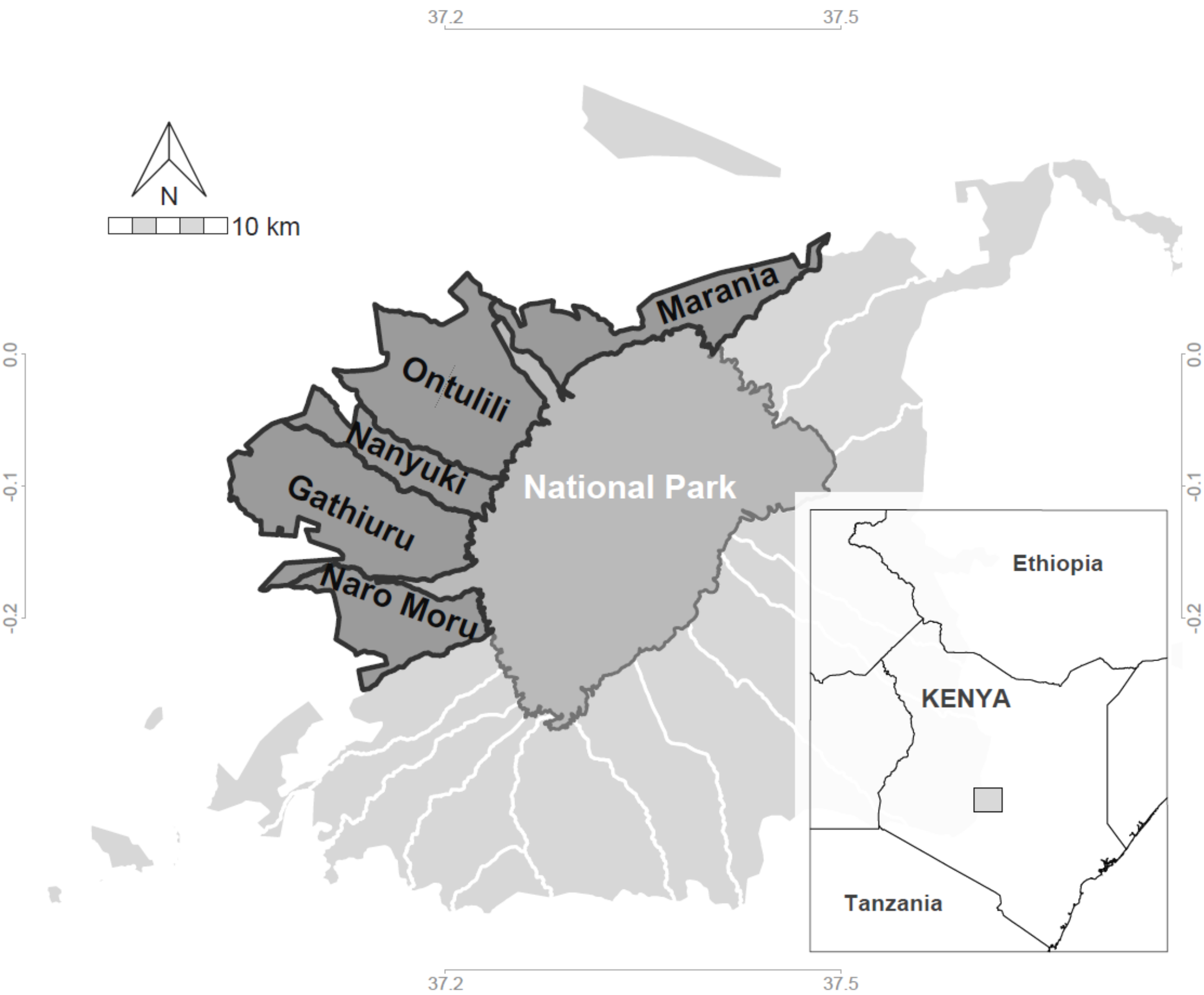
[a] This represents the maximum absolute distance (D) between the burned areas' distributions in the 2 time periods.

[b] This represents the value below which 2 ranked distributions can be considered as taken from the same population.

TABLE 3 Fire statistics for Mt. Kenya.

TABLE 4 Burned area by vegetation type and study period.

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



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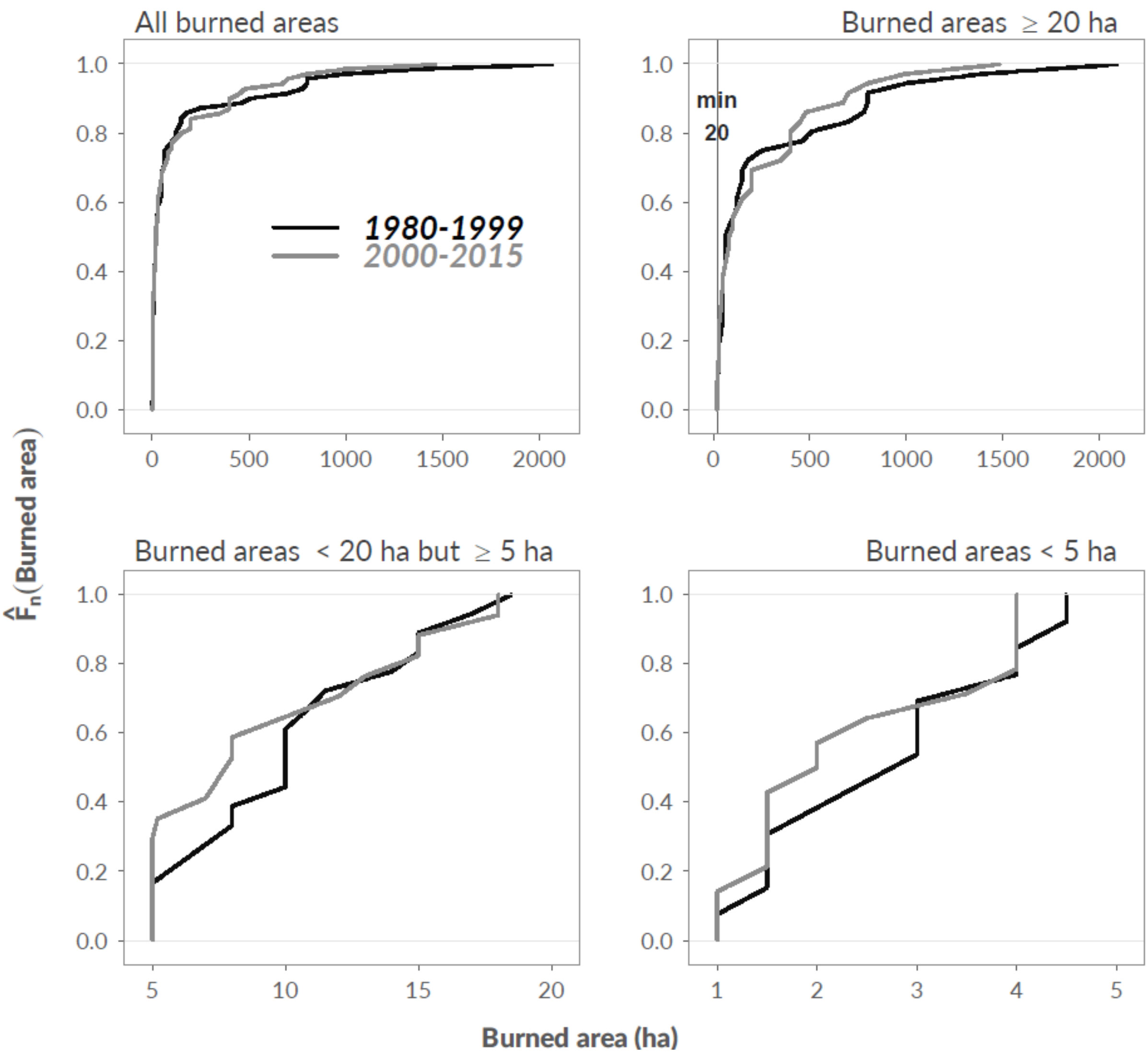

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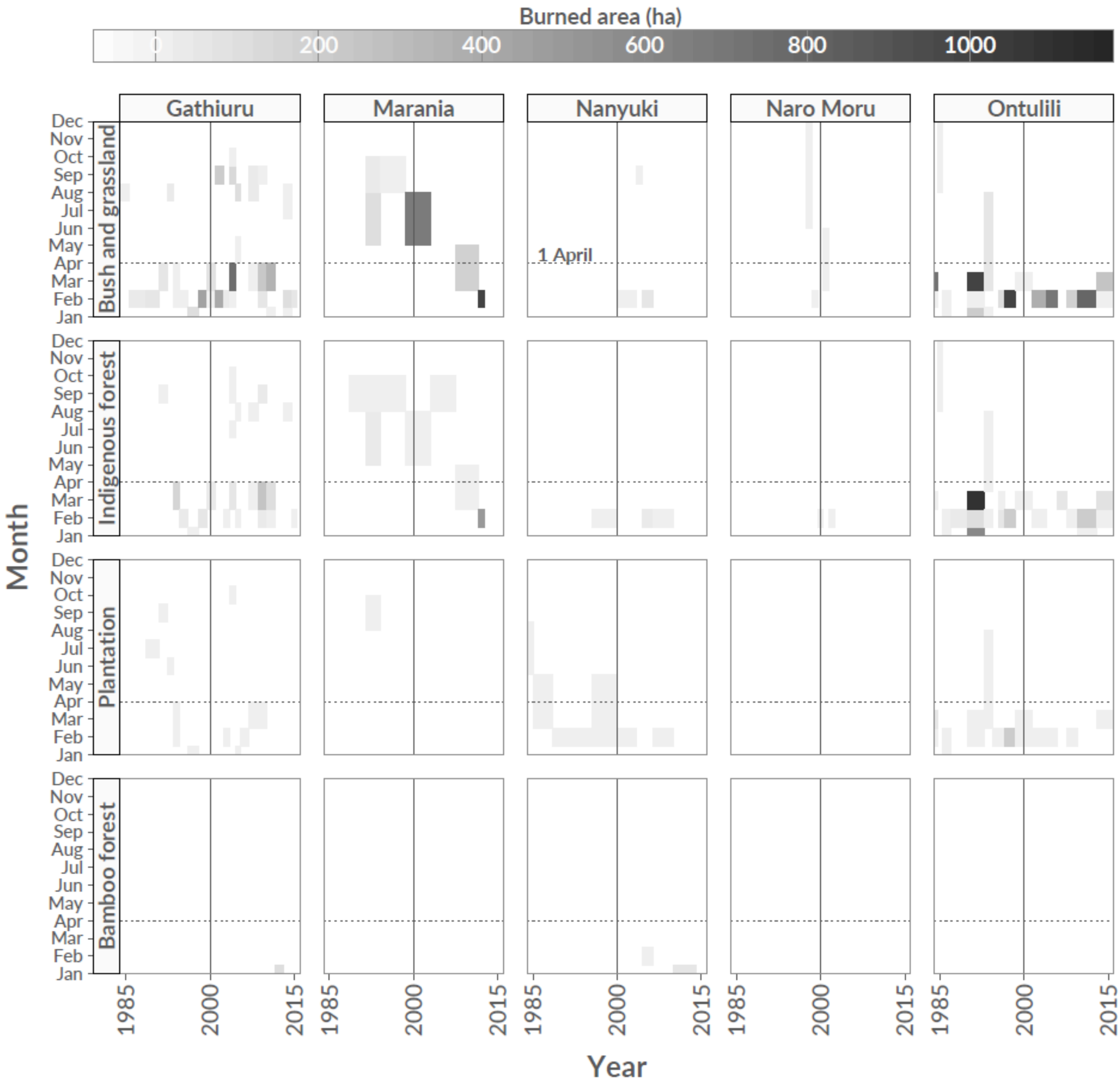

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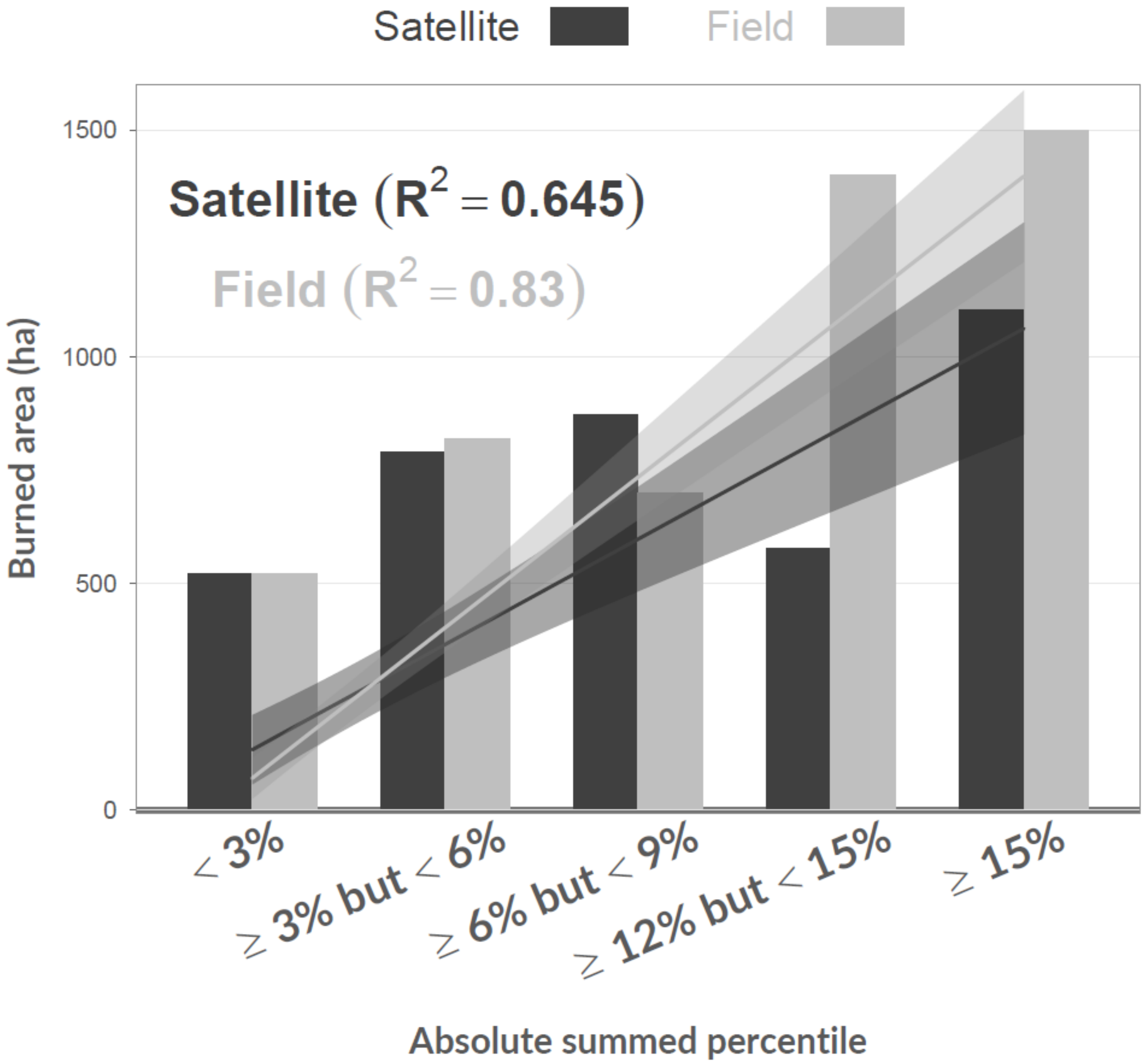

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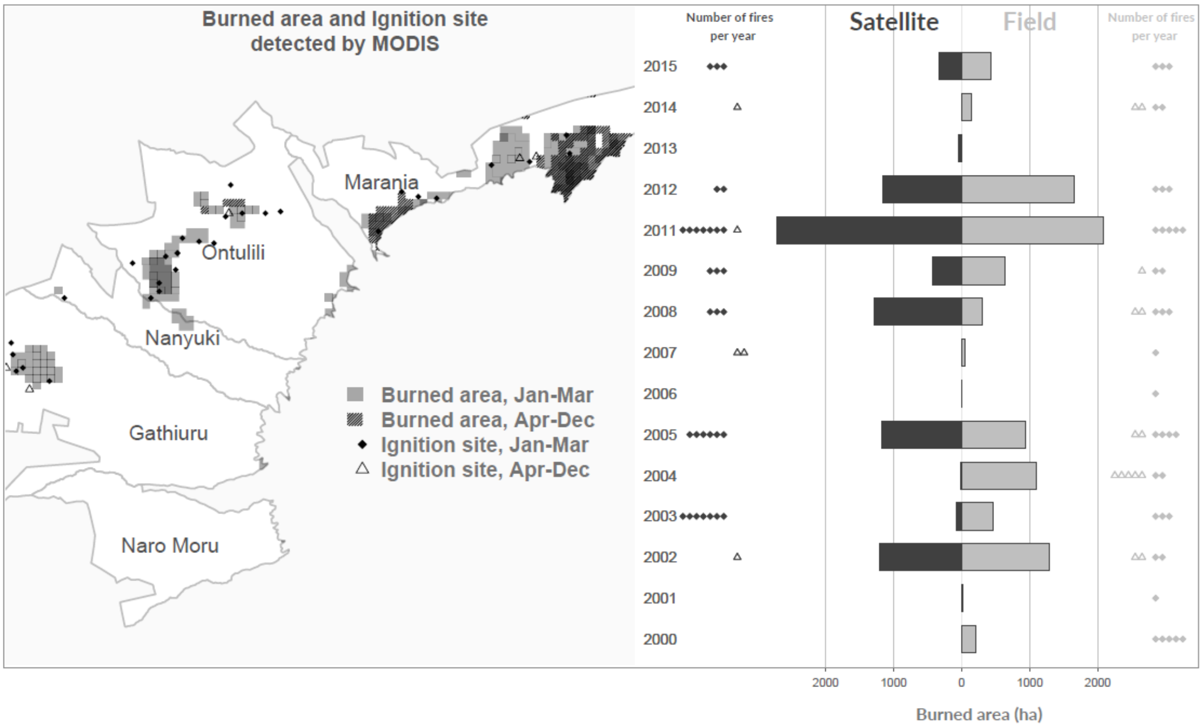

FIGURE 5 Comparative documentation of burned area. Map represents burned areas and ignition sites (as classified by Dioszegi, 2018) for satellite data only. The bar chart on the right compares burnt areas between satellite and field data for 2000–2015. Black dots and white triangles evidence the seasonality 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])

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**

Table 2: Results of Kolmogorov-Smirnov (K-S) and Kruskal-Wallis (K-W) tests conducted on burned area size as detected in the 2 study periods.

		Fires by extent of burned area		
	All fires	**≥20 ha**	**<20 but ≥5 ha**	**<5 but ≥ 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[a]	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[b]	**18.092**	**13.135**	**9.171**	**8.299**

Note: because of the small number of cases, we excluded areas of <0.5 ha from the analysis.

[a] This represents the maximum absolute distance (D) between the burned areas' distributions in the 2 time periods.

[b] This represents the value below which 2 ranked distributions can be considered as taken from the same population.

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)	9,924.15	9,312.45	**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**

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	6,627	7,396	34.5	**38.4**
Indigenous forest	2,884	1,674	15.0	**8.7**
Plantation	413	87	2.1	**0.5**
Bamboo forest	**0**	**155**	**0.0**	**0.8**

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	3,483	**692**
Marania	7,857	2,385	**5,551**
Nanyuki	5,805	242	**148**
Naro Moru	7,871	28	**2**
Ontulili	15,825	3,174	**2,046**
Total	**53,726**	**9,312**	**8,439**

7.2 Analysis of spatio-temporal occurrence of fires as a result of drought and land-use activities in Mount Kenya Forest and National Park

remote sensing

Article

Analysis of spatio-temporal occurrence of fires as a result of drought and land-use activities in Mount Kenya Forest and National Park

Kevin W. Nyongesa[1], Christopher Pucher[1], Gergo Dioszegi[2], Anja Klisch[2], Claudio Poletti[3], Harald Vacik[1]

1 Institute of Silviculture, University of Natural Resources and Life Sciences, Vienna (BOKU); Peter-Jordan-Strasse 82, A-1190 Vienna, Austria; kevin.nyongesa@boku.ac.at, christoph.pucher@boku.ac.at, harald.vacik@boku.ac.at

2 Institute of Surveying, Remote Sensing and Land Information, University of Natural Resources and Life Sciences, Vienna (BOKU); Peter-Jordan-Strasse 82, A-1190 Vienna, Austria; anja.klisch@boku.ac.at, gergo.dioszegi@boku.ac.at

3 Department of Land, Environment Agriculture and Forestry, University of Padua, Padua, Italy; claudio.poletti60@gmail.com

* Correspondence: kevin.nyongesa@boku.ac.at; Tel.: +4368860599334

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Abstract: Satellite data can be used to investigate spatio-temporal occurrence of fires as a result of drought and land-use activities. In this study remote sensing data are used to obtain the Normalized Difference Vegetation Index (NDVI), the Vegetation Condition Index (VCI), number of fires and burnt area to analyze the role of droughts and land use activities on the occurrence, location and severity of fires in Mount Kenya Forest and National Park. The specific objectives of this research were to: (i) describe spatio-temporal patterns of fires in the National Park (NP), the Forest Stations (FS) and on Farmlands (FL) from 2003 to 2018; (ii) examine relationships between precipitation and the observed spatial-temporal patterns of fires; (iii) perform a time series analysis of the NDVI and VCI to examine their relationship with fire occurrences. We were able to characterize a spatio-temporal pattern of fires as a result of droughts. It was found out that besides human activities which are the major cause of fire ignitions, low precipitation and Vegetation Condition Index (VCI) contributes to a higher number of fire ignitions and a larger area burnt in Mount Kenya Forest and National Park. In this context during the dry season of the year, a slightly higher correlation was observed between number of fires, burnt area and VCI in the Forest Stations (FS) than National Park (NP) and Farmlands (FL). The findings of this study should support the forest and fire managers of Mount Kenya Forest and National Park to improve the fire monitoring, planning of resources and fire suppression activities.

Keywords: Fire occurrence; spatio-temporal, MODIS; National Park; NDVI; VCI; precipitation; time series; forest; human activities; burned area; Mount Kenya

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1. Introduction

Mount Kenya Forest and National Park was inscribed as a UNESCO World Heritage Site in 1997 [1]. It is a very important national asset for economic, environmental protection, social and cultural values and should be conserved in order to realize all these benefits [2]. It is one of the most important catchment areas that provide about 40% of Kenya's water through orographic precipitation and runoff into major rivers [3-5]. However any disruption in precipitation runoff as a result of deforestation, droughts and fires in Mount Kenya Forest and National Park has caused devastating impacts on water availability and quality, as well as production of hydroelectric power in Kenya [2,4,6,7].

The changing climate, vegetation dynamics, human activities, and forest management influence the occurrence of fires in Mount Kenya Forest and National Park [8,9]. The majority of fires are caused by humans accidentally or intentionally as part of agro forestry practices, charcoal production or poaching activities [10-12]. The combination of environmental changes and human activities has led to many huge and catastrophic wildfires [2,7]. However investigations of paleoecology in the Mount Kenya region indicate that fires have occurred in the area since at least 26,000 years BP, despite the scarce effects of natural ignition sources [5]. Several studies have shown that wildlife, tree and plant species in Mount Kenya Forest and National Park also benefit from the occurring fires [13,14]. Fire tolerance varies by vegetation community with grass being adapted to frequent fire, the Ericaceous zone tolerant of some fire activity, and the forests and bamboo zones lacking fire tolerance [13]. Erica species on Mount Kenya Forest and National Park resprout from lignotubers following fire, but require longer recovery time than grasslands [13,15]. In the case of too frequent fires, grasses may invade forest land resulting in vegetation type-conversion in Mount Kenya Forest and National Park [16].

Remote sensing is a valuable approach to reconstruct fire history, locate fire hot spots, map the burnt areas and monitor current fires [17,18]. Accurate and timely information on the vegetation condition and distribution based on remote sensing data is one of the key elements for understanding how changes in precipitation patterns (e.g. drought periods) and disturbances like fires can affect land use and land cover [19,20]. Timely detection of droughts and forest fires can play a crucial role in assisting the KFS and KWS managers to control the ignition and spreading of fires. Satellite data can be useful to detect fires in near real time as compared with conventional methods such as fire watch towers or patrolling currently applied in Kenya [18,21]. The most commonly used satellite data for the fire detection currently are the Moderate Resolution Imaging Spectroradiometer (MODIS) TERRA and AQUA with a 250 m spatial resolution and Suomi NPP (National Polar-orbiting Partnership) Visible Infrared Imaging Radiometer Suite (VIIRS), the former has the spatial resolution of 1 km and the later has 375 m [18]. In scientific literature, time series of the Normalized Difference Vegetation Index (NDVI) and the Vegetation Condition Index (VCI) are widely used to identify vegetation anomalies as a result of drought [5,20-22]. The NDVI and VCI values are usually lower during droughts compared to the normal growing conditions in the same region and growing season [20]. There is also a seasonal lag trend observed in the response of the vegetation to precipitation depending on the vegetation type [20,21].

The aim of this study was to investigate the role of droughts and land use activities on the occurrence, location and severity of fires in the National Park (NP), the Forest Stations (FS) and on Farmlands (FL). The findings of this study should support the KFS and KWS to improve fire management activities in Mount Kenya Forest and National Park. The specific objectives of this research were to: (i) describe the human activities that cause fires and how they contribute to spatio-temporal patterns of fires in Mount Kenya Forest and National Park from 2003 to 2018; (ii) examine relationships between precipitation and the observed spatial-temporal patterns of fires from 2003 to 2018; (iii) perform a time series analysis of the NDVI and VCI to detect droughts and examine how they influence fire occurrences in Mount Kenya Forest and National Park from 2003 to 2018.

The hypotheses of our study were:

1. Spatio-temporal patterns of fires in Mount Kenya Forest and National Park are a result of droughts that have occurred from 2003 to 2018
2. The lower the Vegetation Condition Index (VCI), the higher the number of fire ignitions and the larger the area burnt in Mount Kenya Forest and National Park is

In the following sections, we will introduce the study area and describe the materials and methods used to analyze the relationship. The presentation of the results will allow testing of the hypothesis, followed by a critical discussion and providing some conclusions.

2. Materials and Methods

2.1. Description of the Study Site

Mount Kenya is located to the east of the Great Rift Valley, along Latitude 0°10′ S and longitude 37°20′ E and was formed as a result of volcanic activity with a base diameter of approximately 120km [1,2]. It bestrides the equator in the central highland zones of Kenya [1]. It is protected and managed by the KWS and KFS. The National Park (NP) covers 71,510 ha and is located above the timber line and stretches up to the peak of Mount Kenya [7]. The 19 forest stations cover 213,082.64 ha and are surrounded by Farmlands (FL) owned by communities that engage in smallholder agriculture and have a history of encroaching on the forest areas [2,7]. The growing population has been increasing the demand for land, timber and non-timber forest products and has led to increased encroachment, degradation and fires in Mount Kenya Forest and National Park [2,7,12]. The zoning of Mount Kenya forests into management blocks has an influence on the type of human activities allowed in those blocks and has an influence on the ignition probability of fires [2]. Blocks zoned for grazing usually experience more regular fires than blocks zoned for water catchment conservation [2].

The temperature patterns are shaped more by time of day and elevation than season [23]. The windward side of the mountain (southeastern slopes) receives approximately 2250 mm of rainfall while the leeward side of the mountain (northwestern slopes) receives about 900 mm [23]. The lower montane forests on Mount Kenya are similar in structure and appearance to tropical rainforests beginning at elevations of 1200 m and extend up the mountain to elevations of 2500 m [1,2]. Above the lower montane forests is the bamboo zone (*Arundinaria alpina*) at elevations of 2200–3200 m [2]. Unlike other East African mountains, the bamboo zone on Mount Kenya is well-developed, and less fragmented [13]. At elevations of 2500–3500 m lies the upper timberline forest zone [2]. These forests are more open with dense shrubs, grass, and dominated by the African pencil cedar (*Juniperus procera*) [2]. During the rainy season, the grasses and shrubs usually grow very rapidly and dry up during the dry season and this increases fine fuel accumulation and continuity [12]. The Heathland and chaparral (*Ericaceous*) zone occurs above the tree line at elevations over 3500 m and is more continuous on the eastern slope [2]. The Afro-alpine zone also referred to as Paramo begins at approximately 4000 m and is characterized by dwarf vegetation [2]. Further up from the Paramo is the Nival zone which is a cold desert belt consisting of mostly moraine, gravel, and stones [2,13].

2.2 Focus group discussions on human activities in Mount Kenya Forest and National Park

On the 10 November 2016, a focus group discussion was held with 24 participants that included the Chief Ecosystem Conservator, KFS forest managers, rangers, Kenya Forestry Research Institute (KEFRI) personnel, CFA members and other stakeholders. The group was guided by a facilitator who introduced and moderated the topics for discussion on: how certain human activities in Mount Kenya Forest and National Park influence the ignition of fires; and how the KFS, KWS, and CFAs were collaborating in the implementation of fire management plans, fire monitoring, fire prevention, fire-fighting, the reduction of hazardous fuels, and the maintenance of ecosystem health.

We then calculated the relative importance ($relImp$) of human activities that cause fires as follows:

$$relImp_{(\%)} = \left(\frac{w_{i\sim h}}{\sum w_{1\sim h}}\right) \times 100$$

$relImp$ is the calculated relative importance as a percentage, h indicates a given human activity and i a belonging forest station iterated over 1 to 19 (since there are 19 forest stations), w is the weighted value of the outcomes from the focus group discussions [9].

2.3 Fire occurrence and burnt area data

The data set of daily fire occurrences ranging from January 2003 to December 2018 was obtained from the Fire Information for Resource Management System (FIRMS) Archiving and Distributing MODIS Active Fire Data [24]. We have obtained the burnt area fire product MCD64A1 from the MODIS-FIRMS data. Besides information about the confidence of detection and the type of detected land cover, the main product of the algorithm is the differentiation between pixels with burnt and non-burnt areas. The MCD64A1 product combines data from two satellites (AQUA and TERRA) and returns estimated burnt areas monthly based, with a spatial resolution of around 500 m. In this study, MODIS MCD64A1 product polygons were utilized to select burnt areas within the study area. Another MODIS product, MCD14DL-Collection 6, that detected fire occurrences on a monthly basis, was also used in our study [24]. We divided Mount Kenya Forest and National Park into three major land use types: the National Park (NP), Forest Stations (FS) and Farmlands (FL). Possible ignition spots in the NP, FS and FL were displayed to visualize the spatial extent of the burnt areas and ignition sites in Mount Kenya Forest and National Park [16].

2.4 Climate data in Mount Kenya region

Empirical monthly precipitation data from 2003 to 2018 was obtained from three metrological weather stations. Kalalu and Munyaka weather stations that are located at the foot and Naro Moru weather station that is located near the peak of Mount Kenya [25]. Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) data v2.0 was used to generate the monthly precipitation at 0.05° spatial resolution [26,27]. A comparison of the CHIRPS precipitation data and those obtained from the three weather stations in Mount Kenya region was done to determine any deviations in the accuracy of the CHIRPS precipitation data. We used CHIRPS precipitation data to explore the relationship between precipitation, fire occurrence and burnt area in Mount Kenya Forest and National Park from 2003 to 2018.

2.5 Analysis of inter-annual variability of NDVI and VCI

MOD09Q1 and MYD09Q1 collection 6 surface reflectance products were obtained from NASA's Land Processes Distributed Active Archive Center (LP DAAC) [28]. Normalized Difference Vegetation Index (NDVI) images have been calculated with 8 days temporal and 250 m spatial resolution. The NDVI data was filtered with BOKU's MODIS data processing chain [20]. The processing uses the Whittaker smoother, which fits a discrete series to discrete data and puts a penalty on the roughness of the smooth curve [29]. The smoothing takes into account the quality of the observations according to the MODIS VI Quality Assessment Science Data Set (QA SDS) and the compositing day for each pixel [20]. The resulting NDVI time series has a temporal resolution of 7 days spanning from 2003-2018. We derived monthly NDVI values by averaging the 7-day images for each cell. We performed a time series analysis of the NDVI to explore the inter-annual variability from 2003 to 2018 using R scripts. The mean NDVI values were randomly stratified into three periods (2003 to 2008, 2009 to 2013 and 2014 to 2018) to evaluate any changes in land use. We then calculated monthly VCI by applying the following equation (1) on the final NDVI data for each month on each cell.

$$\mathrm{VCI} = 100 \times \frac{\mathrm{NDVIi} - \mathrm{NDVImin}}{\mathrm{NDVImax} - \mathrm{NDVImin}}, \qquad (1)$$

So, for example for February: NDVIi would be the value for February 2006. NDVImin and NDVImax would be the minimum and maximum NDVI value observed for February from 2003 to 2018 for that cell. The numerator is the difference between the actual and the minimum values of the NDVI and is indicative of the meteorology and vegetation information of a specific period. The maximum and minimum values of the denominator reflect the best and worst conditions of vegetative growth and the difference between them reflects the condition of the local vegetation [26,30,31]. The VCI contains both real-time and historical information of the NDVI. The VCI ranges between 0 and 100 in which smaller VCI values below 35% indicate higher degrees of drought [26,32,33]. A time series analysis of the VCI was done to explore the relationship between drought and fire occurrences in Mount Kenya Forest and National Park from 2003 to 2018. We also explored the relationship between the number of fires and burnt area and VCI in the NP, FS and FL. We then analyzed relationships between number of fires, burnt area and the VCI in forest stations on the Northwest side that have a medium fire danger (Nanyuki), high fire danger (Ontulili) and those on the Southeast side that have a low fire danger (Chuka and Chogoria).

2.7 Linear Regression

Linear regression is used to predict the value of a variable based on the value of two or more other variables like analyzing a dependent variable (in this case VCI) in light of related independent variables (burnt area and number of fires). It allows us to determine the relative contribution of each of the predictors to the total variance explained. In this paper, we tried to quantify the susceptibility of VCI to changes in burnt area and number of fires. Before we chose to analyze our data using linear regression, we made sure that assumptions required for linear regression were met. We checked the existence of a linear relationship between VCI and each of the independent variables (burnt area and number of fires). We also checked the VCI correlation with burnt area and number of fires in Mount Kenya Forest and National Park.

3. Results

3.1. Human activities in Mount Kenya Forest and National Park

Results show that the type of human activities that cause fires vary between forest stations in Mount Kenya Forest and National Park. Arson, honey collection, grazing, farming and charcoal burning are the leading causes of fire in Mount Kenya Forest and National Park (Figure 1).

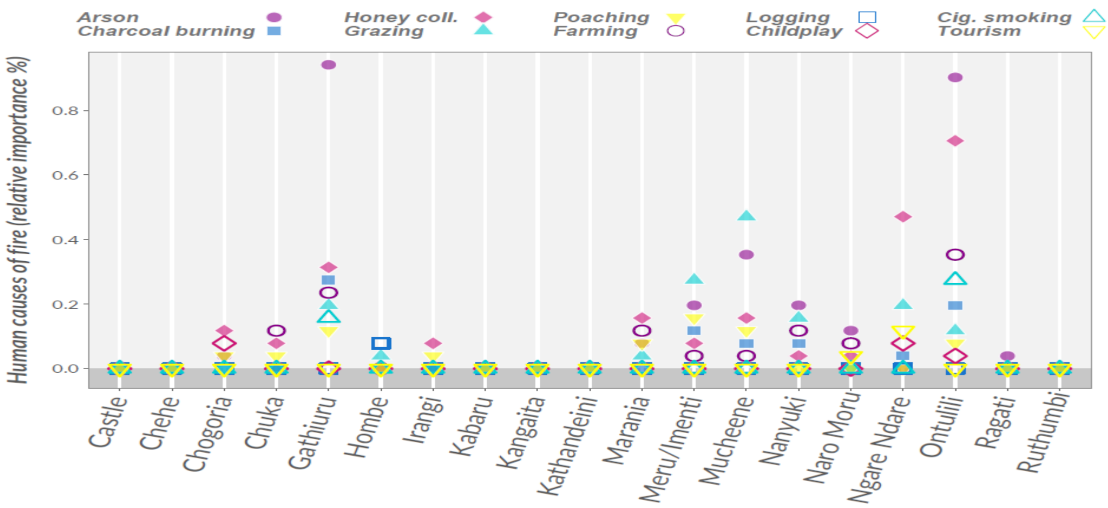

Figure 1: The type of human activities expressed in relative importance on a scale ranging from 0 to1 to show how they cause fires in Mount Kenya Forest and National Park.

3.2 Fire occurrence and burnt area in Mount Kenya Forest and National Park

Results also show that most of the fire ignitions took place in the Northwestern slopes as compared to the Southwestern slopes. Most of the fires occurred in the National Park (NP) and it had the largest burnt area as compared to Forest Stations (FS) and Farmlands (FL) (Figure 2). The results show that from 2003 to 2018 the NP has experienced 530 fire ignitions and 581.8 Km^2 of burnt area, followed by FS that has experienced 358 fire ignitions and 275.3 km^2 of burnt area and the FL which has experienced 269 fire ignitions and 102.5 km^2 of burnt area (Figure 2). The December to March season (red color) has on average a high number of fire ignitions and burnt area compared to the other seasons and there are some differences observed between the land use types during the different seasons (Figure 2). FS have a high number of fires and large burnt area during the July to September seasons (light blue) as compared to the NP and FL (Figure 2). However the NP has a high number of fires and large burnt area during the December to March season as compared to FS and FL (Figure 2).

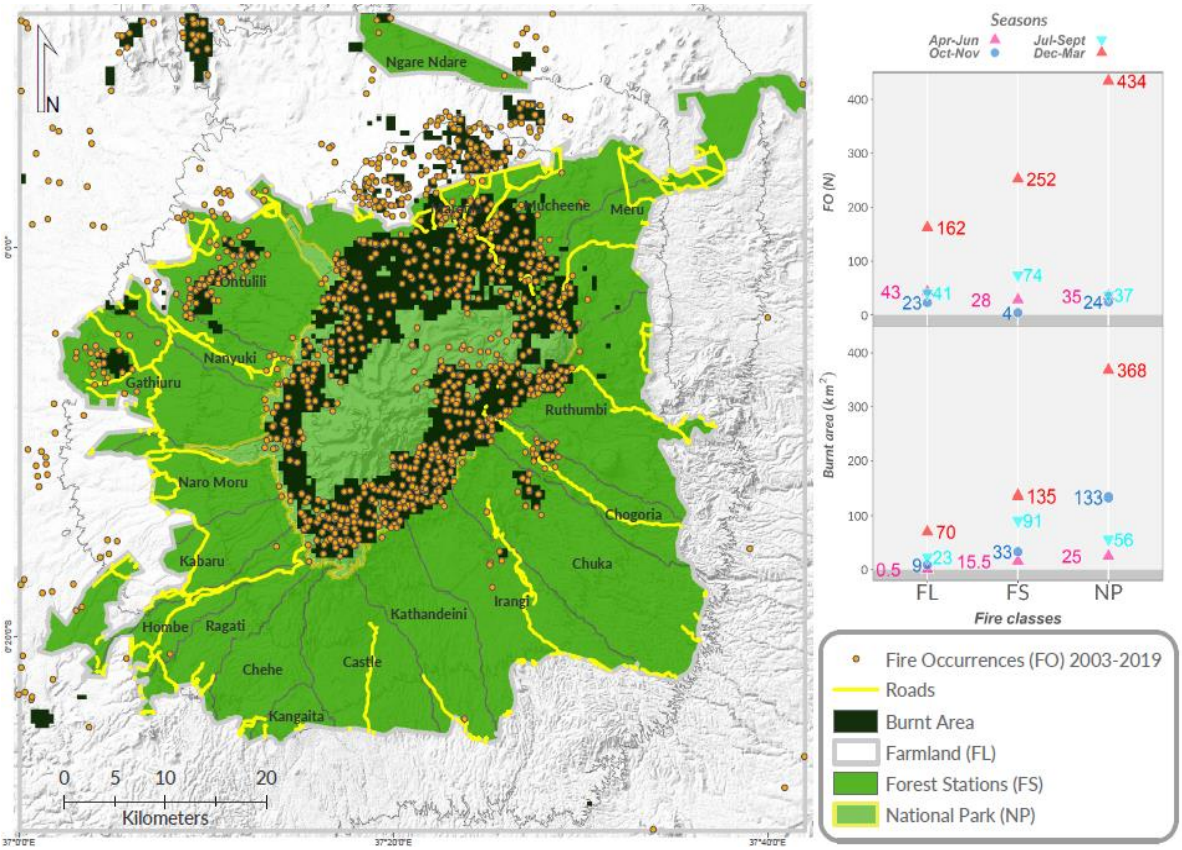

Figure 2: The spatial distribution of the number of fires and burnt areas according to the land use types (NP, FS and FL) and seasons in Mount Kenya Forest and National Park from 2003 to 2019.

Interesting to see is that the number of ignitions is not going hand in hand with the amount of burnt area for the different seasons of the year (Figure 3). The year with the highest burnt area was 2006 with more than 120 km^2. It is followed by 2008 and 2012 as both had more than 85 km^2 and 2009 is third with more than 70 km^2. In other years less than 20 km^2 of burnt area can be found (Figure 3). In general the results show that the years 2006, 2008, 2009 and 2012 had more fire ignitions and burnt area compared to the other years (Figure 3). However in 2008, 2014 and 2016, the months of July, August and September had more fire ignitions and burnt area compared to the months of the period December to March (Figure 3).

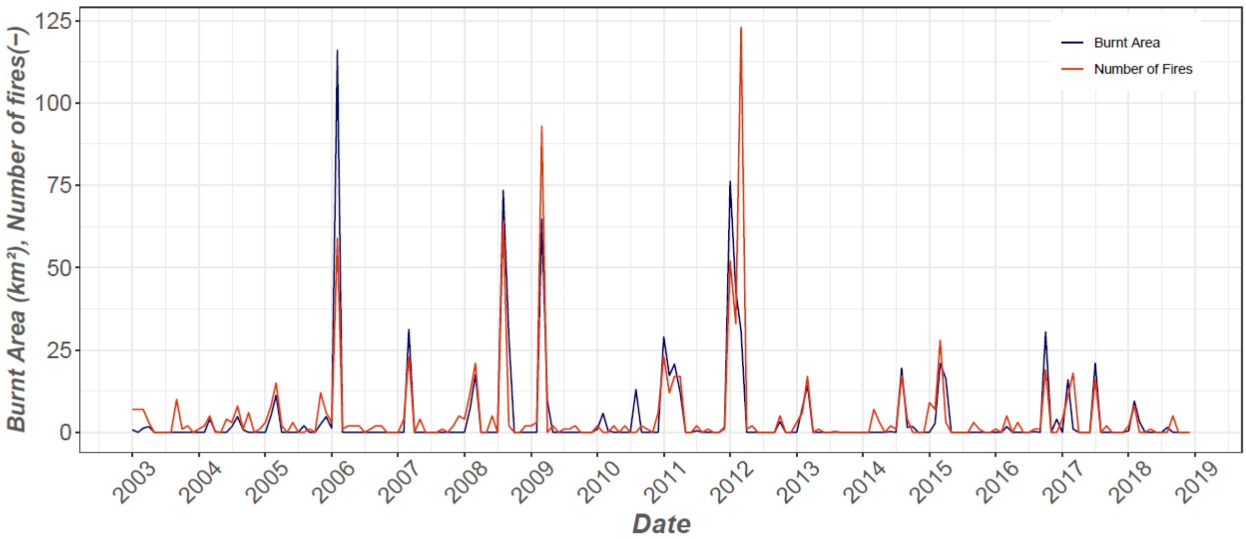

Figure 3: The number of fires and burnt area in Mount Kenya Forest and National Park from 2003 to 2018

3.3 Relationship between precipitation, number of fires and burnt area in Mount Kenya Forest and National Park

The spatially explicit estimation of the precipitation data based on the CHIRPS approach seems to be generally a good fit for our study area as the North West side is drier than the South East side of Mount Kenya Forest and National Park (Figure 4).

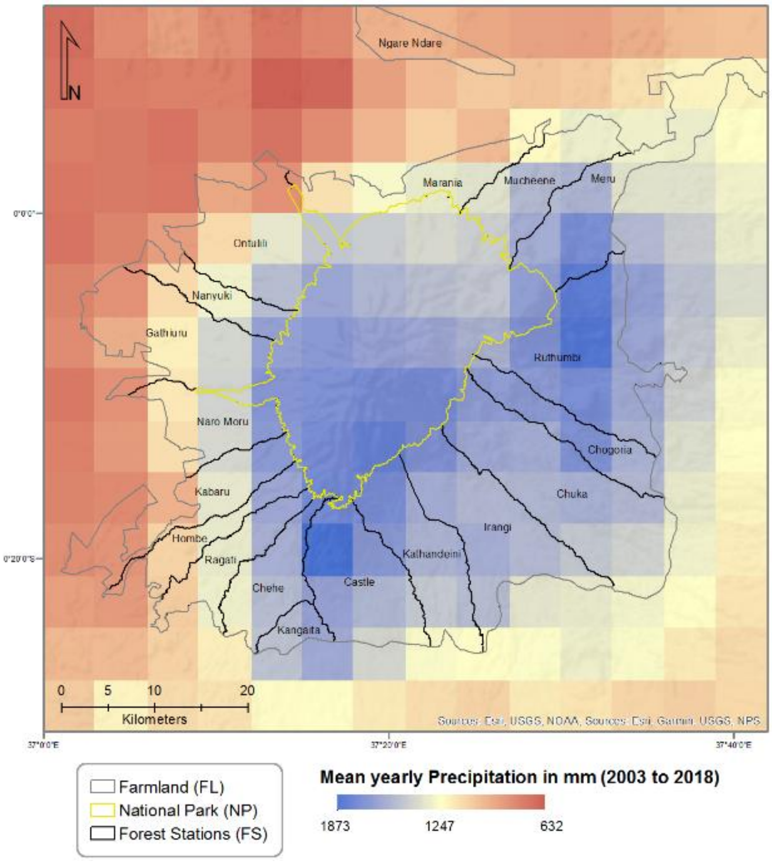

Figure 4: A map of the spatial pattern of precipitation in Mount Kenya Forest and National Park from 2003 to 2018

The temporal trends of the precipitation data derived from the CHIRPS data set and the weather stations indicate that the wet season months are April to June and October to November and the dry season months are July to September and December to March (Figure 5). We also compared the absolute values of the empirical weather records observed at the weather stations with the CHIRPS data set (Figure 5). Results show that there are few variations between CHIRPS and weather station data in the years 2007, 2011, 2012 and 2014, where the CHIRPS estimated a higher amount of monthly precipitation than that recorded by the three weather stations (Figure 5). In 2003, 2013 and 2018, the CHIRPS underestimated the amount of precipitation received in some months (Figure 5).

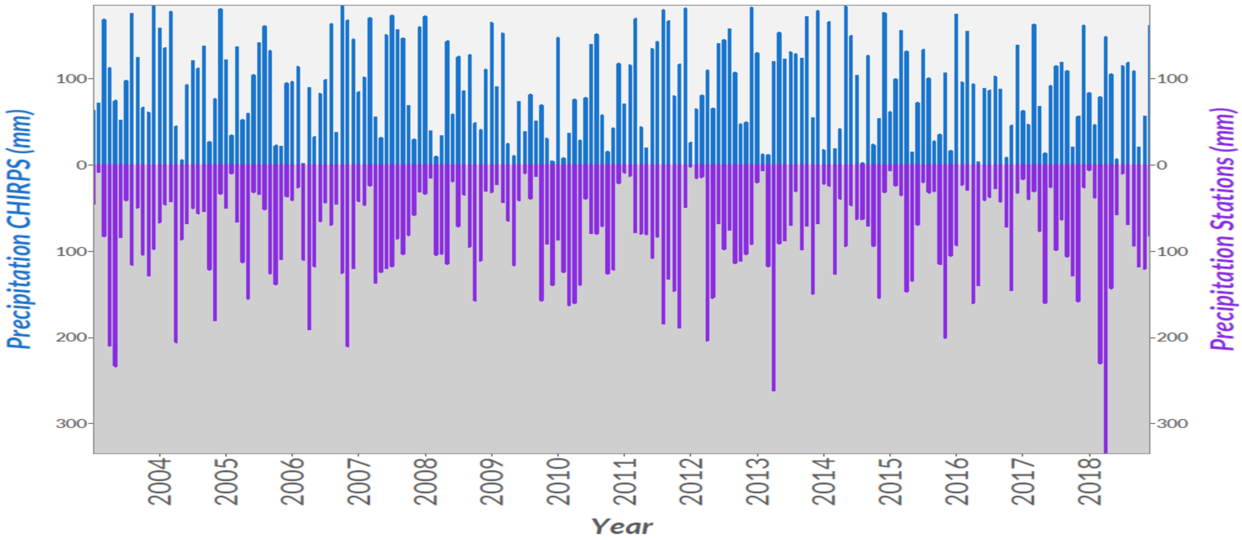

Figure 5: Monthly precipitation trends in Mount Kenya Forest and National Park from 2003 to 2018

The monthly trends between the numbers of fires, burnt area and the CHIRPS precipitation data for Mount Kenya Forest and National Park are as shown in Figure A1 and A2 in the Appendix. Results show that MODIS-FIRMS satellite detected a high number of fires and large burnt areas during the dry season compared to the wet season in Mount Kenya Forest and National Park (Figure 6). Results from the correlation analysis show that an increase in precipitation has a slight negative effect on monthly number of fires and burnt area during the dry and wet season in Mount Kenya Forest and National Park (Figure 6).

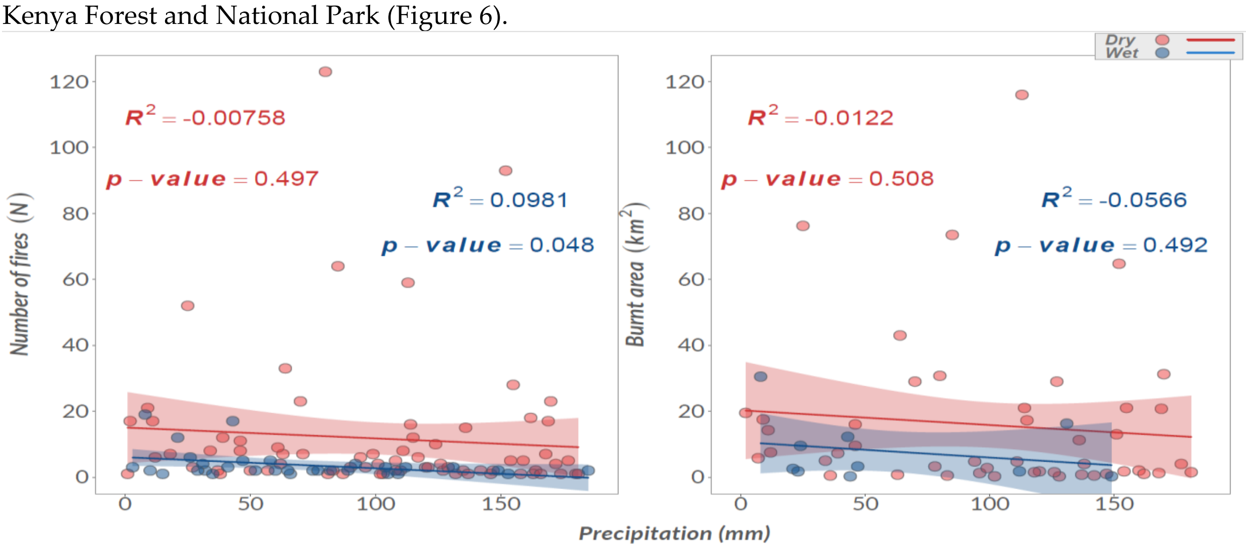

Figure 6: Correlation between number of fires (left), burnt area (right) and precipitation in Mount Kenya Forest and National Park.

3.4 Spatio-temporal trends of NDVI and VCI in Mount Kenya Forest and National Park

The NDVI has been fluctuating up and down in Mount Kenya Forest and National Park and follows the seasonal increase and decrease of the precipitation. The mean monthly NDVI values have been fluctuating from 0.62 to 0.72 during the wet season except in 2011 and from 0.46 to 0.58 during the dry season (Figure 7). The lowest mean monthly NDVI values of below 0.5 were detected in between June to August in 2006, 2008 to 2011, 2014 and 2016. The highest mean monthly NDVI values of 0.70 and above were detected in October 2004, December 2006 and October 2011. The results show that the mean monthly NDVI from 2009 to 2013 was lower (red dotted line) than the mean monthly NDVI from 2003 to 2008 and 2014 to 2018 (Figure 7). However, there is no general trend observed of decreasing NDVI values over time.

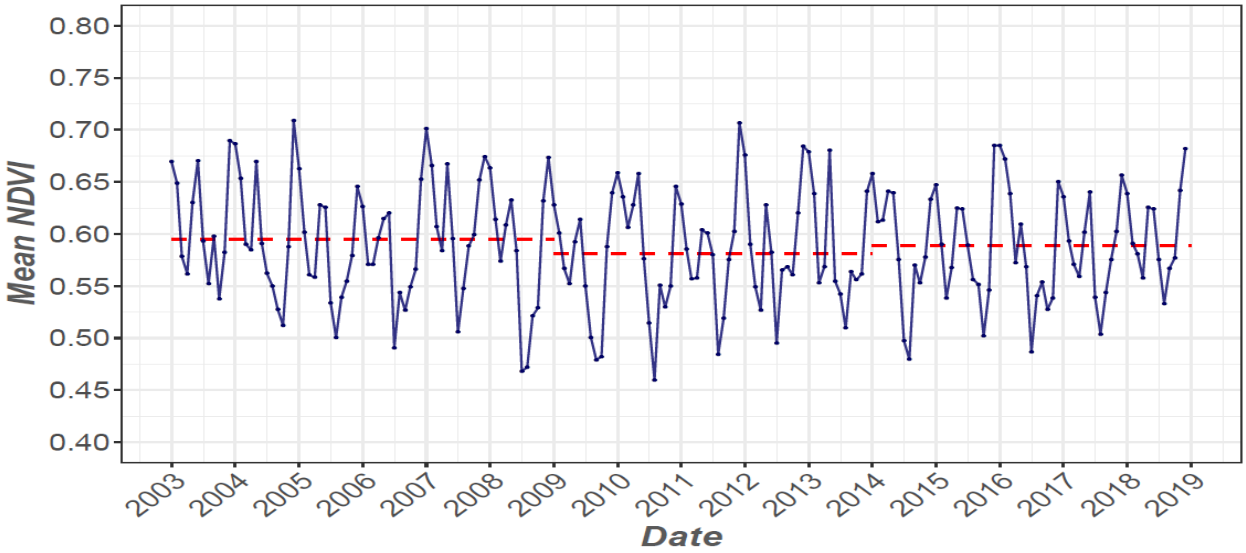

Figure 7: Mean monthly NDVI in Mount Kenya Forest and National Park with the mean NDVI (red dotted line) for the periods 2003 to 2008, 2009 to 2013 and 2014 to 2018

Results show that there is a temporal variability in the relationship between CHIRPS precipitation data and the mean VCI values from 2003 to 2018 (Figure 8).

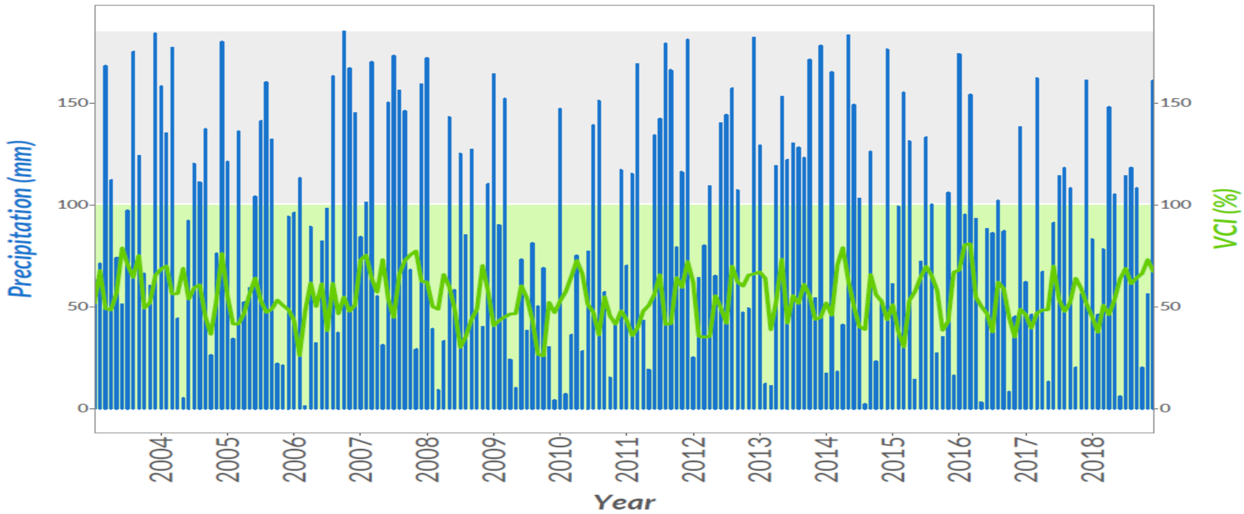

Figure 8: Temporal variability in the relationship between CHIRPS precipitation data and the mean VCI values in in Mount Kenya Forest and National Park from 2003 to 2018

Results show that from 2003 to 2018, there are several months with the monthly VCI values below 35% indicating that Mount Kenya Forest and National Park has experienced several droughts. Results show that from 2003 to 2018, Mount Kenya Forest and National Park experienced six droughts in February; three in October; two in March, July, August, and September; and one in April and December respectively (Table 1)

Table 1: Years with monthly VCI values below 35% in Mount Kenya Forest and National Park

Monthly VCI below 35%												
Year	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004										x		
2006		x					X					
2008							X	x				
2009									x	x		
2010								x				
2011		x							x			
2012		x	x	x								
2015		x	x							x		
2016											x	
2017		x										
2018		x										

Taking a closer look at the month of February, it becomes evident that there are large variations in the VCI values between the years. The "drought" in Figure 9 indicates the threshold for experiencing a drought (VCI<35%). In the year 2006, the month of February had the lowest average monthly VCI value and in 2016, the highest VCI value was slightly above 82%.

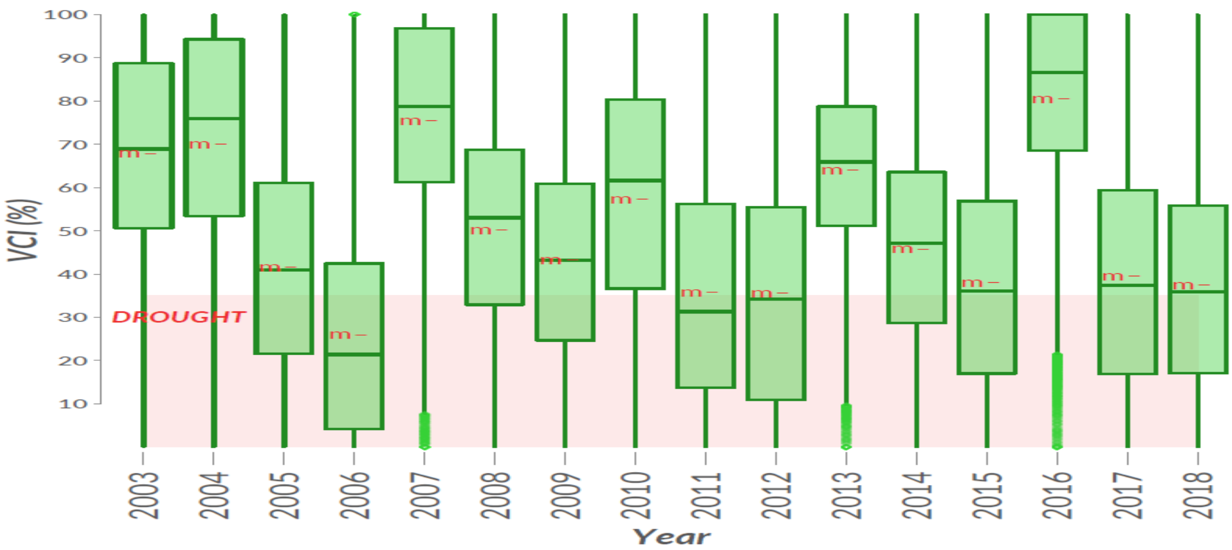

Figure 9: Temporal variability of the VCI in Mount Kenya Forest and National Park where m- indicates the mean VCI in the month of February from 2003 to 2018

Results show that the VCI differs in space in NP, FS and FL (Figure A3 in the Appendix). Selecting again the month of February as an example it can be seen, that there is a huge spatial variation of the VCI values in the NP, FS and FL (Figure 10). In the year 2006, a large area of the NP, FS and FL had a brown to red color indicating a VCI of 0 to 20%. A large area was therefore affected by drought and only a small area did not experience a severe drought. On the other hand results show that in 2016 a large area of the NP, FS and FL around Mount Kenya Forest and National Park had a light green to dark green color indicating a VCI of 70 to 100 % on the VCI scale. This means that in 2016 a large area was not affected by drought (Figure 10).

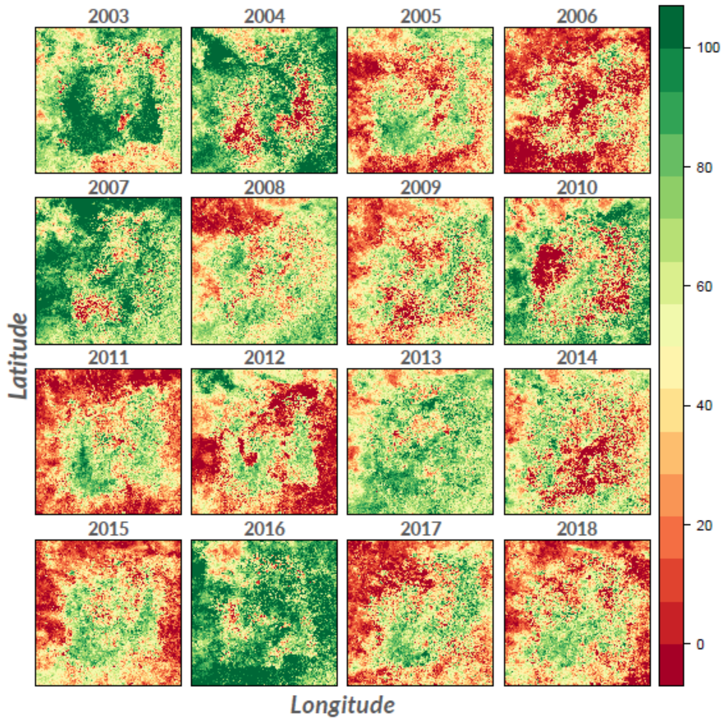

Figure 10: Spatial variability of the VCI in the month of February in the National Park, Forest Stations and Farmlands around Mount Kenya Forest and National Park from 2003 to 2018

3.7 Relationship between number of fires, burnt area and VCI

We analyzed the relationship between the numbers of fires, burnt area and VCI and the correlation analysis shows that there is no effect of VCI on number of fires during wet season. However, there is a slight relationship between VCI and number of fires in the dry season and the VCI has a similar effect on burnt area during the dry and wet seasons (Figure 11).

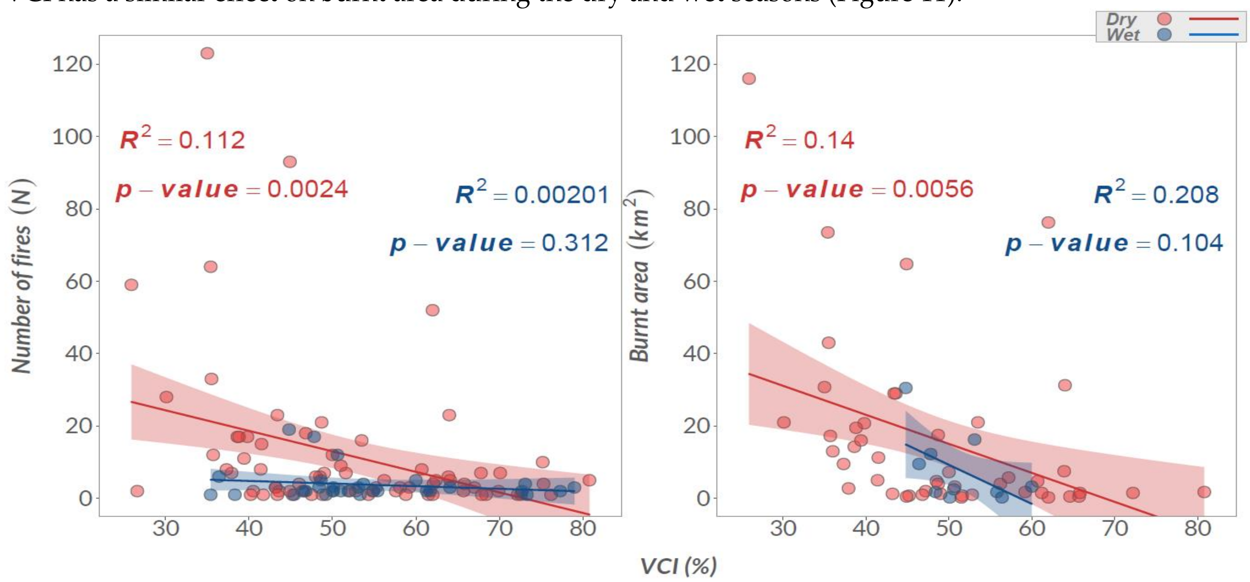

Figure 11: The effect of the VCI on the number of fires (left) and burnt area (right) during dry and wet season in Mount Kenya Forest and National Park from 2003 to 2018

Correlations between number of fires, burnt area and VCI reveal that there are minor differences between the NP, FS and FL. It also shows that there are some similarity in the effects of VCI on the number of fires and burnt area in three land use categories. Slightly higher correlations between the number of fires, burnt area and VCI are visible for FS with higher R^2 and lower p-value than for NP and FL (Figure12).

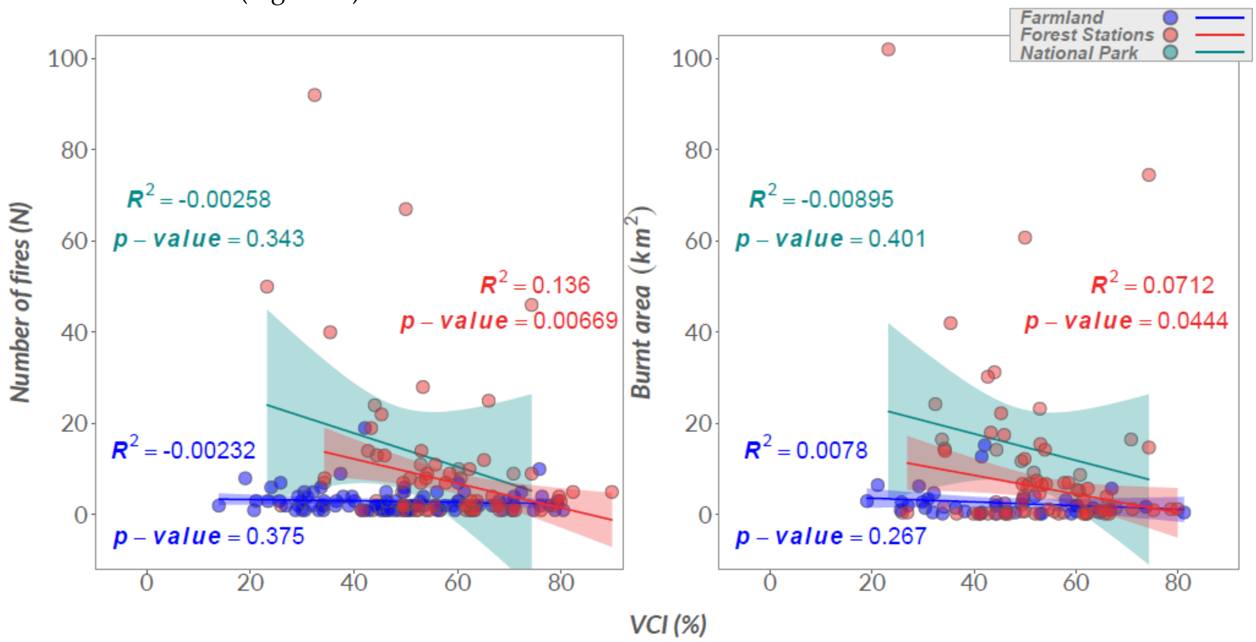

Figure 12: The effect of VCI on the number of fires and burnt area in National Park (NP), Forest Stations (FS) and Farmlands (FL) around Mount Kenya Forest and National Park from 2003 to 2018

Correlations between number of fires, burnt area and VCI show that there are only minor differences between forest stations on the Northwest side that have a medium fire danger (Nanyuki), high fire danger (Ontulili) and those on the Southeast side that have a low fire danger (Chuka and Chogoria). It also shows that there are some similarities in the effects of VCI on the number of fires and burnt area in forest stations that have a medium to high fire danger and those that have a low fire danger (Figure 13, 14).

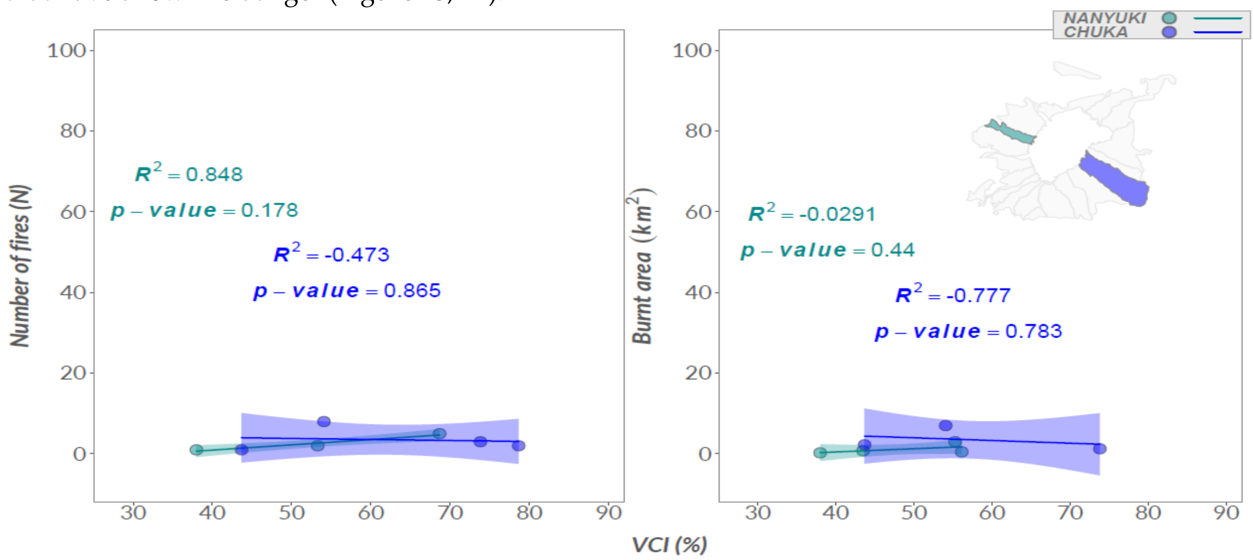

Figure 13: The effect of VCI on the number of fires and burnt area in Nanyuki forest station that has medium fire danger on the Northwest side and Chuka forest station that has a low fire danger on the Southeast side of Mount Kenya Forest and National Park.

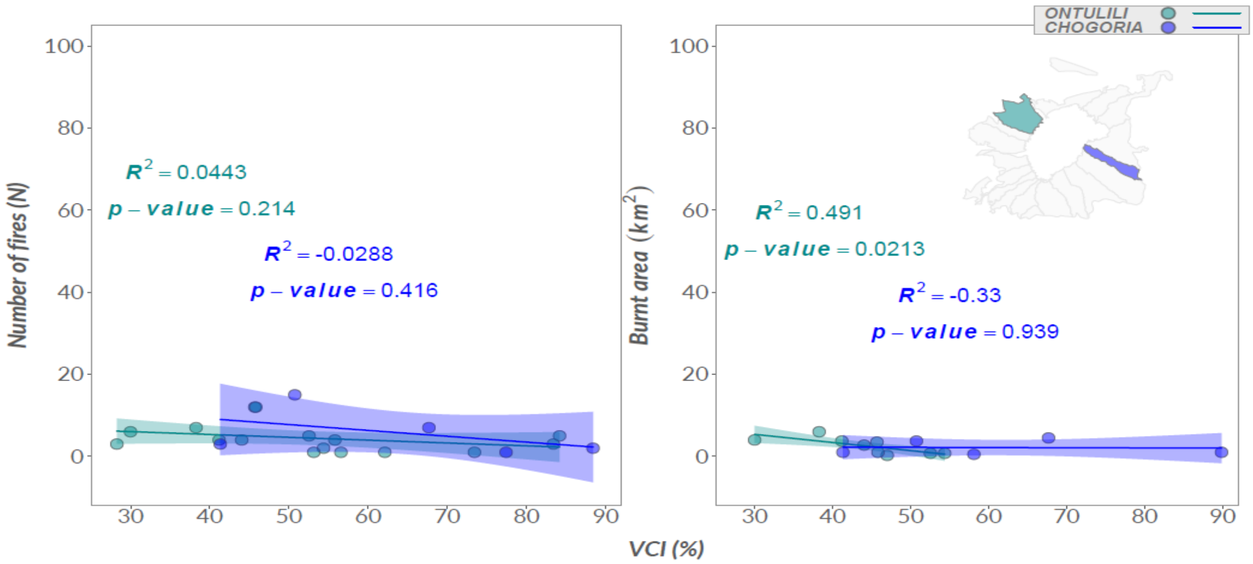

Figure 14: The effect of VCI on the number of fires and burnt area in Ontulili forest station that has a high fire danger on the Northwest side and Chogoria forest station that has a low fire danger on the Southeast side of Mount Kenya Forest and National Park.

4. Discussion

4.1 Impact of human activities on the spatio-temporal patterns of fire occurrence

Human activities vary between forest stations in Mount Kenya Forest and National Park. This is because the Kenya Forest Act 2005 provides different socio-economic activities for the establishment of Community Forest Associations (CFAs) with user groups [9]. Communities living around Mount Kenya Forest and National Park use fire as a tool in land management [12]. Perennial grassland fires are common in many parts of Mount Kenya Forest and National Park each year during the dry season and the months of December to March usually have a high number of fire occurrences and large burnt areas and may be attributed to the seasonal increase of human activities in these months [9]. The burning of old grass so that new grass can grow when the rain comes is a common practice done by migrant pastoralists who come to graze their livestock in Mount Kenya Forest and National Park during the dry season [2,7,9]. Communities around Mount Kenya Forest and National Park also use fire to prepare their farmlands and break impenetrable bushlands, control weeds, pests and parasites and try to keep wildlife away from homes [9]. However the decline in number of fires and burnt area in the months of July, August and September can be attributed to human activities changes like seasonal farming patterns (crops on field) and the migration of pastoralists (Maasai and Samburu) out of Mount Kenya Forest and National Park in search of pasture and water for their livestock in the low plains [9,12]. The KFS and KWS have however continued to practice fire suppression campaigns instead of using prescribed burning activities to manage fuel accumulation in Mount Kenya Forest and National Park [2,7]. This has resulted to an increase in the number of catastrophic fires that have caused damage to the forests, socio-economy, and environment in Mount Kenya region [2,9]. Based on the land use classes, our study established that most of the fire ignitions and burnt area was in the NP, followed by FS and then FL located in the leeward side (northwestern slopes) of Mount Kenya Forest and National Park from 2003 to 2018 [5,34].

4.2 Relationship between precipitation and fire occurrences

Other studies using ground stations and satellites to monitor weather conditions have shown that the windward side (southeastern slopes) of Mount Kenya Forest and National Park receives more rainfall with approximately 2250 mm while the leeward side of the mountain (northwestern slopes) receives about 900 mm [23]. The drier conditions on the leeward side make the area to be prone to more fires than the windward side of Mount Kenya Forest and National Park [34]. In comparison of the empirical data from the weather stations with the CHIRPS precipitation data it can be assumed, that the real weather conditions were even more severe, as the CHIRPS precipitation data underestimated the drought conditions to some extent. Studies have also shown that Mount Kenya Forest and National Park fire seasons are usually defined as January-March and July-September [2,5,7,34]. But our analysis of MODIS-FIRMS data from 2003 to 2018 showed that the month of December is also fire prone and needs to be included in the fire season of Mount Kenya Forest and National Park. A study done by [34] found out that the years 2007 and 2012 had the highest number of fire ignitions. Our study confirmed that, in the years 2006, 2008 and 2009 a high number of fires and large burnt areas were observed. Most of these fires took place in the months of December, January, February and March as compared to July, August and September except in the year 2008. Generally the human activities coupled with low precipitation, high temperatures and increased wind speed contribute to the high number of fire ignitions and burnt area in Mount Kenya Forest and National Park [9]. We found out that an increase in precipitation had a slight negative effect on the monthly number of fires and burnt area detected by MODIS-FIRMS satellite during the dry and wet season in Mount Kenya Forest and National Park. This is also in line with a study done by [34] which focused on the fire occurrence on Mount Kenya and patterns of burning, who established that the number of fire ignitions and burnt area decreased as precipitation increased and vice versa.

4.3 Relationship between droughts and fire occurrences

Several studies have been conducted to monitor ecosystem dynamics using NDVI and climate variables to assess long term trends in dryland vegetation variability [35]. A five-year analysis of NDVI [36] for grassland drought assessment over the central Great Plains of the United States found out that NDVI was low during the drought period. Other Studies have found out that the maximum and minimum values of the NDVI reflect the best and worst conditions of vegetative growth and the difference between them usually reflects the condition of the local vegetation [26,30,31]. This study indicated that the mean monthly NDVI from 2009 to 2013 was lower because of the two drought periods that occurred in 2009 and 2012 [20].

Studies done by [20,37] have classified drought levels in Kenya and Eritrea using a VCI above 35% to represents no drought conditions. Our study used the same threshold of VCI values below 35% to indicate drought conditions in Mount Kenya Forest and National Park. Similar studies by [38] that used the VCI to monitor agricultural drought were able to found out the major historical agricultural droughts in Ethiopia and the geographical regions that were most exposed to recurrent cycle of drought events. Also the studies by [39] used a three-monthly aggregated vegetation condition index (VCI3M) for classifying the rainy and dry season from 2003 to 2014 and for the development of a fully operational processing chain for mapping drought occurrence. In this context the extent and strength of the nationwide droughts are comparable to our findings. In our study especially the monthly VCI values in February were below 35% indicating that Mount Kenya Forest and National Park was also affected during the severe nationwide droughts [20].

Fire as disturbance has been known to affect the VCI [19,20]. As a result, if the burnt areas in Mount Kenya Forest and National Park were large, they might have also caused a drop in the VCI after the fire events that occurred between 2003 and 2018. However our study found that there is no effect of VCI on the number of fires during the wet season as the increased precipitation makes the fuel moisture content very high and probability of fire ignitions in Mount Kenya Forest and National Park to be very low [2,7]. However, our results show there is a slight relationship between VCI and number of fires in the dry season and the VCI has a similar effect on burnt area during the dry and wet seasons. This is because whenever the VCI value increases above 35% during the wet or dry season, it indicates that the fuel conditions are not favorable for large fires [37] and this result in the reduction in the number of fire ignitions and burnt area in Mount Kenya Forest and National Park [34].

Correlations between number of fires, burnt area and VCI reveal minor differences between the NP, FS and FL. This is related to the temporal and spatial differences in VCI values depending on the season and the land use types [20,37]. A study by [34] found out that the moorland in the Mount Kenya National Park has had the highest number of fires occurrences from 2000 to 2015 in the area characterized by Ericaceous vegetation, which is an open community of bushes often discontinuous and merging into Afromontane shrub land and has had the highest number of fires occurrences as a result of human activities from 2000 to 2015. Our study also found out that was a slightly higher correlation between the number of fires, burnt area and VCI in the FS that had a higher R^2 and lower p-value than for NP and FL. This is related to the fact that during the rainy season the ericaceous vegetation usually grows very fast and dries up quickly during the dry season resulting in a low VCI as compared to the other forest vegetation in Mount Kenya Forest and National Park. As a result the ericaceous vegetation accumulates large amounts of fuel during the dry season and increases the risk of fire outbreaks [5,34]. Our results also show that VCI has no effect on the number of fires and burnt area between forest stations on the Northwest side that have a medium to high fire danger and those on the Southeast side that have a low fire danger. This is because forests in Mount Kenya Forest and National Park usually have a high VCI and have spatially explicit heterogeneous vegetation that is less fire prone as compared to the moorland during the dry season. As a result the vegetation regulates pick flows, intercept precipitation and is improving the ground water recharge and steady the discharge during the season thus performing water catchment functions better than the moorland in Mount Kenya Forest an National Park [4]. The changing climate and the increasing human activities are likely to contribute to increased fire outbreaks in future unless proper Integrated Fire Management (IFM) practices are developed and implemented by the KFS, KWS managers and communities living around Mount Kenya Forest and National Park [9].

5. Conclusions

This study used the VCI to detect vegetation anomalies as a result of drought, taking into consideration the variability caused by seasonal change for each land use type (forests, national park and farmlands). The distribution of drought and fire impacts in Mount Kenya Forest and National Park will be more remarkable by visualizing the difference in vegetation conditions between dry and years with an average precipitation. Based on our findings, the hypothesis "The lower the Vegetation Condition Index (VCI), the higher the number of fire ignitions and the larger the area burnt in Mount Kenya Forest and National Park is" was found to be true. The hypothesis "Spatio-temporal patterns of forest fires in Mount Kenya Forest and National Park are a result of droughts during the period 2003 to 2018" was also found to be true. However human activities are a major cause of fire ignitions Mount Kenya Forest and National Park irrespective of the season. These results are expected to be useful when communities will be involved the development and implementation of integrated fire management approaches in Mount Kenya Forest and National Park. The generated MODIS satellite fire alerts can be disseminated to the KFS and KWS for further planning and management of targeted suppression activities in Mount Kenya Forest [5,16]. These findings will support the implementation of fire management strategies in areas where the land-cover types show heterogeneous mosaics, in regions where the network of existing meteorological stations does not cover certain remote areas, and in areas where landscape vulnerability to droughts and fire is vital to the livelihood of the communities living in that region. To improve our study findings, future monitoring studies need to focus on the change of seasonal human activities, on the role of anthropogenic driven land-cover changes before and during the study period and on the climate variables (precipitation and temperature) in the determination process for vegetation anomalies as a result of drought and fires.

Author Contributions: The conceptualization was done by K.W. N. and H.V.; methodology, K.W. N., H.V., C.P., G.D., A.K. and C.P.; validation, K.W. N., H.V., A.K.; formal analysis, G.D., C.P. and A.K.; investigation, K.W. N., H.V., C.P., G.D and A.K.; data resources, C.P., G.D. and A.K.; data curation, G.D., C.P. and A.K.; writing—original draft preparation, K.W. N., H.V.; writing—review and editing, K.W. N., H.V., C.P., G.D. A.K. and C.P; visualization, G.D., C.P. and A.K.; supervision, H.V.; project administration, K.W.N.; and funding acquisition, K.W. N., H.V.

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Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results

Appendix A

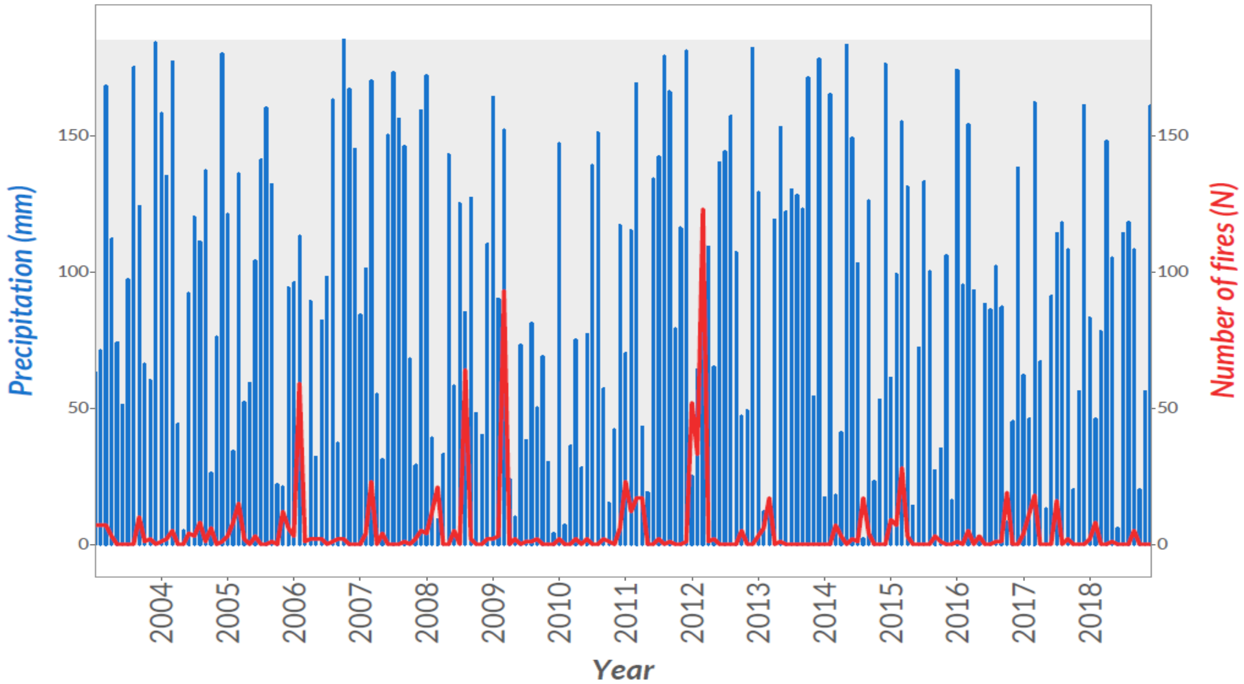

Figure A1: The monthly trends between the numbers of fires and the CHIRPS precipitation data for Mount Kenya Forest and National Park

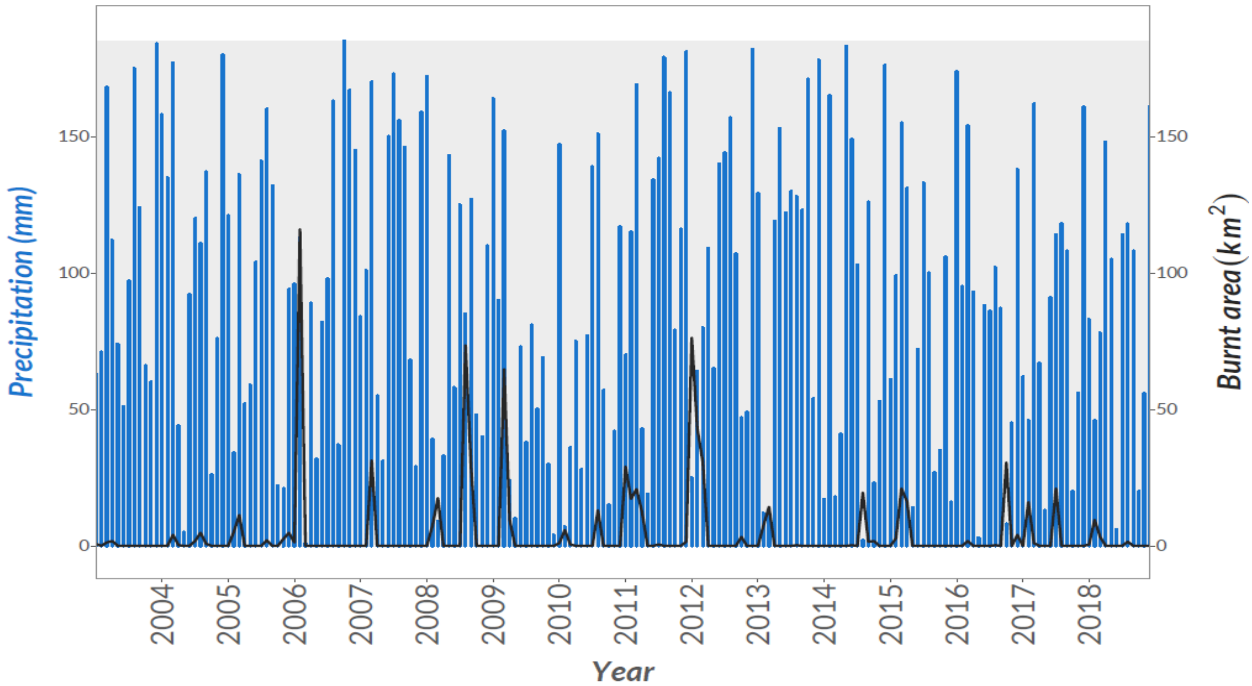

Figure A2: The monthly trends between the burnt area and the CHIRPS precipitation data for Mount Kenya Forest and National Park

remote sensing

MDPI

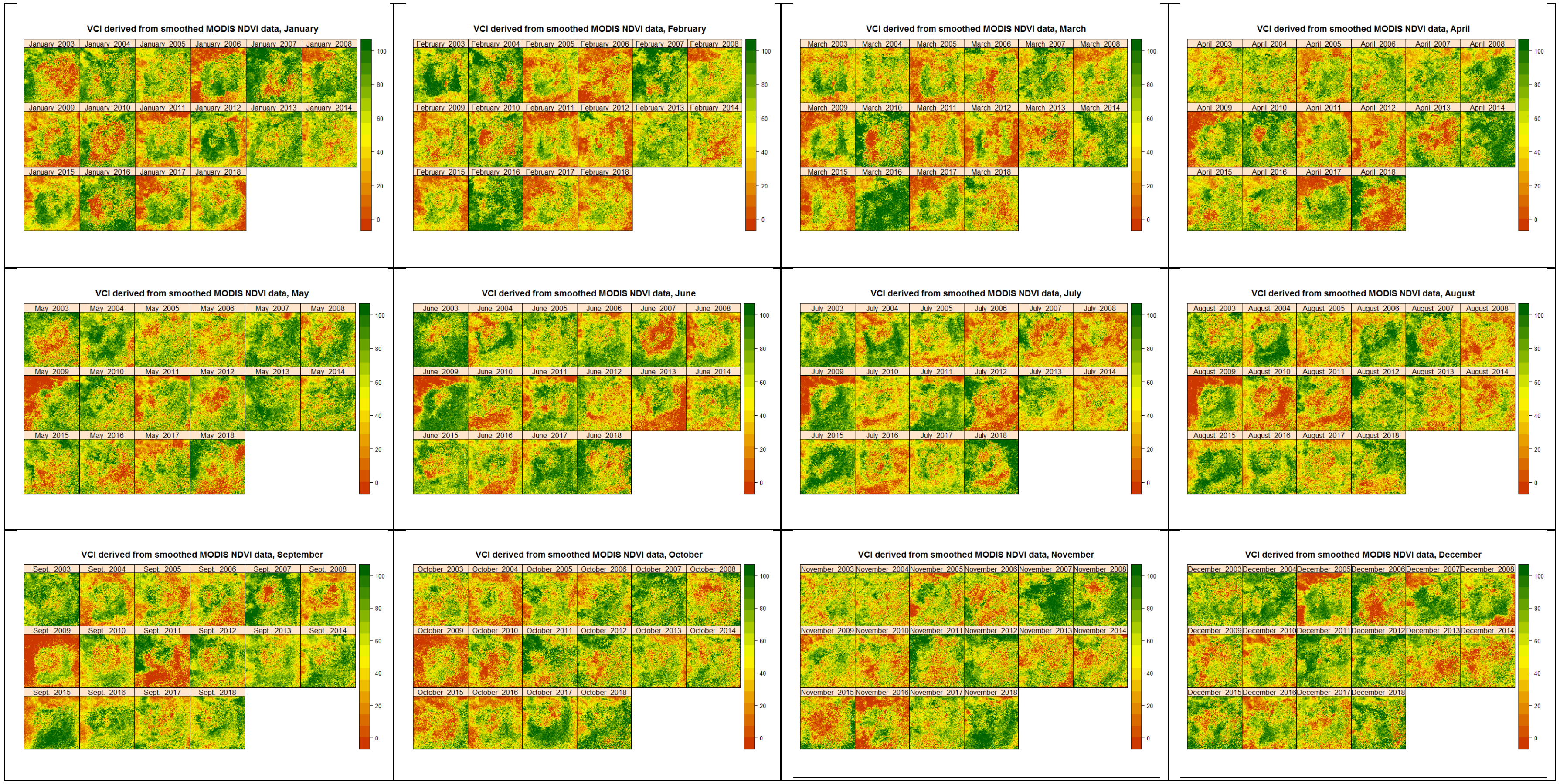

Figure A3: Spatial variability of monthly VCI from 2003 to 2018 in Mount Kenya Forest and National Park

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7.3 Evaluating Management Strategies for Mount Kenya Forest Reserve and National Park to Reduce Fire Danger and Address Interests of Various Stakeholders

forests

Article

Evaluating Management Strategies for Mount Kenya Forest Reserve and National Park to Reduce Fire Danger and Address Interests of Various Stakeholders

Kevin W. Nyongesa * and Harald Vacik

University of Natural Resources and Life Sciences, Vienna (BOKU) 1; harald.vacik@boku.ac.at
* Correspondence: kevin.nyongesa@boku.ac.at; Tel.: +4368860599334

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Abstract: A Multi-Criteria Analysis (MCA) approach was employed for evaluating and selecting the best management strategy for Mount Kenya Forest Reserve and National Park (MKFRNP). The MCA approach used a set of objectives and criteria (O&C) to address the complexity of the decision problem in a transparent and understandable way, which also facilitated the active participation by diverse professionals, experts, and interest groups. The management strategies were developed to fulfill the key components of MKFRNP management and the current situation in the study area. The seven management strategies focused on climate change mitigation, protection of water catchments, education and research, stakeholder involvement, biodiversity conservation, timber production, and community interests. Forest stations with differing fire danger levels (very high, high, moderate, and low) were selected to compare the performance of the management strategies. The strategies were assessed qualitatively on their potential to improve the current situation according to the entire set of O&C. The Analytic Hierarchy Process (AHP) was employed to identify the best management strategy according to the overall preferences of all stakeholder groups. The AHP indicated that a strategy focusing on community interests provided the best option to address the current management challenges in all the seven forest stations independently of their fire danger levels. Biodiversity conservation should also be considered by resource managers in order to reduce fire danger and increase the benefits obtained by different stakeholders in MKFRNP.

Keywords: Multi-criteria analysis (MCA); objectives and criteria (O&C); fire danger; benefits; forest managers; wildlife managers; management strategies (MS); community forest associations (CFAs); Stakeholders; analytic hierarchy process (AHP)

1. Introduction

Mount Kenya Forest Reserve and National Park (MKFRNP) is a UNESCO World Heritage Site [1] and a major forested water catchment area in Kenya [2]. It is jointly managed by the Kenya Forest Service (KFS), the Kenya Wildlife Service (KWS), and the Lewa Wildlife Conservancy [3]. Although some management successes for biodiversity conservation have been achieved in the MKFRNP, tremendous threats and pressures still remain [3]. Kenya's fast-growing population has increased pressure on MKFRNP resources over the past three decades [4]. The main source of this pressure arises from the depletion of forest resources and degradation within and near to the populated areas around MKFRNP [1,5,6]. As resources become scarce on private and community land, the population has been turning to the neighboring protected areas of MKFRNP for livelihood resources [7]. This has led to a depletion of resources, degradation, and increased wildfires. Besides human encroachment and land use change, invasive species, allocation of forest land to some communities and influential individuals by the former governments, cultivation of marijuana

(*Cannabis sativa* Linnaeus), pests and diseases, tourist or visitor related impacts such as poor waste management and human-wildlife conflicts have been observed [8]. This is mainly due to unsustainable use levels and patterns that have occurred as a result of poverty, poor or inappropriate management skills and weak management institutions and systems [5].

Natural fires in MKFRNP are caused by lightning [7] but most of the fires are recorded by KFS and KWS as “unknown causes”, making it difficult to estimate their social, economic, cultural and ecological effects [7]. According to the KFS and KWS, human-caused fire ignitions in MKFRNP are more likely to increase in the future, because climate change may affect fire season length and severity [4]. Communities living around MKFRNP use fire as a tool in land management and occasionally the fires go out of control causing unintentional wildfires in MKFRNP [7]. Perennial grassland fires are common in many parts around MKFRNP because each year during the dry season, communities set grasslands on fire to keep them open and to facilitate the growth of new grass for livestock, especially before the rain begins. Farmers around MKFRNP use fire to prepare their farmlands, to break impenetrable bushlands, control weeds, pests, and parasites and to keep wildlife away from homes. Bushland and forest fires are also common in MKFRNP because some community members use fire to burn charcoal, harvest wild honey, and hunt and roast game meat in MKFRNP [4]. Some other activities such as children carelessly playing with fire, the throwing of lit cigarette butts and poor handling of campfires have also contributed to the ignition of wildfires in MKFRNP [7]. Arsonists have caused wildfire ignitions in MKFRNP as a way of revenging on the KFS and KWS for being excluded from accessing some benefits from the forest resources. Wildlife poachers also ignite wildfires to escape being arrested and prosecuted by the KFS and KWS. Inter-community conflicts over water and pasture grounds between the locals (Kikuyu, Meru, and Embu) and the pastoralists (Samburu and Maasai) having been a source of fire ignitions in MKFRNP and are likely to increase [7]. During years of extreme drought, migrant pastoralists usually come to graze in MKFRNP, set fire to the old grass to facilitate the growth of new grass, and then move away in search of good pasture grounds. This practice has been causing huge fires and conflicts, due to the loss of grazing grounds for the locals, primarily the Kikuyu, Meru, and Embu communities who depend on the grasslands within MKFRNP for grazing their livestock [4,7]. Additionally, the intensified cultivation of exotic fire-prone tree species like cypress (*Cupressus lusitanica* Mill.), patula pines (*Pinus patula* Schiede Ex Schltdl. & Cham), radiata pines (*Pinus radiata* D. Don), blue gum (*Eucalyptus saligna* Smith), and rose gum (*Eucalyptus grandis* W. Hill Ex Maiden) will increase fire hazard in the future [4].

Ground fires, surface fires, and crown fires have occurred in MKFRNP grasslands, farmlands, bushlands and forests [4,6]. The KFS and KWS fire records from 1980 to 2017 show that MKFRNP has experienced about 210 wildfires. Most of these wildfires in MKFRNP occurred in the months of January, February, March, September, and October. The fire records also show that from 1980 to 2017, more than 668 Ha of plantations, 21,276 Ha of bushland and grassland, 267 Ha of bamboo, 6727 Ha of indigenous/natural forests and 11,175 Ha of moorland were burned by wildfires in MKFRNP. According to the KFS and KWS fire records from 1980 to 2015, the estimated firefighting cost and the fire damages were $ 134,759.84 and $ 4,712,384.96 respectively [6].

The community members and other stakeholders (user groups) with interests in MKFRNP have been obtaining their licenses from the government of Kenya through KFS and KWS [6]. The licenses are mainly obtained for the practices of: conserving biodiversity, conducting education and research, harvesting timber and poles, grazing livestock, collecting firewood, beekeeping, collecting herbs and spices, collecting wild fruits, collecting water, farming trout fish (*Oncorhynchus mykiss* Walbaum), providing hotel and cottage services as well as ecotourism, practicing of cultural rituals, farming under the Plantation Establishment and Livelihood Improvement Scheme (PELIS) and acting as community scouts in MKFRNP [1,3]. Despite the KFS and KWS efforts to license some of the user groups’ activities in MKFRNP, not all their interests have been addressed. This is because there have been cases of conflicting interests between the KFS, KWS and the user groups or between the different user groups.

The Mount Kenya Forest Reserve (MKFR) management plan 2010–2019 was developed by the KFS to guide the establishment, development and sustainable management, including conservation and rational utilization of the forest and allied resources for socio-economic development [3]. The MKFR management plan 2010–2019 was prepared in compliance with the legal requirement of the Forests Act, 2005 under section 35 that provides a mandatory legal requirement for preparation of management plans of all state, local authority and provisional forests. The MKFR management plan 2010–2019 considers the draft Forest Policy No. 9 of 2005; the KFS Strategic Plan 2009/10–2013/14; the Environmental Management and Coordination Act (EMCA), 1999; the Wildlife (Conservation and Management) Act, Cap. 376. The MKFR management plan 2010–2019 also considers the Water Act, 2002, other policies and legislative frameworks whose objectives have a direct impact on sustainable conservation, management, and utilization of MKFRNP [3].

Several management strategies that are in line with the MKFR management plan 2010–2019 have been suggested by different stakeholder groups that have interests in MKFRNP. The KFS and saw millers have suggested that a management strategy which satisfies wood production interests, in terms of timber and poles is the best. However, scientific experts from Egerton University, University of Natural Resources and Life Sciences, Vienna (BOKU) and Kenya Forest Research Institute (KEFRI) have suggested that increased plantation establishment for timber and poles will contribute to the national climate change mitigation interests through carbon sequestration and will also improve the protection function such as reduction of soil erosion and landslides. The KFS and Community Forest Associations (CFAs) confirm that an increased timber and poles production will help to achieve income interests through the creation of employment opportunities in the forestry sector [7]. The scientific experts have also suggested the need for establishing plantations with indigenous tree species like Meru oak (*Vitex keniensis* Turrill) and African pencil cedar (*Juniperus procera* Hochstetter. ex Endlicher) that can be used for sawn timber and poles and still contribute to carbon sequestration. Some CFA members have suggested that the best management strategy should satisfy agriculture interests by providing grazing grounds for livestock and using former harvested areas to cultivate crops and plant trees under the Plantation Establishment and Livelihood Improvement Scheme (PELIS) [4]. Additionally, the CFAs suggest that increased access to non-timber forest products such as foraging of wild fruits, hunting of game meat, fishing, collection of honey and herbal medicine would satisfy the needs of the local people. In this context, the energy demands also can be fulfilled by fostering firewood collection and charcoal making [6]. But on the other hand, the scientific experts have suggested that the use of energy efficient cooking stoves by communities can help to reduce the growing demand for firewood collection and charcoal making in MKFRNP. The counties and water resources management authorities (WRMAs) consider that increased charcoal burning and timber harvesting will affect water quality and quantity [7]. They have therefore suggested management strategies that will help to increase the protection of water catchments against human-caused deforestation and degradation [3]. Further, scientific experts, the KWS, biodiversity conservation organizations such as Lewa Wildlife Conservancy (LWC) and Mt. Kenya Wildlife Trust (MKWT) have argued that increased plantations consisting of exotic trees such pines, cypress and eucalyptus will contribute to increased wildfire danger, affect the growth of indigenous trees, decrease wildlife forage and breeding habitats in the MKFRNP [4]. The KWS, LWC, and MKWT suggest that the maintenance of wildlife species diversity, tree species diversity, plant species diversity, the elephant migration corridor, key habitats, and protected areas can meanwhile increase income from tourism. But the scientific experts have suggested that tourist activities in MKFRNP should be well regulated because uncontrolled campfires may cause unintentional wildfires leading to degradation of some key habitats and protected areas. The scientific experts, KWS, LWS, and MKWT also oppose the increase of CFAs access to non-timber forest products, firewood and charcoal because of unsustainable use levels and patterns as a result of poverty that have endangered wildlife and tree species [1].

The Mount Kenya Ecosystem (MKE) management plan 2010–2020 was developed by KWS through a participatory planning process involving various stakeholders, under the coordination of a core planning team that comprised representatives of KWS and KFS managers and planners, national environmental management authority (NEMA) and the water resources management authority (WRMA) regional officers in charge of the MKE [1]. The MKE management plan 2010–2020 has been developed in line with the KWS Protected Area Planning Framework (PAPF). Unlike other types of plans where management actions are often stated but not expounded, management actions in PAPF-based plans are elaborated to improve understanding increasing prospects of implementation. These plans adopt an ecosystem approach addressing conservation issues holistically and actively involving KWS, KFS, and local communities.

The implementation of the MKFR management plan 2010–2019 and MKE management plan 2010–2020 presents a complex decision-making challenge to the KFS, KWS, community forest associations (CFAs) and other stakeholders on how to reduce fire danger and increase the benefits obtained by different stakeholders in MKFRNP [1,3]. Therefore, there is a strong need to develop and choose the best management strategy for MKFRNP that can help to reduce the fire danger and address the interests of various stakeholder groups [1,3]. Multi-Criteria Analysis (MCA) can help to solve such complex multi-criteria decision problems that include qualitative or quantitative aspects [9,10]. Strong technical and theoretical support for MCA procedures exists, and they are designed to consider an intuitive and transparent participation of multiple experts and stakeholders. Considering stakeholder knowledge will contribute to the general acceptability of the results [9,11,12]. One of the MCA tools that has been used widely by natural resource managers in complex decision-making situations is the Analytical Hierarchy Process (AHP) [13]. The AHP was introduced by Thomas Saaty in 1980 [14] and helps to reduce complex decisions to a series of pairwise comparisons, and then by synthesizing the results, the AHP helps to capture both the subjective and objective aspects of a decision [9]. Therefore, this paper will demonstrate how the AHP can support resource managers, communities and other stakeholders in finding the best management strategy that will help reduce fire danger and increase the benefits obtained by different stakeholders in MKFRNP. The best management strategy will then be jointly implemented by the KFS, KWS, CFAs, WRMAs, NGOs, counties, religious organizations, and other stakeholders with interests in MKFRNP.

The objectives of this project were (i) to develop the Management Strategies (MS) which meet the demands for integrated fire management, (ii) to develop Objectives and Criteria (O&C) for the evaluation of the strategies with all stakeholder groups and (iii) to apply the AHP to propose the best management strategy that reduces fire danger and increases the benefits obtained by various stakeholders in MKFRNP. In the following sections, we will introduce the methodological steps for the MCA, present the case study and draw some conclusions on the selection of the best management strategy.

2. Materials and Methods

2.1. Description of the Study Sites

MKFRNP is located to the east of the Great Rift Valley, along Latitude 0°10′ S and longitude 37°20′ E. It bestrides the equator in the central highland zones of Kenya [15]. The mountain is situated in two Forest Conservancies and five forest management zones, namely, Nyeri and Kirinyaga in Central Highlands Conservancy and Meru Central, Meru South and Embu in Eastern Conservancy [3]. The MKFRNP has been divided into 23 forest stations as shown in Figure 1. The national park covers 71,510 Ha and the forest reserve covers 213,082.64 Ha [3,16]. Mt. Kenya was formed as a result of volcanic activity and it has a base diameter of approximately 120km. The mountain's highest peaks Batian (5199 m) and Nelion (5188 m) are located in the national park [15]. The altitudes with the highest rainfall are found between 2700 and 3100m, while above 4500m most precipitation falls as snow or hail and frosts are common above 2500m above sea level (asl) [3]. Rainfall pattern in the MKFRNP ecosystem is bimodal. It ranges from 900 mm in the north (leeward side) to 2300 mm on the southeastern slopes (windward side) of the mountain with maximum rains falling during the months of March to June and October to November [16]. The driest months are

January and February and the windward side experiences the strongest effects of the trade wind system. The diurnal temperature ranges in January and February may be as high as 20 °C. The Eastern side (windward side) of the MKFRNP receives more precipitation and is less prone to fires as compared to the Western side (Leeward side) which experiences more fires throughout the year [7]. The climate varies with the altitude and temperatures at MKFRNP are cooler than throughout most of the country. The climate there is either subtropical or temperate. There is still a rainy season from March to May and from October to December when it is drizzly and cloudy [17]. Rainfall is moderate on the lower slopes and heavier higher up. The sunniest months are from December through March [18]. The peak of MKFRNP is always covered in snow [15]. The climate of MKFRNP region is largely determined by altitude. There are great differences in altitude within short distances, which determine a great variation in climate over relatively small distances. Average temperatures decrease by 0.6 °C for each 100m increase in altitude [3]. An afro-alpine type of climate, typical of the tropical East African high mountains, characterizes the higher ranges of MKFRNP [3].

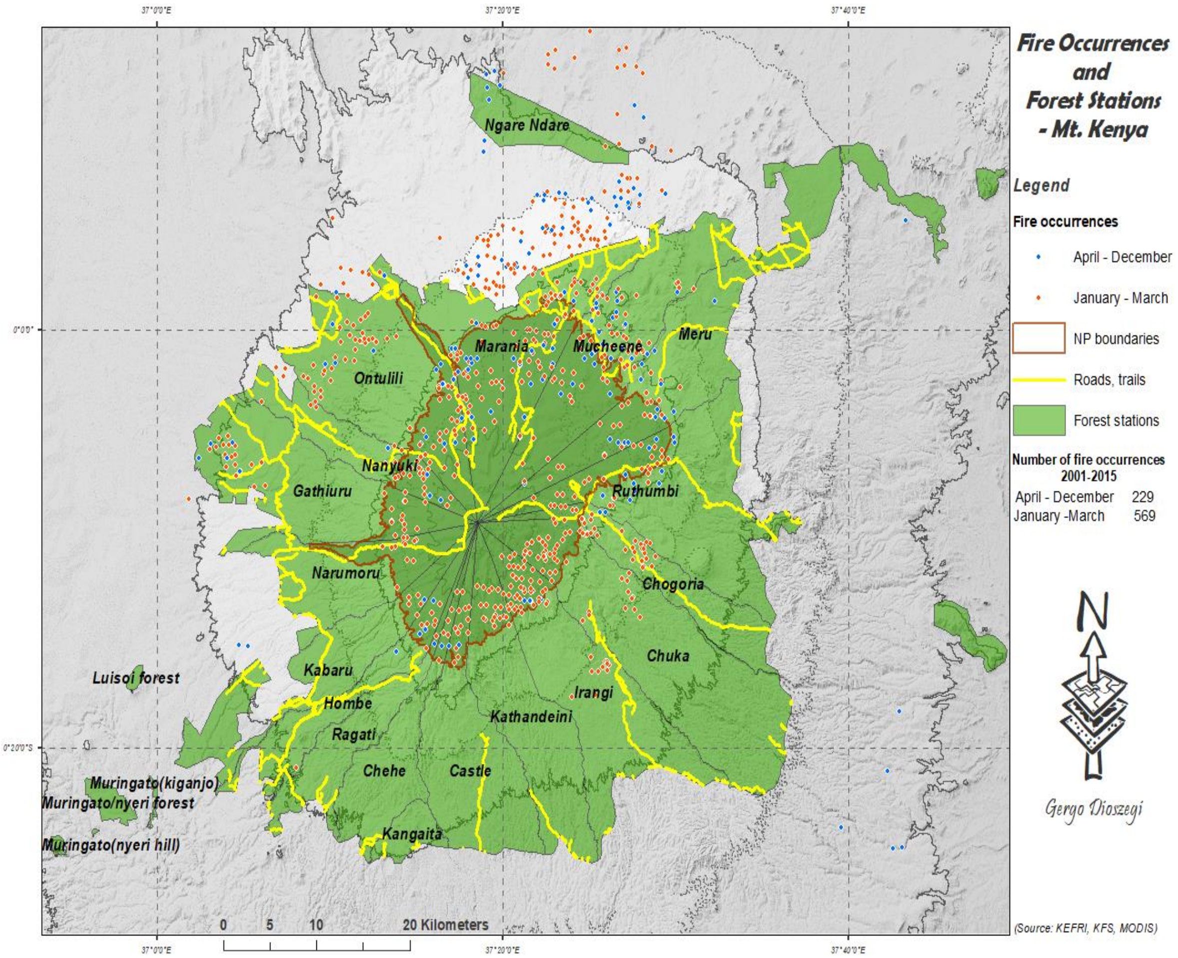

Figure 1. A map of Mount Kenya Forest and National Park showing forest stations, national park, roads, trails and the seasonal fire occurrences from 2001 to 2015 (Source: KEFRI, KFS, MODIS).

MKFRNP is an important reservoir for biodiversity and several studies have identified 880 plant species, subspecies and varieties belonging to 479 genera in 146 families below the 3200 m altitude [3]. There are at least 11 endemic species of higher plants and more than 150 species that are near endemic [3]. Vegetation types and species distribution are distinguished according to the different climatic zones and altitudes, most obviously through variation in vegetation structure, cover and composition [3,4]. The moorland (ericaceous belt) lies between 3000 m and 3500 m asl and is mainly covered with giant heath, African sage (*Artemisia afra* Jacquin Ex Willdenow), several gentians (*Swertia spp* Linnaeus), smaller trees in glades, such as the East African rosewood (*Hagenia *abyssinica* Willdenow), St. John's wort (*Hypericum spp* Linnaeus) and trees that are covered with moss and lichens (*Usnea spp* Dillenius Ex Adanson) [3]. The pure bamboo (*Arudinaria spp* Michaux) zone occurs between 2550 and 2650m asl while the mixed bamboo with indigenous trees zone extends from 2500 to 3200m asl and is dominated by the African alpine bamboo (*Arudinaria alpina* Schumann), real yellowwood (*Podocarpus latifolius* Thunberg Ex Mirbel) [3]. The elderberry (*Sambucus africana* Standl.) grows on openings during the transition phase of collapsed bamboo stems [3,4]. The bamboo zone is absent in the northern side of MKFRNP due to drier conditions [3,6]. The indigenous forest zone starts at 2400m down to 2000m asl and is dominated by *Podocarpus latifolia* mixed with brittle-wood (*Nuxia congesta* R. Brown Ex Fresen.) at the upper altitudes [3,4,6] while moist forests of East African camphorwood (*Ocotea usambarensis* Engler), forest newtonia (*Newtonia buchananii* Buchanan), woodland croton (*Croton sylvaticus* Hochst. Ex C. Krauss), musine croton (*Croton megalocarpus* Hutchinson), forest bonsai (*Premna bonsai* Linnaeus), silver oak (*Brachylaena huillensis* O. Hoffmann) and cape chestnut (*Calodendrum capense* Thunberg) occur at lower altitudes between 1450 and 2400 m asl [3]. Plantation zone extends from 2200 m to 2400 m asl and the main commercial tree species planted include Cypress, Pines, and Eucalypts while plantations of indigenous species mainly include Meru oak (*Vitex keniensis* Turrill) and African pencil cedar (*Juniperus procera* Hochstetter. ex Endlicher) [4]. Tea (*Camellia sinensis* Linnaeus) is also grown in MKFRNP. The Nyayo Tea Zone was opened up by the Nyayo Tea Zones Development Corporation which was established by Legal Notice No. 265 of 1986 with the aim of promoting forest conservation by providing a buffer zone to check against human encroachment into forest reserves. The total area opened up during the clearing for establishment of the tea belt in Mt. Kenya was 1194.8 hectares out of which 787.9 hectares are currently under tea, 241.8 hectares are under fuel wood plantations and another 165.1 hectares which were also cleared were replanted with indigenous trees [3,4].

Mt. Kenya is considered as a holy mountain according to the Kikuyu community traditions. This is because they traditionally believed that their God "Murungu" or "Ngai" dwelled on top of this mountain. There is also the saying that term Kikuyu originates from the Mukuyu tree (*Ficus sycomorus* Linnaeus) [1,4]. According to the Kikuyu culture, three sacred trees make the community believe that they should conserve the MKFRNP: Mukuyu tree (*Ficus sycomorus* Linnaeus), Mugumo tree (*Ficus thonningii* Blume), and Mukurwe tree (*Albizia gummifera* J.F. Gmel.) [4]. They are used during various rituals and ceremonies [3]. Nobody in the community is allowed to cut down or set fire to these trees and this is similar to other places in Africa and contributes to the efforts of conservation [4].

The Mt. Kenya region has a very high population growth rate [7]. The total population of the communities that live within the districts that border the MKFRNP was 24.4 million in 2009 [3,7]. Human activities in MKFRNP to obtain water, firewood, honey, charcoal, timber, poles, and grass for livestock, income from tourism, game meat, fish, herbal medicine have increased over the past three decades [3,4,6]. Various agro-forestry practices have been adopted which include tree planting in woodlots and cropland around homesteads and along farm boundaries. A good number of people in the area operate small business enterprises that include shops, kiosks, selling milk and other farm products, selling timber and wood products, honey, firewood and charcoal [7]. Other community members engage in quarrying and breaking ballast while others derive their livelihood from providing casual labor on the farms while others are formally employed [1,3,4]. The operating of hotels around the MKFRNP promotes employment both directly and indirectly through the flow of demand for goods and services [4]. A few small-scale farmers around MKFRNP have also initiated fish farming projects for the growing market especially in the local hotel industry [4].

MKFRNP is known to have a long fire history and fire has influenced the vegetation in the landscape because some plant species require fire to germinate, establish, or to reproduce, and total fire suppression not only eliminates these species, but also affects the animals that depend upon them [4,6]. MKFRNP has some fire-dependent species like *Juniperus procera*, *Bambusa vulgaris* (Schrad Ex J.C. Wendl.) and *Hagenia abyssinica* that usually regenerate after fire [4]. Native perennial grasses also regrow from root systems that are rarely damaged by fires that occur in MKFRNP [4,7].

Fire is the only natural factor which also supports the reproduction of the afro-alpine vegetation (chaparral). Older stands of chaparral dry up causing huge fuel accumulation over larger areas thus fire is necessary for the plants to remain vital [4]. However, the current banning of all fires from current land use practices by KFS and KWS might lead to an accumulation of fuel loads, which would play a major role in future wildfire outbreaks in MKFRNP [4].

Plantations of exotic tree species like pines, cypress and eucalypts have been established in MKFRNP by the KFS for the pulp and timber industry. Several studies show that exotic tree species contribute to changes in the patterns of anthropogenic ignitions, flammability of exotic species, forest ecosystem structure, and process and fuel loads [4]. Fire stimulates the release of large amounts of seeds from the serotinous cones of *Pinus radiata* and can create favorable conditions for germination and establishment [4,6,7]. Recovery in fire-resistant Eucalypt species in MKFRNP is by resprouting from epicormic strands (i.e., regeneration from meristem strips, usually extending from the inner to outer bark on aboveground branches and stems, which produce buds), and/or from basal buds. Unmanaged fires may contribute to an increase of exotic species in the natural environment like MKFRNP [4]. However, the use of prescribed fires for fuel management is not practiced by KFS and KWS in MKFRNP and yet these prevention measures would help to decrease the risk of catastrophic fires [7].

MKFRNP requires the best management strategy that will help communities, natural resource managers and other stakeholders to address both damaging and beneficial fires within the context of the natural environments and socio-economic systems in which they occur, by evaluating and balancing the relative risks posed by fires with the beneficial ecological and economic effects they may cause in a given conservation area, landscape, or region [4]. It should help to identify factors influencing fire ignition as it relates human needs and land use activities to factors influencing fire ignition. The best management strategy should also estimate and ascertain the roles of external drivers in influencing fire danger and the positive and negative effects of fires [1,3,4]. The best management strategy should also help in evaluating the benefits and risks of different management activities and developing fire management guidelines considering human needs and land use activities [4].

2.2. Methodological Approach of the Study

In this study, the methodological approach was classified into seven steps as shown in Figure 2. The facilitators comprising scientific experts from Egerton University, University of Natural Resources and Life Sciences, Vienna (BOKU) and Kenya Forest Research Institute (KEFRI), the KFS managers, KWS managers, the chief Ecosystem conservator, CFAs, NGOs, county water regional officers, other stakeholder groups and the focus group discussions supported the design of the management strategies and the set of O&C for the evaluation. The AHP was applied by a team of experts to select the best management strategy that helps to reduce fire danger and increase the benefits obtained in MKFRNP to fulfill multi-stakeholder interests. The individual steps are described as follows:

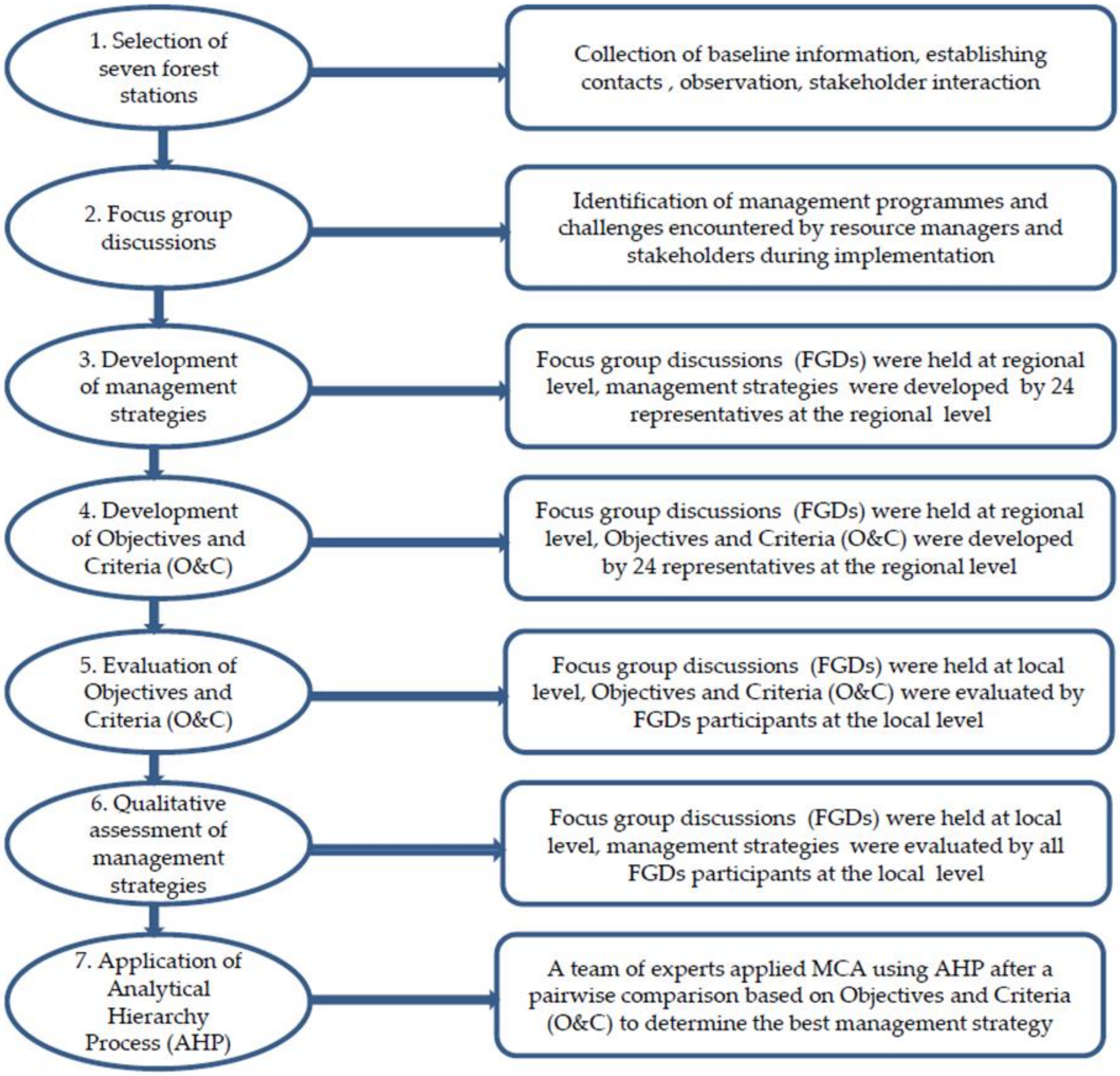

Figure 2. The methodological approach for selecting the best management strategy in Mount Kenya Forest Reserve and National Park (MKFRNP).

2.2.1. Selection of the Seven Forest Stations

In the first stage, the MKFRNP environment was described by collecting background information on management policies, socio-economic activities, and the bio-physical assessments were also done. Then contacts with different key stakeholders were established. This helped to understand the existing rules and regulations that govern decision making processes about resource allocations, such as, provisions that enhance the livelihoods of the local communities and opportunities for income generation activities and existing fire threats to the MKFRNP. The MKFRNP is divided into 23 forest stations and it was not possible to visit all of them during the study because it would have been too costly and time-consuming. Seven forest stations in MKFRNP were then selected based on the description of the current management objectives, benefits obtained by stakeholders and the number of fire incidences recorded by KFS and KWS from 1980 to 2015. The selected forest stations with a very high fire danger are Marania, Ontulili and Gathiuru having experienced 49, 71 and 63 fires incidences respectively in the last 35 years. Nanyuki and Naru Moru have a high to moderate fire danger having experienced 18 and 5 fire incidences respectively. Hombe and Chehe are considered as low fire danger forest stations, each having experienced only one fire incidence in the same period of time. Basic information was gathered on the current management programmes that are being implemented by the KFS and KWS in the seven selected forest stations in MKFRNP as shown in Appendix A.

2.2.2. Focus Group Discussions (FGDs)

A focus group discussion is a productive and positive way to gather people together with similar backgrounds or experiences to discuss a specific topic of interest [19]. There was a need to hold FGDs with various stakeholders living around, working in or with interests in MKFRNP to address the issues affecting the current management. FGDs were then held at the regional level and local levels in all seven forest stations selected for this study, and facilitators from Egerton University, University of Natural Resources and Life Sciences, Vienna (BOKU) and Kenya Forest Research Institute (KEFRI) supported the process. At the regional level, the Chief Ecosystem Conservator, seven KFS forest managers, seven KWS wildlife managers, seven rangers, seven university specialists and one staff member of KEFRI were selected to attend the FGDs based on their gender, level of knowledge and expertise on issues affecting community development, agriculture, forestry, water and wildlife management [5]. The regional FGDs helped to identify the existing management strategies in MKFRNP. At the local level, 21 CFA members were selected in each of the seven forest stations to attend the FGDs. This was mainly based on gender, education, leadership roles in CFAs, experience in firefighting, the needs and benefits that they obtained in MKFRNP. Other community members, village leaders, NGOs, religious groups youth representatives and women representatives were also invited to attend the FGDs to express the opinions of other community user groups that obtain benefits in MKFRNP [20]. The local level FGDs participants with the help of facilitators identified and discussed the challenges affecting the implementation of the existing management strategies and expressed their preferences based on their needs as shown in Appendix B.

2.2.3. Development of Management Strategies (MS)

In the third stage, FGDs were held at the regional level by the seven representatives and facilitators to discuss the existing management programmes and the challenges resource managers were facing in making management decisions on how to reduce fire danger and increase the benefits obtained by the different stakeholders in MKFRNP. Resource managers and stakeholders are facing difficulties to ensure that rare and threatened species, as well as their habitats, are protected. There is a strong need to preserve and restore the existing habitats and improve ecosystem connectivity between them [5,15]. On the other hand, wood and non-wood natural forest products should be sustainably exploited and the commercial production of timber and other forest products should be favored. Plantation forests might help to meet the market demands and restore degraded forest areas. Local communities should be actively involved in forest management activities [3]. MKFRNP plays a critical role in water catchment functions in Kenya and there is a strong need to restore and conserve the water catchment area and control the water collection from rivers [1,3,21]. The MKFRNP offers diverse low impact tourist activities, which help to augment resource protection. Therefore, tourist products and services can be marketed and adequate visitor accommodation facilities can be developed [22,23]. The FGDs participants also stated that during the implementation of the Community Partnership and Education Programme, the resource managers were facing difficulties in improving communication among the people living in the area and minimizing human-wildlife conflicts in adjacent areas [5,20,24]. In this context, staff welfare and motivation are critical components for the success of the conservation efforts and that effective and efficient management infrastructure needs to be provided [1,3,7]. Additionally, it was stated that security presence should be extended across MKFRNP and collaboration with key stakeholders in security matters should be strengthened to ensure that encroachment, marijuana cultivation, accidental forest fires, poaching of wild animals, illegal logging, and other forms of illegal activities are minimized [4,7,23]. After discussing the challenges in natural resource management, the strategies were outlined, describing how to overcome the main problems, ensure stakeholder participation, as well as minimize the perceived future threats. The regional FGDs described and developed nine management strategies with the help of the facilitators in detail for further evaluation.

2.2.4. Developing Objectives and Criteria

In the fourth step, a set of objectives and criteria (O&C) were identified at the regional FGDs over three days. They helped to generate an initial set of O&C for evaluating and selecting the best management strategy that will help to reduce fire danger and increase the benefits obtained by different stakeholders in MKFRNP. A top-down approach was used to ensure that information gathered in the local FGDs was not lost [12]. The O&C set was developed based on the information and experiences affecting community development, agriculture, forestry, water and wildlife management in MKFRNP. Based on the inputs from the seven representatives and stakeholders as well as different international and national examples relevant objectives were identified. Then criteria were defined to decompose the objectives. Finally, the regional FGDs selected 12 objectives and 28 criteria for further discussion and evaluation with participants at the local level in the forest stations. The bottom-up approach was organized in a way to accommodate direct involvement and participation of various stakeholders with interests in the MKFRNP so as to secure their commitment in the long term. In all local level FGDs the participants adapted the O&C to their local conditions and criteria that were less preferred or redundant were excluded from the set. At the end, a final set of 8 objectives and 21 criteria was proposed for the evaluation of the management strategies (Figure 3).

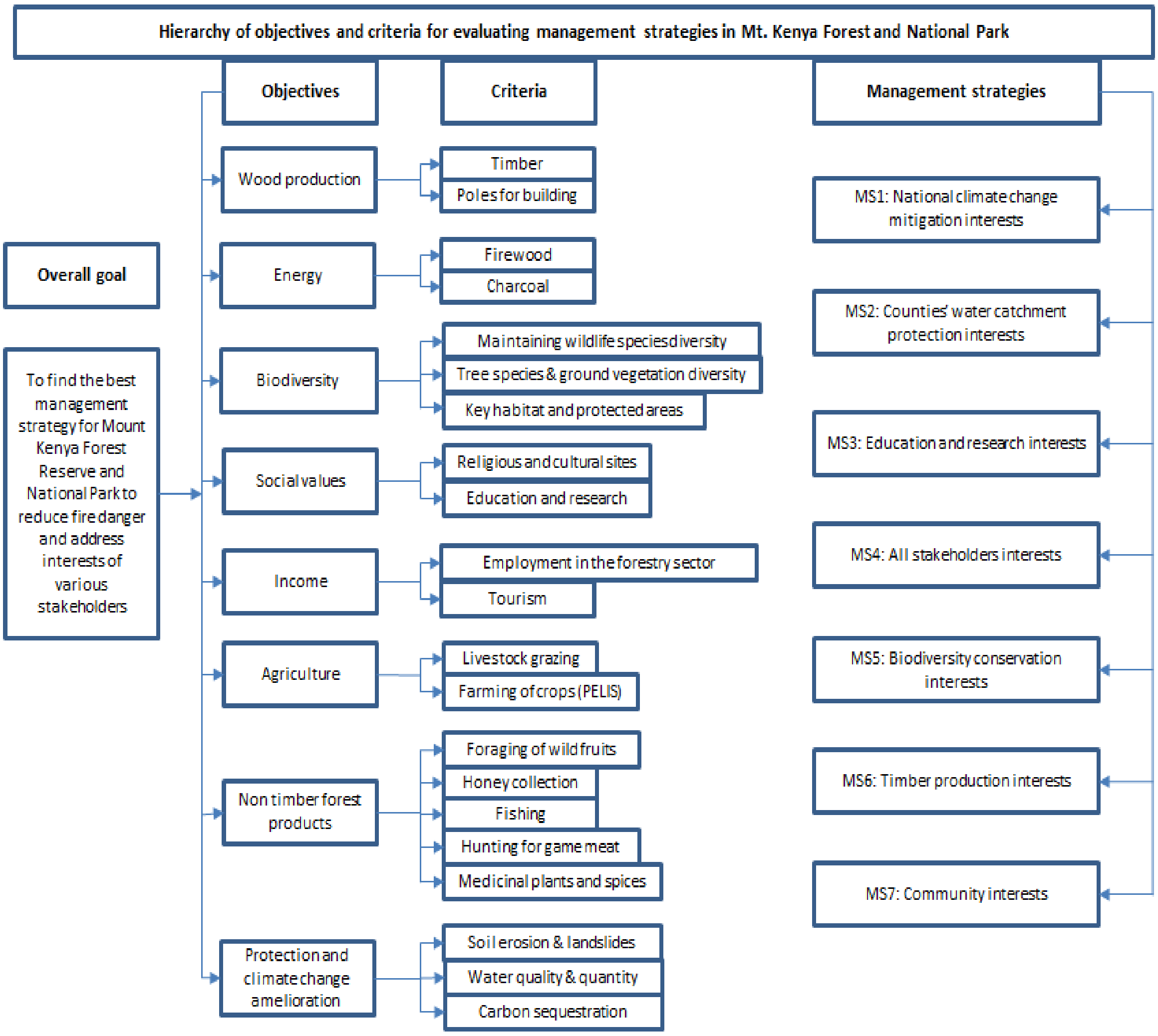

Figure 3. Evaluation hierarchy of the objectives and criteria for selecting the best management strategy in MKFRNP.

2.2.5. Elicitation of Preferences

In the fifth step, the bottom-up approach was used to identify the preferences of the regional and local FGDs participants from the seven forest stations in MKFRNP. A brief introduction about the need for a participatory evaluation of the O&C by all FGDs participants was given by the facilitators. The participants were divided according to their level of expertise and interests, so as to obtain priorities and minimize cases of individuals or certain groups trying to dominate the discussions during local FGDs [25]. Some FGDs' participants were very confident in expressing the importance of certain O&C, while others were challenged by the need to select the most relevant objectives. At the end of the evaluation process, the FGD's participants in each forest station had expressed their priorities by scoring (from 0 to 100) the objectives and criteria at each level. The scores provided by the FGDs participants were later on used to calculate the mean values for each criterion in the seven forest stations in MKFRNP.

2.2.6. Qualitative Assessment of the Developed Management Strategies

At the sixth stage of the local FGDs, the communities were supported by the facilitators to understand how the human activities to obtain several goods and services in MKFRNP are causing wildfires, degradation, influencing tree species composition and endangering wildlife populations. The participants discussed the strengths and weaknesses of the nine developed management strategies. They all shared different views as to which management strategy would best fulfill the different interests of all the stakeholders, overcome the main problems, ensure participation in decision making, as well as minimize the perceived future threats. After intensive discussions, the regional and local FGDs finally selected seven management strategies with the help of the facilitators (Appendix A). Based on their input, the seven management strategies were assessed qualitatively with the help of experts. They evaluated the effect of each management strategy on how it would reduce the fire danger in MKFRNP according to the following statements: "to a very great extent", "to a great extent", "to some extent", "to a little extent", "to a very little extent" or "to no extent" (Table 1). Additionally, the effect of the management strategies on the benefits obtained by stakeholders in MKFRNP was qualitatively assessed based on the defined set of objectives and criteria according to the following statements: "has a positive impact", "has a negative" or "has no impact" (Table 2). The qualitative assessment of the seven management strategies provided the input for the evaluation with the AHP.

Table 1. Evaluation of the seven management strategies and their Integrated Fire Management (IFM) activities qualitatively with regard to objectives and criteria.

IFM Activities Management Activities	Targets	MS1	MS2	MS3	MS4	MS5	MS6	MS7
1. Increase stakeholder participation in IFM decision making;	1.1-Government departments and ministries,	+++++	++++	++++	+++++	+++	+++	++
	1.2-Communities,	++	+	+	+++++	+++++	+	+++++
	1.3-International agencies,	+++++	+++	+++	+++++	++++	+	+++
	1.4-NGOs,	+++	+	+	+++++	+++++	+	+++++
	1.5-Conservationists	+++	+	+++	+++++	+++++	+	+++++
2. Reduce fire hazards and danger (particularly in and around communities and other high value areas)	2.1-Clean up dry litter accumulations	+++	++++	0	++++	+++++	+++	+
	2.2-Close fire prone areas in dry season	+++++	+++++	0	+++++	+++	++++	+
	2.3-Handle inflammable materials safely	+++++	+++++	0	+++++	+++	++++	+
	2.4-Establish firebreaks and forest roads	+++++	+++++	0	+++++	+++	+++++	+
	2.5-Provide adequate equipment	+++++	+++++	0	+++++	+++	+++	+
	2.6-Train fire crews	+++++	+++++	+++++	+++++	+++	++++	+
	2.7-Establish less fire prone vegetation	+++++	+	+	+++	+++	++	+
3. Carefully use prescribed burning where the benefits are clearly defined;	3.1-Establish fire lines	+++++	++++	+++	+++++	+++	+++	+
	3.2-Monitor fuel and weather conditions	+++++	++++	++++	+++++	++++	+++	+
	3.3-Controlled burning of agricultural lands	+	+	+	++++	++++	+	+++++
	3.4-Controlled burning of grassing grounds	+	+	+	++++	+++++	+	+++++
	3.5-Controlled burning of timber slash	+	+	+	++++	+	+	+
4. Monitor & manage fire on communities land and forests;	4.1-Construct look out towers	+++++	+++	0	+++++	+++	+++	+
	4.2-Deploy fire monitoring crew/ scouts	+++++	++++	0	+++++	++++	+++	+++
	4.3-Establish access to water sources	+++++	+++++	0	+++++	+++	+++	+
	4.4-Evacuate people	+++++	+++++	0	+++++	+	+++	+
5. Integrate fire management programs that control invasive plant species;	5.1-Prevention	+++++	++++	+	++++	+++++	+++	+
	5.2-Chemical control	++	++	+	++	++++	+	+
	5.3-Manual control	+++++	++++	+	+++++	+++++	+++	+++
	5.4-Cultural control/ competition	+++	+++	+	++++	+++++	+++	+
	5.5-Biological control	+++	+++	+	+++	+++++	+	+
6. Minimize outbreaks of non-ecological fires in hydrophobic soils;	6.1-Protection plans	+++	+++	+	+++++	+++++	+++	+
	6.2-Protection maps	++++	++++	+	+++++	+++++	+++	+
	6.3-Prevention of erosion	++++	+++++	0	+++++	++++	+++	++
	6.4-Prevention of loss of organic-rich soils	+++++	++++	0	++++	++++	+++	++
7. Incorporate land use & forest managers, CFAs and policy actors in IFM	7.1-Land use planning	+++++	+++	+	+++++	++++	+++	++
	7.2-Forest resource management planning	++++	+	++	+++++	++++	++++	+
	7.3-Community participation in IFM	+	+	+	+++++	+++	+	+++++
	7.4-Laws, policy, institutional framework	+++++	+++++	++	+++++	++++	++++	+
8. Develop a high level of public awareness and support for IFM;	8.1-Public meetings and social groups	+++++	++++	+	+++++	++++	+++	+++++
	8.2-Posters & sign boards	+++++	+++++	++	+++++	++++	+++	+++
	8.3-Radio	+++++	++++	+	+++++	++++	+++	+++
	8.4-TV	+++++	++++	++	+++++	++++	+++	+++
	8.5-Newspapers	+++++	++++	+++	+++++	+++	+++	+
	8.6-Internet	++++	+++	+++++	+++++	+++	+++	++
9. Incorporate traditional fire use and management practices when developing and implementing of IFM strategies;	9.1-Clearing land for PELIS	+++	0	0	+++++	0	++++	+++++
	9.2-Replenishing nutrients on farms	+	0	+	+++++	0	+	+++++
	9.3-Killing woody species in rangelands	+	+	0	+++++	+	+	+++++
	9.4-Encouraging grass growth	+	+	0	+++	++++	+	+++++
	9.5-Increasing wild seed production	+	+	0	+++	++++	+	+++++
	9.6-Honey collection	+	+++	0	++++	++	+	+++++
	9.7-Hunting	+	+++	0	+++	+++++	+	+++++
10. Reducing IFM costs	10.1-Staff salaries	+++	+++	+	++	+++++	+++	++++
	10.2-Equipment purchase	+++	+	0	+++	+++++	++	++
	10.3-Repair and maintenance	+++	+	0	+++	+++++	+++	++
	10.4-Fuel costs	+++	+	0	+++	+++++	++	+++

+++++ to a very great extent, ++++ to a great extent, +++ to some extent, ++ to a little extent, + to a very little extent, 0 to no extent.

According to the evaluation of the seven management strategies (Table 1) and their contribution to Integrated Fire Management activities MS4 (all stakeholder interests) showed the highest number of activities followed by MS5 (biodiversity conservation interests) and MS1 (national climate change mitigation interests). For the qualitative assessment of the management strategies according to the objectives and criteria to increasing the benefits obtained in MKFRNP the stakeholders indicated that MS3 (Education and research interests) has almost no impact, while MS6 (timber production interests) showed even several negative impacts (Table 2).

Table 2. Qualitative assessment of the seven management strategies (MS) based on objectives and criteria (O&C) to determine how they contribute to increasing the benefits obtained in MKFRNP.

Objectives	**Criteria**	**MS1**	**MS2**	**MS3**	**MS4**	**MS5**	**MS6**	**MS7**
1. Wood production	1.1 Timber	+	-	0	+	-	+	+
	1.2 Poles	+	-	0	+	-	+	+
2. Energy	2.1 Firewood	-	-	0	+	-	+	+
	2.2 Charcoal	-	-	0	-	-	-	+
3. Biodiversity	3.1 Maintaining wildlife species diversity	0	+	+	+	+	-	-
	3.2 Maintaining vegetation species diversity	+	+	+	+	+	-	-
	3.3 Key habitat and protected areas	+	+	0	+	+	-	-
4. Social values	4.1 Religious and cultural sites	0	0	0	+	+	0	+
	4.2 Education and research	+	+	+	+	+	0	0
5. Income	5.1 Employment in the forest sector	+	+	+	+	-	+	+
	5.2 Tourism	0	0	0	+	+	-	+
6. Agriculture	6.1 Farming of crops (PELIS)	+	-	0	+	0	+	+
	6.2 Livestock grazing	-	-	0	+	-	+	+
7. Non timber forest products	7.1 Foraging wild fruits	0	0	0	+	+	-	+
	7.2 Honey collection	+	+	0	+	+	-	+
	7.3 Fishing	+	+	0	+	+	-	+
	7.4 Hunting of game meat	-	-	0	-	-	-	+
	7.5 Medicinal plants and spices	+	+	+	+	-	-	+
8. Protection and climate change amelioration	8.1 Soil erosion and landslides	+	+	0	+	+	+	+
	8.2 Water quality and quantity	+	+	0	+	+	-	+
	8.3 Carbon sequestration	+	+	0	+	+	+	-

+ has a positive impact, - has a negative impact, 0 has no impact.

2.2.7. Final Evaluation of the Management Strategies with the Analytical Hierarchy Process (AHP)

With the AHP, pairwise comparisons are made among a defined set of alternative options with regard to an evaluation hierarchy, to provide a cardinal ranking of the alternatives [14]. The technique allows the consistency of the decision makers' evaluations to be checked, thus reducing a potential bias in the elicitation process. Since some of the criteria are always contrasting, the best option is not the one which optimizes each single criterion, rather the one which achieves the most suitable trade-off among the different criteria [14]. The AHP was used to calculate weights for all objectives and criteria of the defined evaluation hierarchy (O&C) based on the preferences that were expressed by the FGDs participants. The higher the weight, the more important the corresponding criterion will be. Finally, the AHP allowed combining the preferences of the seven management strategies with the criteria weights and thus determining a global priority for each strategy.

The pairwise comparisons were not carried out at the field level, due to their complexity, as other studies have described problems related to their time-consuming nature [12]. The mean values for each criterion in the seven forest stations were calculated by the experts based on the scores provided by the participants of the FGDs. The mean values of the scores derived from the FGDs' participants had to be transferred to pairwise comparisons. The scores provided for the objectives and criteria were used to calculate the preferences of the objectives and criteria in the AHP, assuming that the objectives and criteria with a highest score are of higher importance. The qualitative assessment, which provided for the evaluation of the performance of the management strategies (Table 2) was used to derive the preferences for the seven options. The options were ordered according to the qualitative assessment and the preference values were calculated for each strategy for each criterion in the hierarchy using the Expert Choice Software. This helped to identify the best performing management strategies and potential trade-offs with regard to different preferences.

3. Results

3.1. Scoring of Objectives and Criteria by FGDs Participants

The scores (0–55) represent the mean values for each criterion in the seven forest stations that were calculated by the experts based on the scores provided by the participants in the FGDs that were held at the local level. It was found out that the objectives with the highest mean values of the scores are of higher importance. The scores indicate that in all forest stations, firewood got the highest scores, followed by farming (PELIS) and livestock grazing. Water quality/quantity and maintaining vegetation species diversity are ranked third place, timber harvesting was ranked fourth, employment in the forest sector was ranked fifth and tourism was ranked sixth. However, fishing was ranked second last and hunting was ranked last (Table 3).

Table 3. Importance of the Objectives and Criteria in the seven forest stations based on the scores provided by the participants in the focus group discussions (FGDs).

Current management objectives	Benefits obtained by various stakeholders in MKFRNP	Forest stations according to their fire danger						
		Very high fire danger			High fire danger	Moderate fire danger	Low fire danger	
		Marania	Ontulili	Gathiuru	Nanyuki	Naru moru	Hombe	Chehe
1. Wood production	1.1 Timber	40	25	30	25	35	30	0
	1.2 Poles for building	15	20	20	20	15	10	5
2. Energy	2.2 Firewood	45	45	45	45	50	45	55
	2.3 Charcoal	5	5	5	5	10	5	5
3. Biodiversity conservation	3.3 Maintaining wildlife species diversity	25	25	25	25	25	25	30
	3.4 Maintaining vegetation species diversity	25	35	25	35	35	30	35
	3.5 Key habitat & protected areas	20	15	20	20	15	15	30
4. Social values	4.1 Religious & cultural sites	5	5	5	10	10	5	25
	4.2 Education & research	5	5	5	5	5	5	5
5. Income	5.1 Employment in forestry sector	20	30	35	20	25	30	35
	5.2 Tourism	30	20	20	30	20	20	5

6. Agriculture	6.1 Livestock grazing	35	30	35	35	40	30	35
	6.2 Farming of crops (PELIS)	35	40	45	35	30	45	0
7. Non timber forest products	7.1 Foraging of wild fruits	5	10	5	5	5	10	10
	7.2 Honey collection	20	20	15	25	5	15	20
	7.3 Fishing	5	0	5	5	5	0	0
	7.4 Hunting of game meat	0	0	0	5	0	0	0
	7.5 Medicinal plants & spices	5	10	5	5	5	10	10
8. Protection, water and climate change amelioration	8.1 Prevention of soil erosion & landslides	25	15	15	20	20	20	35
	8.2 Water quality and quantity	30	30	35	25	35	25	35
	8.3 Carbon sequestration	15	15	15	10	10	15	10

3.2. Preferences of Objectives and Criteria for Different Fire Danger

The priorities of the objectives according to the fire danger categories (reference scenario, very high fire risk, high fire risk, moderate fire risk, and low fire risk) vary. For the "reference" scenarios of all the eight objectives were equally weighted (1/8 = 0.125). We found that the biodiversity conservation objective was ranked first for all four scenarios, agriculture was ranked second for forest stations with a very high and moderate fire danger, climate change amelioration was ranked second for forest stations with a high and a low fire danger (Figure 4).

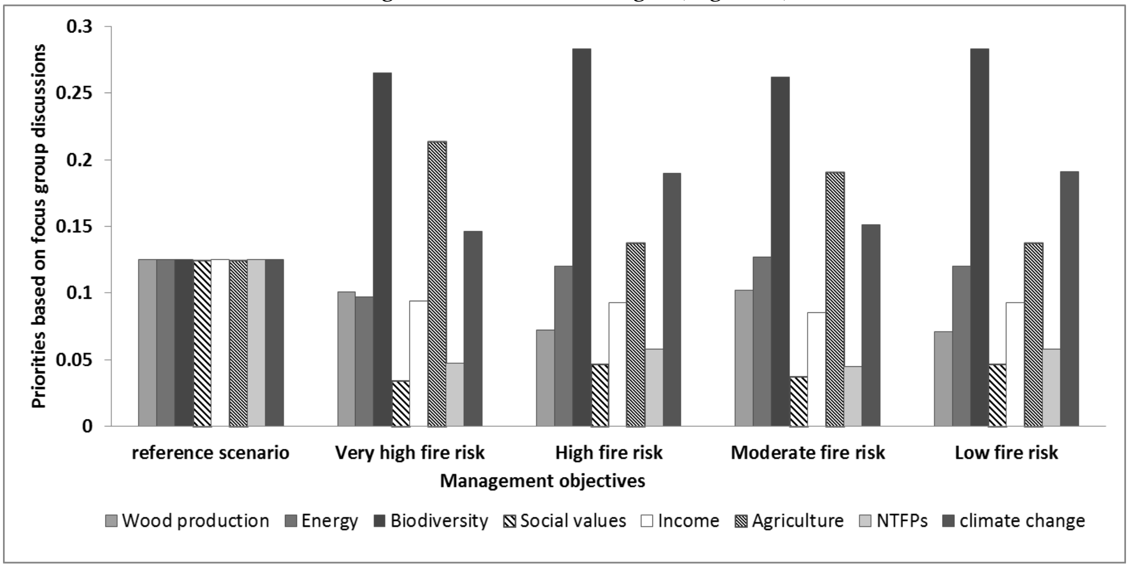

Figure 4. Priorities of management objectives according to the fire danger categories.

The priorities of the criteria according to the fire danger categories (reference scenario, very high fire risk, high fire risk, moderate fire risk, and low fire risk) also vary. We found that firewood, timber, livestock grazing and employment in the forest sector are highly preferred criteria in the seven forest stations according to the preferences derived by the PWC with the AHP (Appendix C).

3.3. Priorities of the Management Strategies

The priorities of the management strategies according to the fire danger categories (reference scenario, very high fire risk, high fire risk, moderate fire risk and low fire risk) are presented in Figure 5. We found out that although the seven forest stations had a different fire danger, all the FGDs participants rated MS7 (community interests) first based on the weights given to all objectives and criteria. Only in the reference scenario (with equal weights for all objectives) was the MS5 (biodiversity conservation) ranked first. The second and third ranked strategy for the four different fire danger categories were MS5 (biodiversity conservation) and MS4 (all stakeholders interests) respectively. The MS3 (education and research) was classified as the least preferred strategy in each case.

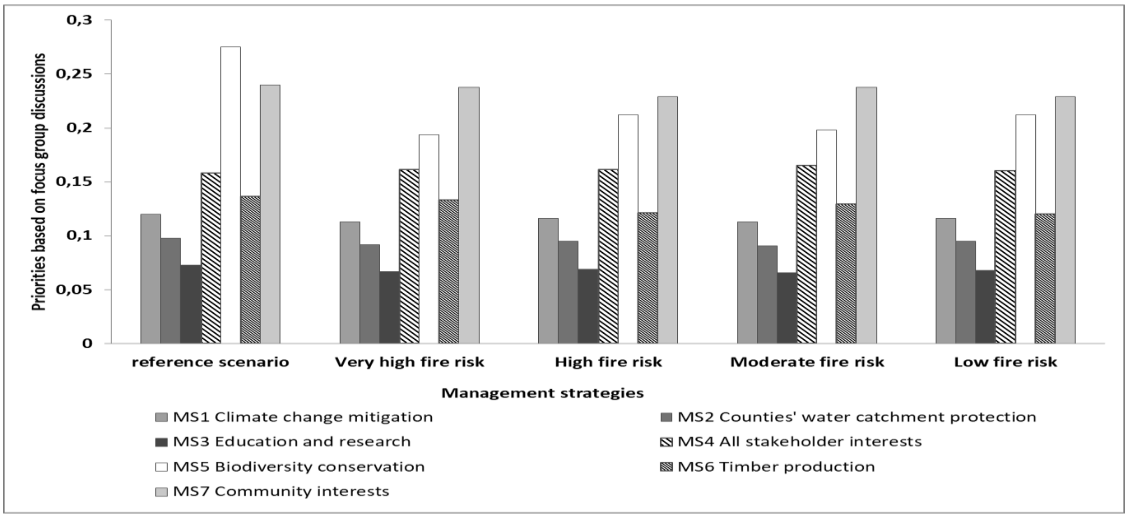

Figure 5. Priorities of the seven management strategies for the reference scenario and the four fire danger categories.

4. Discussion

4.1. Use of MCA in the evaluation of Management Strategies

Our analysis provides important insights into the application of a MCA approach to develop management strategies, objectives and criteria that can be used to identify, structure, monitor and evaluate the best management strategy that will help to reduce fire danger and increase the benefits obtained in MKFRNP. Other studies have also shown that MCA is both an appropriate and useful approach for capturing diverse views, objectives and perspectives of different stakeholders involved in decision making [14].

The careful selection of FGD participants during the study, helped to develop and evaluate the seven management strategies based on the identified objectives. A team of professional experts in the application of MCA techniques was selected and made responsible for supporting the process of comparing management strategies. The interaction between the facilitators, FGDs' participants, and experts was undertaken by having a high number of meetings within a short period of time [26]. However, it was found out that the FGDs' participants were had difficulties in expressing their preferences with regard to the management strategies, and importance of objectives and criteria. Many of them were not familiar with the forestry and wildlife terms that were used in the qualitative evaluation, while others did not understand well how the scoring and ranking of the developed management strategies, objectives and criteria was to be done and this made the exercise challenging and time-consuming. The developed management strategies varied both in the temporal and spatial scale to meet the various stakeholder interests and this made it even more difficult for the participants to evaluate the strategies. Another observation was that some FGDs' participants only preferred objectives that required a shorter time to be achieved and therefore had strong interests in having them implemented [9,27]. This indicates that the best management strategy that is applicable on the entire area of MKFRNP has to help reduce the fire danger and consider both the short term and long-term interests of the different stakeholder groups for it to be accepted and implemented [9,13].

The facilitators used a mixture of a bottom-up and a top-down approaches during the regional and local FGDs. This allowed for keeping a consistent overall framework for the evaluation, while including inputs from the participants in a participatory way. The FGDs' participants were able to express their own preferred management strategies, objectives and criteria and appropriately address some of the challenges in the qualitative assessment. This helped to accurately structure the problem, increase transparency and improve the quality of the decision-making process by contributing to a participatory implementation [9,12].

The use of MCA for evaluating the management strategies for implementation in MKFRNP helped to address the stakeholder interests and provided a framework for evaluating trade-offs in a transparent and understandable way [9,28,29]. The application of the MCA allowed the team of experts to come up with solutions which resulted in higher level of overall stakeholder satisfaction [12].

Several studies have shown that the use of the AHP can impose several challenges, as it can be time-consuming when scores and ranking of the participants are transferred to pairwise comparisons [9,25,30]. AHP allows the use of both qualitative and quantitative information when comparing the performance of alternatives [14]. However, very often it is not possible to consider quantitative information in assessing management strategies with regard to the effectiveness to fire management or in improving the livelihood conditions. Therefore, transferring the qualitative ratings to pairwise comparisons is useful [12]. The analysis with the AHP allowed for the sensitivity of each management strategy to be identified by varying the weights assigned to each objective.

4.2. Performance of Management Strategies

MS1 (national climate change mitigation interests), MS5 (biodiversity conservation interests) and MS6 (timber production interests) are long term management strategies. MS2 (counties' water catchment protection interests), MS3 (education and research interests), MS4 (all stakeholder interests) and MS7 (community interests) are short-term management strategies. However, the results indicate that MS5 and MS7 are almost equally preferred. This indicates that long and short-term aspects are considered as relevant by the various stakeholders. To achieve sustainable management of MKFRNP, other programmes should offer a similar degree of importance for the improvement of community livelihoods [31]. Objectives such as wood production, biodiversity conservation, protection, and climate change amelioration require long-term management to provide positive outcomes and meet various stakeholder interests. However, energy, social values, income, agriculture and non-timber forest products require short-term management activities [9,32].

The current management strategies being implemented by resource managers have focused more on the conservation of biodiversity and have paid less attention to fulfilling other objectives such as wood production, energy, social values, non-timber forest products, protection and climate change amelioration [33]. The KFS and CFAs have been implementing the Mount Kenya Forest Reserve (MKFR) management plan 2010–2019 that considers sustainable management, including conservation and rational utilization of the forest resources for socio-economic development [1]. On the other hand, the KWS has been implementing the Mount Kenya Ecosystem (MKE) management plan 2010–2020 that has Ecological Management programme that aims at addressing biodiversity restoration and protection, linking ecosystems, and carrying out applied research to understand how the ecosystem functions [1]. Biodiversity conservation is seen as basis for the functionality of MKFRNP ecosystem including fuel wood, soil fertility, water, timber, poles, wildlife, tree species, agriculture, non-timber forest products, protection, climate change amelioration, culture and scenery [9,34,35]. Since MS5 is effective in conserving biodiversity, reducing fire danger and increasing the benefits, it has the greatest likelihood of being socially, economically and politically acceptable. When MS5 is fully implemented in MKFRNP, it is possible that many of the current management problems might be reduced [9]. However, although the biodiversity conservation objective is ranked first by all the participants of the FGDs, the results of the analysis indicate that MS7 (community interests) is the most preferred management strategy followed by the MS5 (biodiversity conservation interests). This means that the resource managers will have to work closely with all stakeholders so that the selected management strategy addresses threats like poaching of wildlife and control of wildfires, which threatens all conservation targets and requires long-term monitoring as well [1].

Agriculture was ranked as the second most relevant objective and therefore it is obvious that MS7 (community interests) was more preferred by the FGDs' participants. This is in line with other studies that have shown that communities in developing countries are more concerned with socio-economic activities aimed at achieving their livelihood benefits such as employment, farming activities, firewood collection, water collection, grazing, honey collection, tourism, herbal medicine, hunting or timber production [36–38]. During preference elicitation, the FGDs participants scored hunting low because it is prohibited by law to hunt in MKFRNP. Some community members have been prosecuted for being involved in wildlife poaching, by getting imprisoned and or paying heavy fines [5]. Most of the community members living around MKFRNP prefer growing food crop, cash crop and keeping livestock and these are reasons why fishing was scored low by FGDs participants [4]. Fishing in MKFRNP's rivers, dams and lakes is legal but only a few small-scale farmers around MKFRNP have initiated fish farming projects for the growing market especially in the local hotel industry [4]. The growing population and the increasing human demands pose a serious question as to how long this management strategy may address the growing stakeholder interests [5]. The findings of this study show that the decision-makers and policy actors need to consider biodiversity and community interests in the decision-making process. This will allow them to select and implement the best management strategy that reduces fire danger and increases the benefits obtained in MKFRNP.

5. Conclusions

This is the first time that O&C have been developed for assessing management strategies in MKFRNP through a participatory process with all stakeholders. Due to the shortage of time, limited number of experts in stakeholder groups and the limited number of reliable data sources available, this limits the results of our study to some extent. However, because of the quite robust results, it can be assumed that the findings are applicable to other forests stations as well. It is possible to adapt the evaluation framework and revise the management strategies based on a more widely-based discussion with different stakeholder groups. Applying O&C assessments for the sustainable management of MKFRNP has the potential to reduce the information gap between decision-makers at the local and national levels.

In the year 2014, the parliament of Kenya passed the county governments' fire and disaster management bill that prepared the ground for the country to establish and implement integrated fire management approaches in the future [4]. Even though the Kenya Grass Fire Act, Cap 327, provides a regulation for planned burnings of bushes, shrubs, grass, crops, and stubble within protected areas, the KFS and KWS have continued to practice fire suppression campaigns instead of using prescribed burning activities to manage fuel accumulation in MKFRNP [4]. This is mainly based on the belief that any disturbance, such as fire, disrupts the progress towards an equilibrium state [4]. Total fire suppression and other human-caused environmental changes have resulted in huge and catastrophic wildfires in MKFRNP [7].

The performance of the management strategies might be different in other forests and national parks in Africa, where conditions are slightly different and where different views of stakeholders may be present. However, our study presents recommendations for further policy options that consider forest health, productivity and socio-economic values, as basic requirements for improving the livelihoods of the people. Moreover, forest and wildlife management need to take into account how the involvement of the local communities in the decision-making process could be developed, with the main goal of stimulating the development of commonly accepted management strategies for MKFRNP. Resource managers can make better management decisions in the future to ensure that: rare and threatened species are protected, restored and monitored; habitats are protected, preserved and restored; ecosystem connectivity is established to increase resilience; and Mt. Kenya ecosystem functioning is understood [5,15]. Further research needs to be carried out in other forest and national parks in Kenya, as different stakeholder interests, vegetation and wildlife species, and threats require adapted management strategies and a revised evaluation framework.

40. **Author Contributions:** K.W.N. and H.V. worked jointly on the study design, including guidelines for the focus group discussions; Kevin W. Nyongesa performed the interviews and facilitated the focus group discussions; K.W.N. and H.V. analyzed the data; K.W.N. wrote the paper; and H.V. contributed to the paper.

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Appendix A: Developed management strategies (MS) and the main activities that need to be implemented in MKFRNP

Table A1. Developed management strategies (MS) and the main activities that need to be implemented to reduce fire danger and increase the benefits obtained in MKFRNP.

Developed management strategies (MS)	Management activities in MKFRNP	Integrated Fire Management (IFM) activities in MKFRNP
1. MS1 Climate change mitigation interests	1.1-Increasing the capacity of carbon sinks through reforestation for timber and poles; 1.2-Reducing deforestation by arresting and prosecuting those involved in illegal logging and encroachment of settlements in to MKFRNP 1.3-Educating communities on adaptation and mitigation of climate change through the local media and village meetings	**1. Increase stakeholder participation in IFM decision-making;** 1.1-Government departments and ministries, 1.2-Communities, 1.3-International agencies, 1.4-NGOs, 1.5-Faith based organizations (FBOs), 1.6-Conservationists **2. Reduce fire hazards and danger (particularly in and around communities and other high-value areas);** 2.1-Clean up litter and rubbish accumulations 2.2-Reduce fuel loads (deadwood, grass) 2.3-Close hazardous areas to use during periods of extreme fire weather conditions 2.4-Handle inflammable materials safely 2.5-Establish firebreaks 2.6-Construct forest roads 2.7-Provide adequate equipment 2.8-Train fire crews 2.9-Establish less fire prone vegetation **3. Carefully use prescribed burning where the benefits are clearly defined and the danger can be cost-effectively managed;** 3.1-Establish fire lines 3.2-Monitor weather conditions 3.3-Monitor fuel conditions 3.4-Controlled burning of agricultural lands
2. MS2 Counties' water catchment protection interests	2.1-Increasing the quantity, improving the quality of water by planting trees in deforested areas, by arresting and prosecuting those involved in illegal logging, encroachment of settlements and illegal cultivation in water catchments; 2.2-Ensuring the existence and implementation of watershed management regulations by the counties' water ministries and watershed management groups in conjunction with CFAs; 2.3-Managing sloping lands properly by planting trees, bamboo and grasses to reduce soil erosion and landslides in MKFRNP	
3. MS3 Education and research interests	3.1-Improving skilled scientific research capacities by collaborating with institutions of education and research like KEFRI, local and international universities; 3.2-Providing well defined information in precautionary and protective measures to resource managers on weather conditions (droughts, temperature, precipitation, storms), pests, diseases, fires and invasive species; 3.3-Exchanging of technology and expertise knowledge on how to use modern forestry equipment, provide open access to education and research information on MKFRNP	
4. MS4 All stakeholder interests	4.1-Promoting ownership and user rights by providing equal opportunities to all stakeholder groups through registration and provision of licenses; 4.2-Strong law enforcement capacity by employing more rangers, fire patrol crews to arrest and prosecute all people involved in activities such as poaching of wildlife, illegal timber logging, illegal water abstraction, illegal charcoal burning, illegal burning of farmlands and grasslands without permission;	

	4.3-Participate in policy establishment and awareness creation at local and national level through discussion forums, engaging political members to lobby for policy reforms in forestry and wildlife sector, strengthening multi-level institutional participation in policy formulation and ensuring local people participate in decision making as stipulated in the policy documents on participatory management of MKFRNP	3.5-Controlled burning of grassing grounds 3.6-Controlled burning of timber slash **4. Monitor and manage, rather than suppress, fires that are of minimal danger to communities, infrastructure or resource values;** 4.1-Construct look out towers
5. MS5 Biodiversity conservation interests	5.1-Ensuring the trees species diversity is conserved and the endangered tree species are protected from illegal loggers through increased patrols, arrest and prosecution of culprits; 5.2-Ensuring the wildlife species diversity is conserved and the endangered wildlife (Rhinos, elephants) are protected from poachers through increased patrols, arrest and prosecution of culprits; 5.3-Key wildlife habitats are protected from human destructive human activities through increased patrols, arrest and prosecution of culprits involved in destruction of key wildlife habitats through illegal grazing, illegal farming, illegal charcoal burning, illegal timber logging and illegal wildlife hunting; 5.4-Reduction and control of invasive alien plant and animal species through prevention, chemical control, manual control, cultural control or competition and biological control in MKFRNP	4.2-Fire monitoring crew/ scouts 4.3-Establish access to water sources 4.4-Evacuate people **5. Integration of fire management programs aimed at the reduction and control of invasive alien plant species;** 5.1-Prevention 5.2-Chemical control 5.3-Manual control 5.4-Cultural control/ competition 5.5-Biological control **6. Minimize the potential occurrence of**
6. MS6 Timber production interests	6.1-Improving the quality of timber produced by thinning and pruning, establishing more timber plantations in deforested areas through PELIS; 6.2-Ensuring timber resource inventories are conducted and timber logs are well priced; 6.3-Managing of wildfires in timber plantations by reducing fuel loads through firewood collection, cutting grass to feed livestock and controlling the use of fire by farmers during land preparation; 6.4-Protect timber plantations from illegal loggers through increased patrols, arrest and prosecution of culprits; 6.5-Reducing game damage on timber plantations through installation of electric fences; 6.6-Ensuring fare allocation of CFAs the harvested areas for plantation establishment and livelihood improvement scheme (PELIS) by considering their registration and participation in management activities	**ecological undesirable fires in ecosystems that have hydrophobic soils;** 6.1-Protection plans 6.2-Protection maps 6.3-Prevention of erosion 6.4-Prevention of loss of organic-rich soils **7. Incorporate land use, forest resource, catchment area and community planning in IFM activities at all appropriate scales;** 7.1-Land use planning 7.2-Forest resource management planning 7.3-Community participation in fire management
7. MS7 Community interests	7.1-Enhancing CFA members participation in fire management by providing training in fire monitoring and firefighting; 7.2-Training CFA members to improve farming of crops and planting of trees under (PELIS), beekeeping in forest to improve their livelihoods; 7.3-Training and supervising CFAs on when to use fire during the farming (PELIS) and honey collection activities within the forest to minimize cases of uncontrolled wildfires;	7.4-Laws, policy and institutional framework **8. Develop a high level of public awareness and support for IFM;** 8.1-Public meetings 8.2-Posters 8.3-Sign boards

	7.4- Enhancing formation of more CFAs so that they can participate in programmes aimed at encouraging use of fuel efficient wood stoves, payment of firewood collection revenue, payment of livestock grazing revenue, payment of herbal medicine collection revenue, 7.5- Encouraging communities to participate monitoring and reporting of timber and wildlife poaching activities by giving them jobs or incentives; 7.6-Enhancing community user rights through establishment of regulations on who has the right to access and use certain resources and to what extent they can use them without depleting or degrading the resources; 7.7-Encouraging community participation in decision making through open discussion forums, FGDs, voting and voicing of their concerns over certain management decisions that contradict their interests; 7.8-Allowing firewood collection, cutting of grass to feed livestock and livestock grazing to reduce fuel loads in MKFRNP	8.4-Radio 8.5-TV 8.6-Newspapers 8.7-Internet 8.8-Social groups **9. Incorporate traditional fire use and management practices when developing and implementing of IFM strategies;** 9.1-Clearing land for agricultural fields 9.2-Replenishing soil nutrients in agricultural fields 9.3-Killing woody species in rangelands 9.4-Encouraging grass growth 9.5-Increasing wild seed production 9.6-Honey collection 9.7-Hunting **10. Reducing IFM costs** 10.1-Staff salaries 10.2-Equipment purchase 10.3-Repair and maintenance 10.4-Fuel costs

Appendix B: The current management objectives in the seven forest stations in MKFRNP

Table B1. The current management objectives that are being implemented by the KFS and KWS and benefits obtained by various stakeholders in the seven forest stations in MKFRNP.

Current management objectives	Benefits obtained by various stakeholders in MKFRNP	Forest stations according to their fire danger						
		Very high fire danger			High fire danger	Moderate fire danger	Low fire danger	
		Marania	Ontulili	Gathiuru	Nanyuki	Naru moru	Hombe	Chehe
1. Wood production	Timber	Y	Y	Y	Y	Y	Y	N
	Poles for building	Y	Y	Y	Y	Y	Y	Y
2. Energy	Firewood	Y	Y	Y	Y	Y	Y	Y
	Charcoal	N	N	N	N	N	N	N

3. Biodiversity conservation	Maintaining wildlife species diversity	Y	Y	Y	Y	Y	Y	Y
	Maintaining tree species & ground vegetation diversity	Y	Y	Y	Y	Y	Y	Y
	Key habitat and protected areas	Y	Y	Y	Y	Y	Y	Y
4. Social values	Religious and cultural sites	Y	Y	Y	Y	Y	Y	Y
	Education and research	Y	Y	Y	Y	Y	Y	Y
5. Income	Employment in forestry sector	Y	Y	Y	Y	Y	Y	Y
	Tourism	Y	Y	Y	Y	Y	Y	N
6. Agriculture	Livestock grazing	Y	Y	Y	Y	Y	Y	Y
	Farming of crops (PELIS)	Y	Y	Y	Y	Y	Y	N
7. Non timber forest products	Foraging of wild fruits	Y	Y	Y	Y	Y	Y	Y
	Honey collection	Y	Y	Y	Y	Y	Y	Y
	Fishing	N	N	Y	Y	Y	N	N
	Hunting of game meat	N	N	N	N	N	N	N
	Medicinal plants and spices	Y	Y	Y	Y	Y	Y	Y
8. Protection, water and climate change amelioration	Prevention of soil erosion and landslides	Y	Y	Y	Y	Y	Y	Y
	Water quality and quantity	Y	Y	Y	Y	Y	Y	Y
	Carbon sequestration	Y	Y	Y	Y	Y	Y	Y

Where Y = Yes and N = No

Appendix C: Priorities of the criteria after the PWC using AHP

Table C1. Priorities of the criteria in the seven forest stations according to the four fire danger categories after pairwise comparison (PWC) by AHP.

Objectives	Criteria	Null	Very high fire danger	High fire danger	Moderate fire danger	Low fire danger
		Priorities	Priorities	Priorities	Priorities	Priorities
1. Wood production	1.1 Timber	0.500	0.750	0.667	0.667	0.667
	1.2 Poles	0.500	0.250	0.333	0.333	0.333
2. Energy	2.1 Firewood	0.500	0.833	0.833	0.833	0.833
	2.2 Charcoal	0.500	0.167	0.167	0.167	0.167
3. Biodiversity conservation	3.1 Maintaining of wildlife species	0.333	0.327	0.311	0.327	0.311
	3.2 Tree species and ground vegetation diversity	0.333	0.413	0.493	0.413	0.493

	3.3 Key habitat and protected areas	0.333	0.260	0.196	0.260	0.196
4. Social values	4.1 Religious and cultural sites	0.500	0.500	0.667	0.667	0.667
	4.2 Education and research	0.500	0.500	0.333	0.333	0.333
5. Income	5.1 Employment in forestry sector	0.500	0.667	0.667	0.667	0.667
	5.2 Tourism	0.500	0.333	0.333	0.333	0.333
6. Agriculture	6.1 Farming of crops (PELIS)	0.500	0.667	0.333	0.333	0.333
	6.2 Livestock grazing	0.500	0.333	0.667	0.667	0.667
7. Non timber forest products	7.1 Foraging wild fruits	0.200	0.221	0.216	0.242	0.216
	7.2 Honey collection	0.200	0.342	0.360	0.242	0.360
	7.3 Fishing	0.200	0.135	0.097	0.242	0.097
	7.4 Game meat	0.200	0.081	0.090	0.030	0.090
	7.5 Medicinal plants and spices	0.200	0.221	0.236	0.242	0.236
8. Protection and climate change amelioration	8.1 Soil erosion and landslides	0.333	0.327	0.327	0.311	0.327
	8.2 Water quality and quantity	0.333	0.413	0.413	0.493	0.413
	8.3 Carbon sequestration	0.333	0.260	0.260	0.196	0.260

Firewood, timber, livestock grazing and employment in the forest sector are highly preferred criteria in the seven forest stations after PWC by AHP.

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7.4 Fire Management in Mount Kenya: A Case Study of Gathiuru Forest Station

forests

Article

Fire Management in Mount Kenya: A Case Study of Gathiuru Forest Station

Kevin W. Nyongesa * and Harald Vacik

Institute of Silviculture, University of Natural Resources and Life Sciences, Vienna (BOKU); Peter-Jordan-Strasse 82, A-1190 Vienna, Austria; Email: harald.vacik@boku.ac.at
* Correspondence: kevisson2005@yahoo.com; Tel.: +43-688-6059-9334

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Abstract: This paper proposes an Integrated Fire Management (IFM) framework that can be used to support communities and resource managers in finding effective and efficient approaches to prevent damaging fires, as well as to maintain desirable fire regimes in Kenya. Designing and implementing an IFM approach in Kenya calls for a systematic understanding of the various uses of fire and the underlying perceptions and traditional ecological knowledge of the local people. The proposed IFM framework allows different stakeholders to evaluate the risks posed by fires and balance them with their beneficial ecological and economic effects making it easier for them to develop effective fire management approaches. A case study of the proposed IFM framework was conducted in Gathiuru Forest, which that is part of the larger Mt. Kenya Forest Ecosystem. Focus group discussions were held with key resource persons, primary and secondary data on socio-economic activities was studied, fire and weather records were analysed and the current fire management plans were consulted. Questionnaires were used to assess how the IFM is implemented in the Gathiuru Forest Station. The results show that the proposed IFM framework is scalable and can be applied in places with fire-dependent ecosystems as well as in places with fire-sensitive ecosystems in Kenya. The effectiveness of the proposed IFM framework depends on the active participation, formulation and implementation of the IFM activities by the main stakeholder groups (Kenya Forest Service (KFS), Kenya Wildlife Service (KWS), and the Community Forest Associations (CFA). The proposed IFM framework helps in implementing cost-effective approaches to prevent damaging fires and maintain desirable fire regimes in Kenya.

Keywords: human activities; participation; firewood; charcoal; grazing; water; honey; farming; community forest association

1. Introduction

Anthropogenic fires have been common throughout the world since the discovery of fire [1] and almost every landscape has a complex history of human land use and natural disturbances [2]. The distinction between 'natural' and 'cultural' landscapes is not always obvious [3] because different communities around the world have been using fire as a tool in land management for many centuries to manipulate vegetation composition, structure, and fuel loads on farmlands, rangelands and other wildland ecosystems [4].

Many communities in Kenya use fire as a tool in land management. Perennial grassland fires are common in many parts of the country because each year during the dry season, communities set grasslands on fire to keep them open and to facilitate the growth of new grass for livestock, especially before the rain begins. Farmers in Kenya use fire to prepare farmlands, break impenetrable bushlands; control weeds, pests and parasites and try to keep wildlife away from homes. Bushland and forest fires are common in Kenya because some community members use fire to burn charcoal, harvest wild honey, and hunt and roast game meat in forests and national parks [5].

Several studies have been done on traditional ecological knowledge based fires and the uncertainty of success of fire exclusion policies [6-8]. Even though the Kenya Grass Fire Act, Cap 327, provides a regulation for planned burnings of bushes, shrubs, grass, crops, and stubble within protected areas, the KFS and KWS have however continued to practice fire suppression campaigns instead of using prescribed burning activities to manage fuel accumulation in forests and national parks of Kenya. This is mainly based on the belief that any disturbance, such as fire, disrupts the progress towards an equilibrium state. Total fire suppression, in combination with other human-caused environmental changes have resulted in huge and catastrophic wildfires in forests and national parks of Kenya [4].

Kenya's fast growing population is increasing the pressure on the available forest resources [9]. Human activities in forests to obtain firewood, charcoal, timber, poles, and grass for livestock have increased tremendously over the past three decades. Additional pressures arise from the demand for good quality water, land for the cultivation of crops, income from ecotourism, herbal medicine, game meat, and honey, among others [9]. As a result, all five key forested water towers (Mt. Kenya, Mt. Elgon, The Cherangani Hills, The Mau Forest Complex, and The Aberdares) have experienced human encroachment, land use change, wildfires, and degradation. The same applies to lowland and coastal forests [10].

The changing climate, vegetation dynamics, human activities, and forest management influence the occurrence of fires [11]. Despite compelling evidence on the role of climate change in influencing fire regimes through changes to temperature, rainfall, humidity, wind, and the amount of carbon dioxide in the atmosphere, humans are most often the leading cause of fire ignition [4]. Human caused fire ignitions in forests and national parks of Kenya are more likely to increase in the future because climate change may affect fire season length and severity [12]. On the other hand, most of the natural fires in forests and national parks of Kenya are generally started by lightning [4]. However, most of the fires caused by lightning are recorded under unknown causes, making it difficult to estimate their social, economic, cultural and ecological effects [4]. According to the KFS, the number of forest fire incidences has increased causing more damage to the forests, socio-economy, and environment. Ground fires, surface fires and crown fires have occurred in Kenyan grasslands, farmlands, bushlands, and forests [12]. As a response, the government of Kenya has initiated a participatory forest fire management program that involves collaboration between the KFS, Kenya Wildlife Service (KWS), the Kenya Defense Forces (KDF), the British Army, Community Forest Associations (CFAs), and other stakeholder groups to work together in forest fire prevention and suppression efforts. However, the termination of donor funding, limited governmental funds to tackle forest fire issues, the retrenchment of human resources within the KFS and KWS, and the lack of adequate equipment and well-trained firefighters have seriously affected the capacity to effectively suppress and combat wildfires [13].

In the year 2014, the parliament of Kenya passed the county governments' fire and disaster management bill that prepared the ground for the country to establish and implement IFM approaches in the future. Currently, there is no IFM policy in place that aims to address both damaging and beneficial fires by evaluating and balancing the associated risks. Existing fire management guidelines do not consider the development of concepts for planning and operational systems that combine prevention and suppression techniques while integrating the use of prescribed fires and traditional burning practices. There is a need to consider social, economic, cultural and ecological aspects in minimizing the damage of catastrophic fires and maximizing the benefits of prescribed fires [13].

Establishing and implementing Integrated Fire Management (IFM) approaches in Kenya would call for understanding the various uses of fire, along with the underlying perception and traditional ecological knowledge of the local people [14–16]. However, at the local level, resource managers have largely been addressing fire as a hazard rather than a tool for land management. The traditional use of fire in Kenya for supporting the livelihoods of the local people needs to be considered when developing and implementing IFM guidelines and policies [17]. There is also a need to give special consideration to social and community values and engage the community in IFM planning and implementation. This will help communities and resource managers in Kenya to find cost-effective approaches to prevent damaging fires, as well as to maintain desirable fire regimes.

The government of Kenya needs to finance, educate, train, equip, and motivate resource managers, rangers, firefighters, CFA members, and forest scouts that are involved in fire prevention and suppression activities to achieve sustainable IFM strategies. Proper mechanisms for addressing inter-community conflicts over the use of forest resources can be incorporated in IFM strategies. IFM principles have to be established in accordance with relevant international laws, taking into account all technological, economic, relevant biological, social, cultural and environmental expert knowledge about Kenya's forests. There is a need to contribute to the implementation of county, sub-national, and national policies and planning mechanisms for establishing or improving the legal, regulatory, and institutional framework required for responsible IFM activities in Kenya's forests.

This paper highlights the importance of developing and using an IFM framework to support communities and resource managers in finding effective and efficient approaches to prevent damaging fires, as well as maintain desirable fire regimes, in Kenya. The objectives of this publication are (i) to propose a framework for an integrated fire management approach, (ii) to apply the framework in a case study, and (iii) to propose fire management guidelines considering the challenges faced by the KFS and local CFA. In the following sections, we will introduce the framework for IFM, present the Gathiuru Forest Station case study and methodological steps for analysis and draw some conclusions on fire management.

2. Integrated Fire Management Framework

There are several Integrated Fire Management approaches that have been suggested and adopted in various countries. The Implementation of the British Columbia Wildland Fire Management Strategy aims at achieving healthier forest and range ecosystems, communities that are less at risk from fire and smoke, and a more cost-effective fire suppression program [18].The Food and Agriculture Organization of the United Nations (FAO) Fire Management Voluntary Guidelines advise authorities and other stakeholder groups that fire-fighting should be an integral part of a coherent and balanced policy applied not only to forests but also across other land-uses in the landscape [17].

Mt. Kenya forest ecosystems are known to have a long fire history and fire has influenced the vegetation in the landscape. Some plant species found in the Mt. Kenya forest require fire to germinate, establish, or to reproduce, and total fire suppression not only eliminates these species, but also affects the animals that depend upon them [16]. The indigenous woody species mostly found in regularly burnt sites in Mt. Kenya include *Juniperus procera* (Hochst. ex Endl.) and *Hagenia abyssinica* (Bruce) J.F.Gmel., while the herbaceous species include *Ferula communis* (Linnaeus), *Gomphocarpus stenophyllus* (Oliv.) and *Cardius keniensis* (Linnaeus) among others [19].

More recent ecological research has shown, however, that fire is an integral component in the function and biodiversity of many natural habitats, and that the organisms within these communities have adapted to withstand, and even to exploit, natural and anthropogenic fires. It is true that in the fire management literature, traditional anthropogenic fires in the pre-industrial era are considered as a part of the historical fire regime and the distinction between anthropogenic and natural fires is difficult because of the uncertainty underlying the extent and scale of pre-industrial era anthropogenic burning [20]. More generally, fire is now regarded as a 'natural disturbance', similar to flooding, wind-storms, and landslides, that has driven the evolution of species and controls the characteristics of ecosystems [16]. Based on these findings from international scientific literature, an IFM framework shown in Figure 1 was designed to support the management of fire sensitive ecosystems, as well as of other ecosystems with more frequent historical fires in Kenya. It considers the fact that ecological benefits of prescribed fires often outweigh their negative effects. A regular occurrence of fires can reduce the amount of fuel build-up, thereby lowering the likelihood of a potentially large wildland fire [21]. Fire removes low-growing underbrush, clears dead or weaker trees, cleans the forest floor of debris, opens it up to sunlight, and reduces competition for nutrients and space, allowing established trees to grow stronger and healthier [22]. The ashes that remain after a fire add nutrients that are often locked in older vegetation to the soil for trees and other vegetation. Fires can also provide a way of controlling insect pests by killing off the older or diseased trees and leaving the younger, healthier trees [21]. Burned trees provide habitats for nesting birds, homes for mammals, and a nutrient base for new plants. Overall, fire is a catalyst for promoting biological diversity and healthy ecosystems. Fire fosters new plant growth and wildlife populations often expand as a result [23].

According to the KFS records, catastrophic fires in Kenya have been causing soil erosion, water pollution, bad air quality (smoke), loss of timber value, loss of livelihood, wildlife to escape onto peoples farms, death of wildlife, loss of wildlife breeding habitats, loss of human life, destruction of properties, loss of grazing grounds, destruction of tourist camps sites, and loss of ecosystem services [4].

The proposed IFM framework helps communities and natural resource managers to address both damaging and beneficial fires within the context of the natural environments and socio-economic systems in which they occur, by evaluating and balancing the relative risks posed by fires with the beneficial ecological and economic effects they may cause in a given conservation area, landscape, or region. It helps to identify factors influencing fire ignition as it relates human needs and land use activities to factors influencing fire ignition. The roles of external drivers in influencing fire danger are estimated, and the positive and negative effects of fires are ascertained. It also helps in evaluating the benefits and risks of different management activities and developing fire management guidelines considering human needs and land use activities (Figure 1).

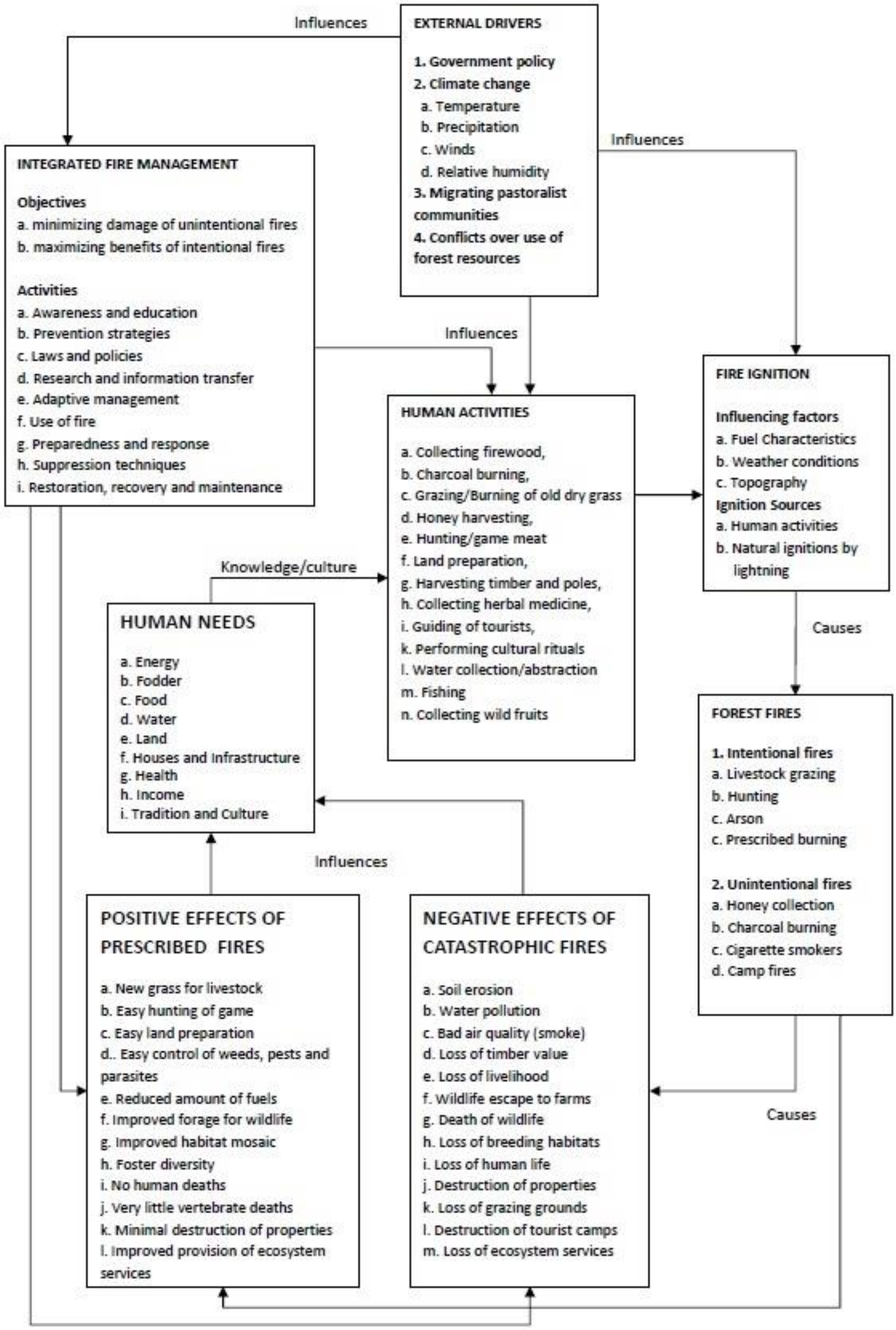

Figure 1. A proposed Integrated Fire Management (IFM) framework that helps communities and natural resource managers address both damaging and beneficial fires in Kenya.

3. Materials and Methods

3.1. Description of the Study Site: Gathiuru Forest Station

Gathiuru Forest is part of the larger Mount Kenya Ecosystem and is one of 18 forest stations. It covers an area of approximately 14,978 ha, which is comprised of 612.5 ha of grassland, 1187.9 ha of bush land, 1995.0 ha of bamboo, and 8625.3 ha indigenous and 2557.6 ha plantation forest areas as shown in Figure 2. Gathiuru Forest is highly prone to wildfire outbreaks and has a high number of recorded fire incidences [24]. The station experienced 63 fire incidences from 1980 to 2015. These fires have burned a total area of 4509.1 ha and the KFS has spent a total of $41,917 on fighting the fires. The total damage caused by forest fires from 1980 to 2015 is estimated to be $443,837.

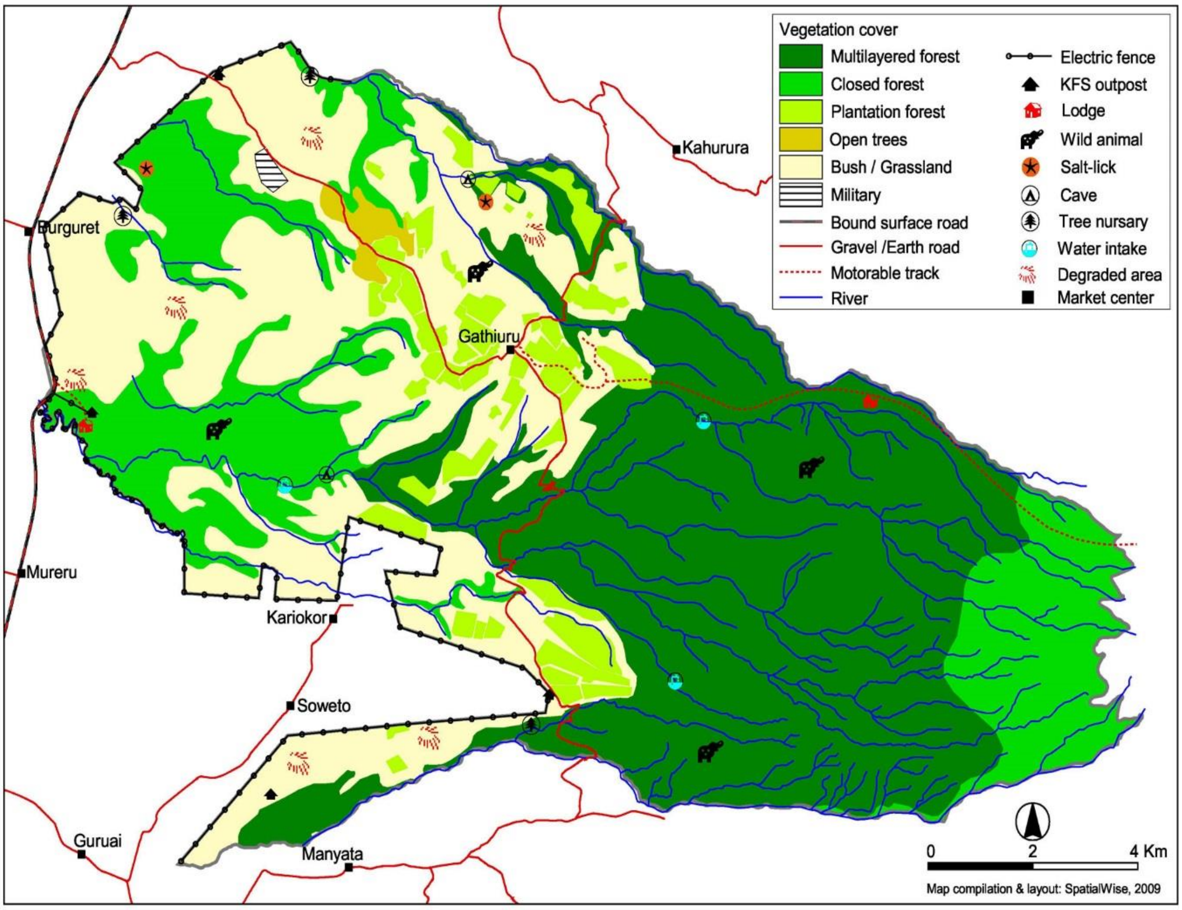

Figure 2. Gathiuru Forest Vegetation Types and Management Units, 2009.

3.2. Methods for Analysing the Conditions

3.2.1. Feasibility Study

A feasibility study was conducted from the 1 to 30 September 2015 in the 18 forest stations that form the Mt. Kenya Forest Ecosystem to establish forest stations that are prone to fires. Out of the 18 forest stations around the Mt. Kenya forest ecosystem, Gathiuru forest station was selected because it had the highest number of fire incidences recorded in the last 35 years compared to all the other forest stations and had fully developed a fire management plan that is under implementation from 2010–2019. It helps to guide fire management activities in high fire risk areas, identify objectives for fire management, outline strategies, and propose works to increase the level of fire preparedness. Formal and informal meetings were held with key resource persons from KFS, CFA members and other stakeholders that are involved in the management of the Gathiuru Forest. A study of primary and secondary data on socio-economic activities, fire records, weather records, and observation and documentation of the fire management plans in Gathiuru Forest Station was completed. An assessment of how well Gathiuru forest station was implementing the fire management plan was also performed.

3.2.2. Questionnaires

Questionnaires were designed and a pilot test was conducted to refine the questions. The questionnaire included: Yes or No responses, with some questions that allowed responses on a Likert type of scale ranging from a very great extent (5) to no extent at all (1) and no response (0); and others where participants were required to express their personal opinions verbally. The questionnaires were used to interview 16 respondents from Gathiuru Forest Station (one KFS manager, one ranger, two CFA leaders, and 12 CFA members) between October 2015 and December 2016. The level of education, gender, and socio-economic activities, motivation, potential, and constraints (problems) affecting forest managers, rangers, CFA members, and other stakeholders' participation in wildfire management in Gathiuru Forest and the surrounding villages were analysed. The awareness about the existence of the fire management plan; fire preparedness plans; damage caused by wildfire to communities and the environment; causes of wildfires; community participation in wildfire management; the channels of communication preferred by forest managers and CFA leaders to receive and give information on fires in Gathiuru Forest and the surrounding villages; and the training of CFA members, rangers, and forest scouts on fire fighting in Gathiuru Forest and the surrounding villages, were also surveyed using questionnaires.

3.2.3. Focus Group Discussions

A focus group discussion is a good way to gather people together with similar backgrounds or experiences to discuss a specific topic of interest. On the 10 November 2016, a focus group discussion was held with 24 participants that included the Chief Ecosystem Conservator, KFS forest managers, rangers, Kenya Forestry Research Institute (KEFRI) personnel, CFA members, and other stakeholders. The group was guided by a facilitator who introduced and moderated the topics for discussion on: how human activities at Gathiuru Forest influence the ignition of forest fires; the positive and negative effects of fires in Gathiuru Forest; and how the KFS, KWS, and CFAs were collaborating in the implementation of fire management plans, fire monitoring, fire prevention, fire-fighting, the reduction of hazardous fuels, and the maintenance of ecosystem health. The focus group discussions helped to gather information on how back firing has been used by firefighters in Gathiuru Forest to stop fire from spreading to other parts of the forest. The focus group discussions also helped in generating different ideas on IFM and how it is implemented in Gathiuru Forest Station.

3.2.4. Ranking of Benefits and Concerns in Gathiuru Forest

Focus group participants were actively involved in the importance ranking of their needs and benefits obtained from Gathiuru Forest. Participants were instructed by the moderators to come up with a list of the needs and benefits that they obtained from Gathiuru Forest and another list showing the concerns about fires in Gathiuru Forest. They voted by putting X or √ autonomously, without being influenced by members of their user groups. The same procedure that was used to vote for the needs and benefits was repeated for the concerns about fires in Gathiuru forest. A final tally was done to establish the total number of votes for each ranking. In the case where there was a tie in the first tally (TALLY I) of the ranking, a second round of voting was done (TALLY II) to determine the final rank of the benefits and concerns.

Data entry of respondents' views collected from the questionnaires, focus group discussions and processing by a ranking procedure was done. Analysis was conducted by using SPSS Statistics software from IBM Company that is located in New York in the United States of America (USA).

4. Results

The human needs and the related land use activities are presented in relation to the major causes of fire ignition. The concerns related to fire and the assessment of the external drivers allows the design of fire management approaches.

4.1. Humans Needs and Benefits in Gathiuru Forest

Common human needs accessed by the local communities in Gathiuru Forest include water use, timber, firewood, livestock grazing, cultivation of crops, collection of herbs for medicinal purposes, and generally contributing to a good life style. Results from focus group discussions show that there are considerable environmental and economic values that support the livelihood of the communities living around Gathiuru Forest. The forests offer diverse resources for consumptive use, and local people are allowed to access these products through a permit and licensing system. Table 1 shows the voting and ranking of the benefits obtained by the CFA in Gathiuru Forest, where using the land as farmland (PELIS) is ranked as first and providing cultural/religious benefits is ranked last.

Table 1. The ranking of benefits obtained from Gathiuru Forest (N = 24).

Rank of Needs & Benefits	Benefit Class	Number of Votes for Benefits Tally I & Tally II	Importance
1	Farmland (PELIS)	17	0.71
2	Water	13	0.54
3	Employment/income	12	0.50
4	Herbal medicine	10	0.42
5	Education & research	9	0.38
6	Timber	8 (11)	0.34
7	Grazing	8 (9)	0.33
8	Honey collection	3	0.13
9	Firewood	2	0.08
10	Cultural and religion	1	0.04

4.2. Human Activities and Their Influence on Fire Ignition in Gathiuru Forest

4.2.1. Perception about Factors Influencing Fire Ignition

Fuel characteristics, weather conditions, topographic factors, and the human activities influence fire ignition in Gathiuru Forest. The analysis of data collected using the questionnaires on the perceptions of the local people about the leading causes of fires in Gathiuru Forest are shown in Figure 3.

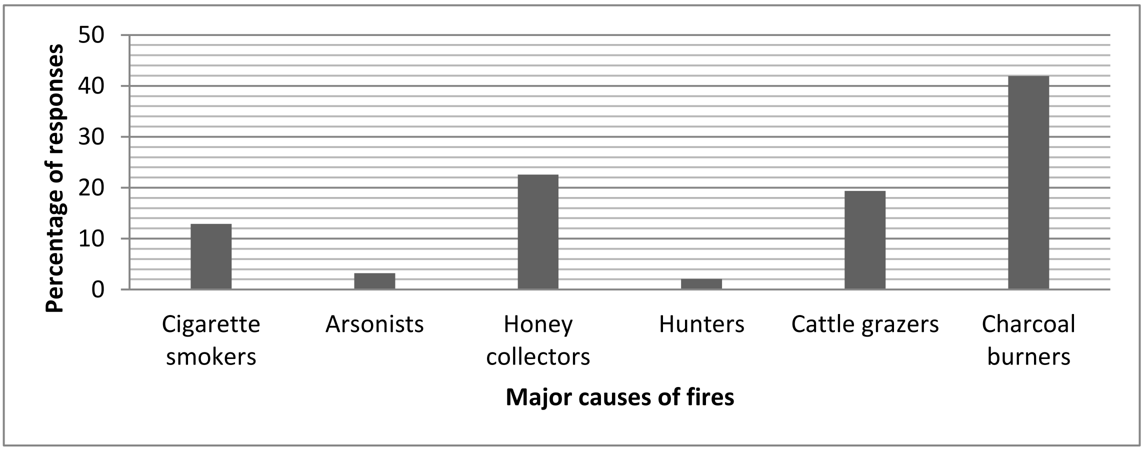

Figure 3. Major causes of fires in Gathiuru Forest indicated by questionnaire respondents (N = 16).

4.2.2. Legal Human Activities in Gathiuru Forest

According to the focus group discussions, farming (PELIS) is one of the activities practised by rangers and CFA members in Gathiuru Forests. The results from the voting and ranking of needs and benefits show that farmland (PELIS) got 17 votes and is ranked as the first benefit obtained by the communities from Gathiuru Forest. But, the use of fire to clear farm plots has been abolished and all CFA members declared that using fire to clear a farm plot would cause a loss of the farmers' user group rights and the plot would be given to a new member.

Communities obtain water from rivers that originate from Gathiuru Forest of the larger Mt. Kenya Water Tower for domestic use, the watering of livestock and, the irrigation of crops. Water abstraction has been licensed in Gathiuru Forest and a water user group has been formed. The results show that water use is ranked as the second most important benefit.

Rangers and CFA members conduct some casual jobs like the thinning and pruning of forest plantations. They get cash payments for these jobs. To reduce the fuel load, they are allowed to collect and sell some of the poles and firewood from thinning and pruning operations. The results show that employment/income is ranked as the third most important benefit.

The collection of herbs and spices for domestic use or commercial purposes by the local communities is currently not licensed and a user group has not been formed. The results show that herbal medicine and spice collection is ranked the fourth most important benefit in the Gathiuru Forest and their collection might cause a reduction of the available fuel.

Several national and international institutions have been doing research projects in Gathiuru Forest and some of their education programs have been considering and respecting traditional knowledge. The trainings allowed a mutual exchange of know-how and experiences between the trainers and the communities. The forests also provide a learning place for the traditional non-formal education that has been passed down for generations about plants and animals and their uses. The results show education and research is ranked as the fifth most important benefit, which shows the potential for KFS, KWS and Laikipia Wildlife Forum (LWF) to continue providing sound training on fire management to local stakeholders and CFA members in Gathiuru forest station.

Saw millers and communities obtain poles and timber from Gathiuru Forest. Logging has been licensed and is one of the leading economic activities as the demand for timber is higher than the supply. The results show that timber harvesting is ranked as the sixth most important benefit.

Grazing and cutting of grass to feed livestock has been licensed and a grazers' user group has been formed in Gathiuru Forest. Additionally, migrant pastoralists do graze their cattle (*Bos-Taurus* Linnaeus.) in Gathiuru Forest illegally during years of extreme drought (2009 and 2017). The results from the focus group discussions show that grazing and cutting of grass is ranked as the seventh most important benefit and the questionnaires indicate that grazing and burning of old grass contributes to 19.4% of the fires in Gathiuru Forest.

Honey collection is practised by communities living around Gathiuru Forest. Bee keeping has been licensed and the bee keepers' user group has been registered. The results show that honey collection is ranked as the eighth most important benefit. However, illegal honey collection is also practised in Gathiuru Forest and the results from the questionnaires show that honey collection contributes to 22.6% of the fires in Gathiuru Forest.

Firewood collection by CFA members is practised in Gathiuru Forest as part of fuel management. It has been licensed and the firewood collectors' user group has been registered. It helps to reduce fuel build up and contributes to lowering the risk of large fires occurring. The results show that firewood collection is ranked as the ninth most important benefit that local people gain from Gathiuru forest.

Gathiuru Forest contains caves that, over centuries, have been used by the Kikuyu, Embu, and Meru communities as sacred cultural and religious sites. Some trees have also been declared as sacred trees and no one is allowed to cut them for any use or set them on fire. The results show that cultural and religious sites is ranked as the tenth most important benefit from the Gathiuru Forest.

4.2.3. Illegal Activities in Gathiuru Forest

Illegal charcoal burning is practised in Gathiuru Forest by communities living around the forest. This has caused fire outbreaks and destroyed large parts of Gathiuru Forest in the past. Results from the questionnaires show that illegal charcoal burning contributes to 42.6% of the fire outbreaks in Gathiuru Forest. However, the practice of illegal charcoal burning is on the decline due to good collaboration between KFS and CFA members in Gathiuru Forest. The illegal charcoal burners have been arrested and prosecuted according to the law. The CFA has also trained community members on using solar energy, gas and other energy-saving stoves.

Results from the questionnaire show that poachers are perceived to contribute to 2.1% of fire ignitions in Gathiuru Forest. Illegal hunters use fire as a hunting tool and to roast game meat in Gathiuru Forest. It was reported from the focus group discussions that sometimes poachers cause fires so that the rangers have to concentrate on fighting the fire, while the poachers escape from being arrested. Interestingly both the illegal activities of charcoal burning and poaching were not mentioned as an important benefit for the local people in the Gathiuru Forest.

Conflicts have occurred between KFS, KWS, CFAs, and other stakeholders over the right to use forest resources. Focus group discussions revealed that conflicts do arise when some locals are not allocated land in Gathiuru Forest to practice farming (PELIS) because the need for farming is higher than land available. Conflicts also arise when the locals are arrested by KFS staff, forest scouts, or CFA members for conducting illegal logging, grazing, collecting firewood, collecting honey, herbal medicine, burning charcoal, or hunting in Gathiuru Forest. The culprits usually set the forest on fire as revenge (arson). Results from the analysis of data from the questionnaires show that arson contributes to 3.2% of the fire ignitions in Gathiuru Forest.

4.3. Concerns Related to Fires

Fires can have several effects on the social, economic, and cultural aspects of the livelihood of local people. Focus group discussions indicated that the participants support the idea that when fire is used and managed properly, it has some positive effects for the communities, but there are also concerns about the damages that can be caused by wanted and unwanted fires that are lit intentionally or unintentionally in Gathiuru Forest. Table 2 shows the voting and ranking of the concerns related to the negative effects of fires by the CFA in Gathiuru Forest, where the loss of grazing grounds (pasture) is ranked as first and the loss of livestock is ranked last.

Table 2. The votes and rank of concerns related to fire effects in Gathiuru Forest (N = 24).

Rank of Concerns	Concerns	Number of Votes for Concerns Tally I & Tally II	Importanc e
1	Loss of grazing grounds (pasture)	9	0.38
2	Loss of wildlife habitat/escape to farms	6	0.25
3	Loss of wildlife	5	0.21
4	Water pollution	4	0.17
5	Bad air quality	3 (3)	0.13
6	Soil erosion	3 (2)	0.12
7	Loss of life	2	0.08
8	Loss of livestock	1	0.04

The respondents of the questionnaires also indicated two main fire seasons per year. The first fire season is from January to March and the second from August to October as shown in Figure 4. Their perceptions nicely correspond to the documented number of fire records per month during the year. This indicates the high awareness of the CFA members regarding the fire seasons in Gathiuru Forest. Most of the fires that occur between January, February, and March are as a result of land preparation during the planting season.

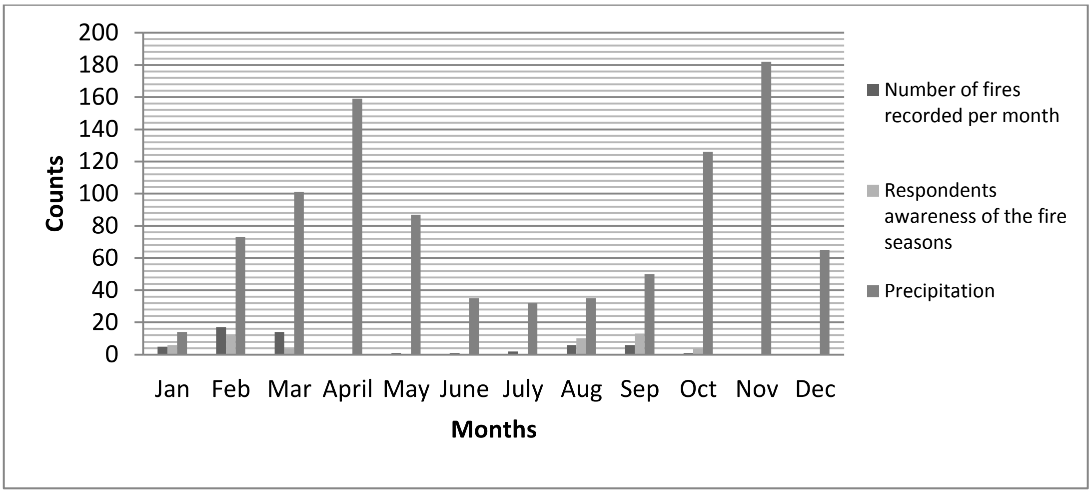

Figure 4. Precipitation, the number of fires recorded by KFS and the fire seasons in Gathiuru Forest based on the perceptions of the local people (N = 16).

4.4. Implementation of Integrated Fire Management

4.4.1. Stakeholder Involvement

The involvement of different stakeholders in the implementation of IFM guidelines varies. Results from the questionnaires show that the leading stakeholders involved in IFM in Gathiuru Forest are forest managers with 34%, CFA members with 33%, and rangers with 27%, while the other stakeholders have only exhibit a value 7%. Appendix B shows the detailed results of the main stakeholder groups involved in the establishment of guidelines for responsible Integrated Fire Management activities in Gathiuru Forest, including their interest, roles, and responsibilities.

4.4.2. Provision of Fire Training and Technical Support to Improve IFM

Results from the analysis of the questionnaires show that KFS and KWS have to some extent been providing fire educational programmes and firefighting training programmes to rangers, CFA members and forest scouts with the aim of improving their knowledge and skills in fire prevention and suppression in Gathiuru Forest. It also indicates that the government of Kenya has only been providing firefighting equipment to the Gathiuru KFS and CFAs to a small extent, as shown in Figure 5. This has greatly affected their ability to fight the huge fires that have been occurring repeatedly in recent years.

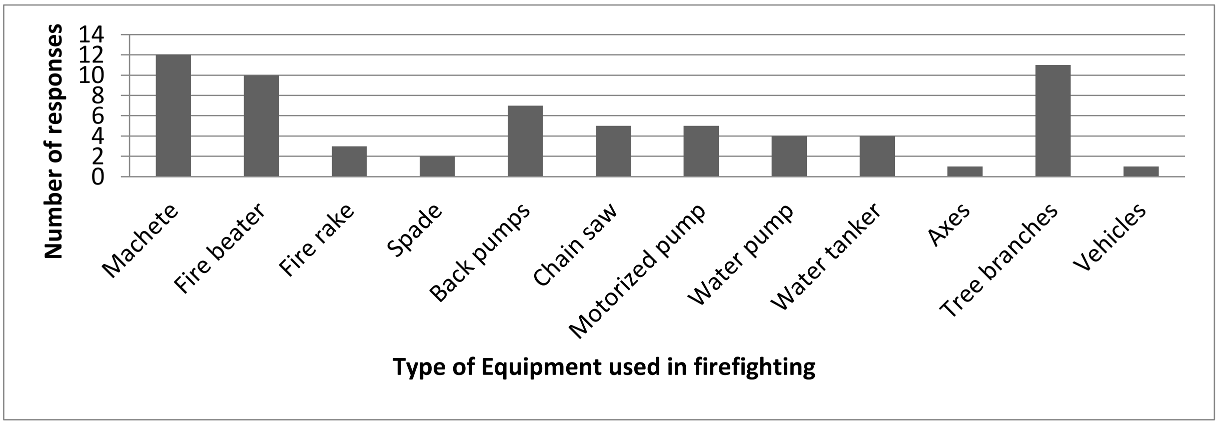

Figure 5. Type of equipment used to fight fires at Gathiuru Forest Station (N = 16).

4.4.3. Existence and Revision of IFM Plans

Results from the analysis on the existence of IFM plans and their revision based on the records of the number of fires that have occurred, the damage caused by those fires, and community participation in Gathiuru Forest show that 6% of the respondents said to a very great extent, 38% said to a great extent, 19% said to some extent, 19% said to a small extent, and 6% said to no extent, while 12% gave no information. This means that the KFS, KWS, and the CFAs have, to a great extent, given special consideration to social, economic, and environmental values of the local community in their IFM planning.

4.4.4. Land Use and Fire Danger Rating in Gathiuru Forest

Results from the analysis of data from questionnaires show that 50% of the respondents said that, to a great extent, there exists a fire risk analysis plan in Gathiuru Forest Station based on land cover, daily weather conditions, and socio-economic activities. Results show that 50% of the respondents said that, to some extent, there exists a regional early warning system about fire outbreaks in the Mt. Kenya Forest.

5. Discussion

5.1. Land Use Practices and Fire Ignition

Gathiuru Forest Station is one of the Mt. Kenya forest stations with a high number wildfire incidences recorded over the last three decades. According to the fire records and interviews conducted, it was found that the charcoal burners, honey collectors, cattle grazers, cigarette smokers, arsonists, and hunters are the main causes for fire ignition in Gathiuru Forest. However, other studies have shown that not all ignitions are directly linked to land use activities, for instance, fires due to arson and the careless disposal of smoked cigarettes are related to social behavior [25–27]. It is important to understand how, at the local level, communities utilize land resources with or without the use of fire and the social behavior that drives ignitions, and incorporate them into integrated fire management approaches as a basis for addressing the risk of fires [28,29].

In many studies, it was found that the growing human population and the increase in per capita food consumption are driving agriculture expansion and affecting natural ecosystems [30]. According to the 2009 Kenya Population and Housing Census, many of the communities living around Gathiuru Forest are poor and do not have enough land for farming [31]. Communities living around Gathiuru Forest also heavily depend on the land resources for preparing the farmland and managing the forests for many ecosystem services and non-timber forest products. The Gathiuru CFA was formed in 2009 to involve the community in Participatory Forestry Management and at the same time to help regulate human activities according to the agreed user rights in Gathiuru Forest. The user groups have the right to conduct their activities within Gathiuru Forest which includes timber production and running saw mills, grazing, firewood collection, beekeeping, collecting herbs, water abstraction, farming trout fish (*Oncorhynchus mykiss* Walbaum), providing hotel and cottage services as well as ecotourism and cultural exhibitions, conducting the PELIS system on farms, and acting as community scouts. The signing of the user group's agreement has enabled the CFA to source funding from other key sources, principally the Green Zones Development Support Project. Each of these user groups has been provided with an area for their business and in the case of a fire outbreak, the whole group will lose their user rights [24].

According to the farming (PELIS) rules and guidelines, the growing of beans (*Phaseolus vulgaris* Linnaeus), potatoes (*Solanum tuberosum* Linnaeus) and onions (*Allium cepa* Linnaeus) has been practiced in Gathiuru forest from 2008 to 2017. PELIS has helped to reduce poverty and to increase food security amongst Gathiuru CFA members involved in the production of high-quality potatoes with an estimated production of 7500 tons per year. From 2008 to 2017 total sales of food crops (potatoes) amounted to KSh 756 million ($7.56 million) and this enabled CFA members to stop depending on the forest resources and start other income generating activities. The use of fire in

Gathiuru Forest is forbidden by the forest station managers according to the PELIS guidelines. The CFA members involved in farming activities are not allowed to use fire for land preparation. This is not compatible with their traditional farming practices. However, farmers still use fire illegally in Gathiuru forest and when these fires get out of control, they usually cause larger unintentional fires.

Firewood is utilized in many parts of the world as a source of energy and is a major focus in the management of primary and secondary forests [32,33]. According to the studies done by CIFOR [34], the increased demand for fuelwood can lead to forest degradation, slow down regeneration, change tree species composition, cause a reduction of tree cover, increase fine fuel (grass) accumulation, and consequently change the rate of wildfire spread [35]. We found out that firewood collection also plays an important role for the CFA members as well. Firewood collection has been licensed and the fee for collecting firewood two or three times per week ranges from KSh 100 to 150. However, the Gathiuru CFA bought 1150 energy saving cooking stoves (jikos) and distributed them among CFA women. This has helped to reduce the fire wood consumption and hence women do not need to go to the forest daily to collect firewood [24]. There is also great potential for Gathiuru CFA members to use the pruned lower branches and thinned small diameter trees for charcoal or briquettes for domestic use or commercial purposes (income) as this may help prevent ladder fuel accumulation, thus partly mitigating fire risk.

Several studies have been done to assess the impacts of cattle grazing on forests fires, water quality, biodiversity, invasive species, soil fertility, regeneration, tree damages, and soil erosion [36–39]. Cattle grazing and cutting of grass to feed livestock is allowed and has been licensed in the Gathiuru Forest. Grazing and cutting grass helps to reduce the fuel load and at the same time minimizes the risk of rapid surface fires occurring. Cattle grazing reduces low ground fuels, which decreases wildfire intensity and the length of flames, thereby reducing the risk of higher fuels (such as branches) catching fire [40]. The CFA is responsible for collecting grazing fees of Ksh. 100 per head of cattle. The agriculture officers have been involved in designing a carrying capacity for cattle grazing in the forest to help reduce the problem of over grazing. When the grass in the grazing area is gone, the cattle grazers are reallocated to another grazing area according to the carrying capacity. The CFA cattle grazers group is not allowed to use fire for managing grasslands in Gathiuru Forest, but is responsible for monitoring and reporting to the forest manager any illegal grazing activities and fire outbreaks so that the culprits are arrested and prosecuted. Nevertheless, there have been many cases of illegal grazing and fire outbreaks caused by illegal grazers (migrant pastoralists) who set grasslands on fire to keep them open and to facilitate the growth of new grass for livestock [24].

Studies of sacred forests and other sacred sites show that religious and spiritual beliefs can sometimes be the motivation for conservation and environmental protection. African indigenous religions view land and its resources as communal property that belongs not only to the living, but also to their ancestors and to future generations [41]. Mt. Kenya is a holy mountain for the Kikuyu community. The term Kikuyu originates from the Mukuyu tree (*Ficus sycomorus* Linnaeus). According to the Kikuyu culture, three sacred trees make the community believe that they should conserve the forest: Mukuyu tree (*Ficus sycomorus* Linnaeus), Mugumo tree (*Ficus thonningii* Blume), and Mukurwe tree (*Albizia gummifera* J.F. Gmel.). Nobody in the community is allowed to cut down or set fire to these trees. This is similar to other places in Africa [42] and contributes to the efforts of conservation.

Ecotourism can be an incentive for conservation activities, and may provide socio-cultural benefits [43] and income for local communities living around nature parks [44,45]. Fires burning camp grounds and other tourist resorts, destroying the national park, and causing evacuations of tourists from fire-threatened recreation sites are a great concern [46]. The CFA ecotourism group views fire in Gathiuru Forest as a serious threat to ecotourism, but studies have shown that there are wild herbivores that benefit from plant regrowth after fires. Using prescribed fires in the landscape can help to maintain native flora and fauna that might attract tourists [47]. The perception of risk and the knowledge about wildfire by tourists has to be considered, as some tourists are not aware of the potential danger of becoming trapped by wildfires or causing a fire due to the negligent handling of barbecue fires or cigarettes [46]. The Gathiuru CFA has established hiking trails that are being used by tourists and also act as fire breaks [24].

Controlled small-scale fires are traditionally used in the African savannah to flush out small mammals for hunting purposes. However, poachers in some areas have carelessly been deploying crude versions of this practice, causing unmanageable bush fires and large-scale destruction [48]. Hunting of game-meat used to be a traditional practice of many communities in Kenya. The communities used fire as a hunting tool and to roast game meat for centuries. With the introduction of a ban on hunting in Kenya in 1977, the hunting practice was rendered illegal. But poachers have continued to use fire as a hunting tool and to distract rangers from arresting them as the rangers try to put out an early fire outbreak, which allows the poachers to escape [49]. The KWS, KFS, and CFAs are working together to ensure there is no more hunting of wildlife in the Gathiuru forest and national Park. Nowadays, the CFA members are educated on how to keep rabbits (*Oryctolagus cuniculus* Linnaeus), chicken (*Gallus gallus domesticus* Linnaeus), sheep (*Ovis aries* Linnaeus), goats (*Capra hircus,* Linnaeus), and cattle (*Bos Taurus*) for producing food and hence the need for game-meat is declining. The legal fine for those involved in illegal hunting has also been increased tremendously to discourage this bad practise [24].

In Africa, the North Western Province of Zambia emerged as the "Honey Province" because of its historical tradition of trading beeswax, its remoteness, and its vast miombo woodlands, and it is presumed that beekeeping started in Ethiopia about 5000 years ago [50]. Some CFA members are involved in bee keeping within Gathiuru Forest. Their practice has been registered and licensed to established apiaries within the forest and some have been trained by KWS on bee keeping, honey harvesting, and processing. The Ogiek tribe in the Great Rift Valley of Kenya is one of the honey hunter-gatherer peoples in East Africa and honey plays a central part in the Ogiek society, being used for food, beer brewing, and trade. Besides using beehives of hollow logs placed in tree branches, the traditional honey collectors in Gathiuru Forest illegally hunt for honey in tree hollows. They use fire to produce smoke and keep away the bees (*Apis mellifera* Linnaeus) before collecting honey and sometimes this causes fires during the dry season, especially when the honey collectors act carelessly [24].

5.2. Positive Social and Environmental Benefits of Precsribed Fires

Gathiuru forest has some fire-dependent species like *Juniperus procera, Bambusa vulgaris* (Schrad Ex J.C. Wendl.) and *Hagenia abyssinica* that usually regenerate after fire. Native perennial grasses also regrow from root systems that are rarely damaged by fires that occur in Gathiuru Forest. Fire is the only natural factor which also supports the reproduction of the subalpine forests as the grass layer of larger areas is cleared by occasional burning [51]. Some scavenger animals like hyenas (*Crocuta Crocuta* Erxleben) and bird species like the black eagles (*Ictinaetus malaiensis* Temminck) have been seen to move to burned areas in Gathiuru Forest as the reduced vegetation allows them to catch prey easily [52]. The use of prescribed fires for fuel management is not practiced in Gathiuru Forest. These prevention measures would help to decrease the risk of catastrophic fires. However, the current banning of all fires from current land use practices might lead to an accumulation of fuel loads, which will have a major role in future outbreaks [53].

5.3. Negative Social and Environmental Effects of Catastrophic Fires

In the last 35 years, catastrophic fires have been occurring during the dry season in January, February, March, July, August, and September, and have burned 4509.10 ha of Gathiuru Forest, destroying plant material and the litter layer. KFS records show that from 1980 to 2015, the total damage caused by catastrophic fires in Gathiuru Forest plantations for timber and pulpwood was $443,837 and the cost incurred while fighting these fires was $41,917 [21].

Plantations of exotic tree species have been established by the KFS for the pulp and timber industry in Kenya. Several studies have been done on how exotic tree species contribute to changes in the patterns of anthropogenic ignitions, flammability of exotic species, forest ecosystem structure, and process and fuel loads [54]. fire also stimulates the release of large amounts of seeds from the serotinous cones of Pinus radiata and can create favorable conditions for germination and establishment [55]. The principal mechanisms of recovery in fire-resistant Eucalypt species are resprouting from epicormic strands (i.e., regeneration from meristem strips, usually extending from the inner to outer bark on aboveground branches and stems, which produce buds), and/or from basal buds [56]. Therefore unmanaged fires may contribute to an increase of exotic species in the natural environment of the forest and national park of Kenya.

Shrubs, forbs, grasses, trees, and the litter layer break up the intensity of severe rainstorms. The stabilisation of the soil by the plant roots, stems, and leaves slows down the water drops and provides time to percolate into the soil profile. The subsequent rains after fires have caused landslides, flash floods, and soil erosion in Gathiuru Forest [57]. The ash from burned sites caused water pollution affecting trout fish farming and heavy sedimentation has been recorded in the seven folk dams that rely on water from rivers in Mt. Kenya Forest [9]. Other studies have also proved that surface water coming from burned areas causes serious water quality problems in streams, lakes, and reservoirs by introducing hazardous chemicals into the water bodies [58].

Fires occurring in Gathiuru Forest have been causing smoke that is spread by wind several kilometres away. Wildfire smoke composition depends on many factors, including the types of vegetation burned and the pollutants in smoke can include deadly gases, e.g., carbon monoxide and many solid and liquid elements often known as particulates or particles [4]. Forest fires have been polluting the air, irritating the eyes, reducing the visibility of travelers, and causing difficulty in breathing to communities living around Gathiuru Forest and several kilometres further away.

Some wildlife has lost its life after huge catastrophic fires in Gathiuru Forest; especially slow moving, sick, or young birds/animals that cannot escape fire [52]. Fires cause a loss of their habitats and provoke them to escape to nearby farms, destroying crops and thus causing huge losses to CFA members who obtain their food and income from Gathiuru Forest. Tourism is also negatively affected after huge fires, as the scenery is destroyed and some wildlife are forced to migrate to other parts of Mt. Kenya Forest.

Conflicts often occur between nomadic groups in Kenya, Uganda, Sudan, Ethiopia, and Somalia over the use of pastures in fragile ecological environments [59]. During years of extreme drought, migrant pastoralists usually come to graze in Gathiuru Forest, set fire to the old grass to facilitate the growth of new grass, and then move away in search of good pasture grounds. This practice has been causing huge fires and the loss of grazing grounds for the locals, who depend on the grasslands within Gathiuru Forest for grazing their livestock. Inter-community conflicts over water and pasture grounds between the locals (Kikuyu) and the pastoralists (Samburu and Maasai) are likely to increase [59].

The highest human fatalities from fighting fires occur in developing countries, with a figure of up to nearly 80% for the period between 1997 and 2006 [53]. This is also one of the most serious concerns in Gathiuru forest. Volunteer fire fighters suffer from the lack of proper firefighting equipment which can be a strong contributing factor in loss of life while fighting huge fires. Fires have also destroyed houses constructed by CFA members within Gathiuru Forest [24].

Loss of livestock has been reported after extreme shortages of pasture caused by drought and fires in the Gathiuru Forest. The poor nutritional status of the livestock does not allow the long distance movement of livestock for pasture and water. Wildfires suppress grass production for about two rainy seasons and it is recommended that pasture grounds must rest for at least one rainy season after a runaway fire, and for at least one rainy season before a prescribed burn. After huge fires, the leftover grass is grazed by wild animals, and may not be suitable for livestock grazing, and this makes weak livestock prone to death or the communities have to sell them at low prices [60].

5.4. External Drivers Influencing Fire Danger

From the discussions with the participants in the focus group, a lot of external drivers that have an influence on fire danger were identified. Besides the changing climatic conditions, government policy and the role of migrating pastoralists were identified. The Kenya forest policy stipulates rules for the establishment of forest management zones to guide the different management strategies and future planning of particular areas to avoid conflicts among different users [61]. The management zones reflect the priority of the different objectives, and generally provide a direction for daily management, as well as long-term decision making with respect to the land use patterns in the ecosystem. The zones include: protection zone (National Park, water catchments); biodiversity conservation zone (indigenous forest); plantation zone cypress (*Cupressus lusitanica* Mill.), patula pines (*Pinus patula* Schiede Ex Schltdl. & Cham), radiata pines (*Pinus radiata* D. Don), blue gum (*Eucalyptus saligna* Smith), and rose gum (*Eucalyptus grandis* W. Hill Ex Maiden); utilisation zone (glades, grasslands, NWFP, tourist sites); rehabilitation zone (these are degraded areas marked for regeneration); and intervention zones-conflict area [9]. The zoning of forests into management blocks affects the type of human activities allowed in those blocks. This has an influence on the ignition probability of forest fires. Blocks zoned for grazing usually experience more regular fires than blocks zoned for water catchment conservation [9]. During the rainy season, the grasses and shrubs usually grow very rapidly and dry up during the dry season. This increases fine fuel accumulation and continuity. The setting of grasslands on fire each year by pastoralists—especially to keep them open and to facilitate the growth of new grass for livestock before the rainy season begins—contributes to fires at Gathiuru Forest Station.

An analysis of KFS records shows that Gathiuru Forest Station has been zoned into three blocks and subdivided into compartments and sub-compartments for easier management. The Gathiuru Block has more plantations and less indigenous forests, the Mugeria Block has intensive PELIS activities, and the Burguret Block has indigenous forest and grasslands and is prone to fire caused by cattle grazers. The cattle grazers' user group has been formed to monitor the number of livestock entering the forest and to prevent any activities that are likely to cause fires in the forest. They also help the forest manager to collect a monthly grazing fee from all registered cattle grazers in Gathiuru Forest.

The Kenya forest policy also stipulates that there must be a forest fire protection unit within every forest station organizational structure. The Ecosystem conservator of the forests appointed at the headquarters helps forest managers to plan, organize, equip, train, and provide follow-up supervision of cost effective fire management at all levels with the KFS. They develop comprehensive nation-wide programs to create awareness about the need for fire protection and control and plan the implementation of risk and hazard reduction. In the field, the KFS Station Forest Managers organize and supervise the activities of the prevention and suppression of forest fires within their areas [61]. At the regional level, the minister for the environment in each county provides firefighting staff, as well as technical and financial support to communities and forest station managers during fire incidences [61].

The meteorological factors that influence the fire weather include high temperatures along with dry, low humidity, and windy weather. Natural, cyclical weather occurrences, such as El Niño events, affect the likelihood of fires by influencing precipitation and the moisture content of plants, and lead to year-by-year variability. Changes in climate are likely to alter the two fire seasons in Gathiuru Forest. According to the Kenyan government [12] projections, temperature and precipitation levels are likely to further alter in Kenya over the course of this century. However, despite compelling evidence on the role of climate in influencing fire ignitions, the majority of ignitions in Kenya are caused by humans, as noted in different parts of the world [11].

Droughts associated with climate change will cause annual flow reductions in most rivers, conflicts over water resources and pasture; and the complete disappearance of the Kilimanjaro, Ruwenzori, and Mount Kenya glaciers by 2015–2020 [62]. Conservation reports indicate that during years with prolonged dry spells, the forests and national parks of Kenya will continue to experience the huge pressure of livestock from pastoral communities, thereby over stretching the available resources [9]. This means that in all likelihood, the pastoralists (Samburu and Maasai) will continue to graze in Gathiuru Forest without considering the local CFA grazers' user group agreements. The setting of old dry grass on fire by migrant pastoralists also contributes to fires at Gathiuru Forest Station.

6. Conclusions

This study investigated an Integrated Fire Management (IFM) framework to address both damaging and beneficial fires. It also evaluated the various uses of fire, the underlying perceptions and the traditional ecological knowledge of the local people. The risks posed by fires were then balanced with the beneficial ecological and economic effects, which will thus support the development of effective fire management approaches. The proposed IFM framework helps in implementing cost-effective approaches to prevent damaging fires and maintain desirable fire regimes in Kenya. The IFM framework is scalable and can be applied in places with fire-dependent ecosystems, as well as in places with fire-sensitive ecosystems in Kenya. However, the fact that exotic tree species are still being established in Kenya's forest raises the concern that needs to be addressed when developing and implementing IFM approaches. Exotic tree species like *Pinus radiata* and Eucalyptus in Kenya's forests may pose a serious threat of changing the fire regimes in the future and may also affect the regeneration of native tree species if proper IFM strategies are not established and fully implemented. The effectiveness is dependent on the active participation, formulation, and implementation of the IFM activities by the main stakeholder groups (Kenya Forest Service (KFS), Kenya Wildlife Service (KWS), and the Community Forest Associations (CFA). The proposed IFM framework also emphasizes the need for the government of Kenya to finance, educate, train, equip, and motivate resource managers, rangers, CFA members, and forest scouts that are involved in fire prevention and suppression activities to achieve sustainable IFM strategies. Identifying potential stakeholders and their interests will help to mitigate conflicts over the use of forest resources in Kenya by following the traditional and legal arbitration mechanisms at the village, regional, and national level. It highlights the need to implement the relevant international, national, and county laws and policies for establishing or improving the legal, regulatory, and institutional framework required for responsible IFM activities in Kenya's forests. The information from the proposed IFM framework may be used by resource managers, policymakers, and researchers to improve or advocate for sustainable land and resource management programmes that consider the fire history of the areas; the ecologically appropriate use and management of fire; and the suppression of unwanted, damaging fire in Kenya's forests.

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Table A1. Stakeholders involved in the management of Gathiuru Forest

Stakeholder	Interests	Activities	Strengths	Weaknesses
KFS	Protection and conservation of forests	-tree planting, establishment of tree nurseries, revenue collection, awareness creation, carrying out patrols, zonation/mapping of forest areas, enforcing forest law and policy	-Forest Act and policy -expertise -support from lobby groups and donors	-inadequate machinery and equipment, inadequate staff, political interference, inefficiency among KFS staff
KWS	Protection and conservation of wildlife	-electric fencing, promotion of tourism, patrolling, enforcement of the wildlife act, establishment of tree nurseries, translocation of wildlife, information dissemination	-Forest Act and policy, Wildlife Act and policy, expertise, support from lobby groups and donors, adequate resources	-poor response to incidences, poor compensation laws, poor collaboration with the community
Saw millers	Profit making	-logging, conversion of logs to timber products, creation of employment, selling timber based products	-have money, Forest Act and policy	-They do not plant trees, illegal access to trees, big contributors to environmental degradation
CFA	Protection and conservation of the forest for community benefits	-tree planting, establishment and management of tree nurseries, controlling forest fires, community policing, generating revenue for the government, managing forest resources	-support from KFS, Forest Act and policy, support from community, support from donors and lobby groups	-lack of finances, poor awareness of CFA activities, among the community members, lack of commitment from CFA officials
Greenbelt Movement	Increased tree cover	-tree planting -promoting community awareness -funding tree planting activities	-community support, support from lobby groups, forest act and policy, have expertise	-failure to fulfil promises -top-down approach in project activities implementation
Nature Kenya	Conservation of the biodiversity	-awareness creation	-adequate resources, support from government bodies such as KWS & KFS, have expertise	-not well known by the community, ineffective community outreach programme
BRWUA	Management and conservation of Burguret River	-supplying water tanks, regulation of water use, supplying drip kits, construction of water pans, construction of foot bridges and livestock watering troughs, tree planting on riparian land	-water act 2002 -support from water users -support from NGOs -support from KFS	-failure to fulfil promises -poor community representation -lack of direct link between BRWUA and the beneficiaries
TIST	Mitigation against climate change	"Promoting" tree planting	-has international funding	-not well known by the community
LWF	Environmental conservation	-creating awareness, funding CBOs	-have adequate financial resources, have expertise	-not known to the community, poor community representation
Ministry of	Food security &	-offering extension services	-Government policy, support	-inadequate staff

Agriculture	facilitating agro-business		from the community, have expertise	
Ministry of Defense	Defending the country	-tree planting, road and bridge construction -water abstraction from Rongai River	-Government policy, have adequate machinery &equipment	None
Ministry of Fisheries & Livestock	Promotion of livestock development	-offer extension services -treatment and vaccination	-have expertise -Government policy	-inadequate staff -services are expensive
Bantu Lodge	Profit making	-tourism -entertainment	-have money, support from Government, create employment	-No tree planting, no community involvement, poor security
UNDP-GEF	Environmental conservation	-establishment of tree nurseries, funding community groups, awareness creation on environmental conservation	-have funds, support from the international community, Government support through KFS and KWS	-lack of follow up project implementation activities, not well known by the community

Source: Gathiuru Forest management plan 2010–2019.

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