

Assessment of Fire Distribution across Elevation Zones Using GIS and Remote Sensing On Mount Mulanje, Malawi

Lucius Malalu

luciusmalalu2002@gmail.com

Malawi University of Science and Technology

Henry Chinthuli

Mount Mulanje Conservation Trust

Research Article

Keywords: Mount Mulanje, Fire occurrence, Vegetation dynamics, Land use and land cover (LULC), Remote sensing, Burned area, Vegetation indices, Post-fire vegetation recovery, Fire management, Malawi

Posted Date: September 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11012933/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: The authors declare no competing interests.

Abstract

Fire is an important disturbance factor influencing vegetation dynamics, ecosystem functioning, and land-cover conditions in mountain environments. This study assessed the spatial occurrence of fire across different vegetation zones of Mount Mulanje and examined its effects on vegetation conditions over a ten-year period. The study focused on five vegetation zones: miombo woodland, evergreen vegetation, grassland, shrubland, and Afro-alpine vegetation. Land use and land cover (LULC) were also assessed using five major classes: forest, grassland, agriculture, bareland, and water. Remote sensing and satellite-derived vegetation indices were used to identify burned areas and compare vegetation conditions before and after fire occurrence. The results showed that a total of 10,766 ha was burned during the study period. Fire occurrence was highly uneven, with grassland accounting for 9,522 ha (88.4%) of the total burned area, followed by shrubland with 642 ha (6.0%), miombo woodland with 346 ha (3.2%), evergreen vegetation with 254 ha (2.4%), and Afro-alpine vegetation with approximately 2 ha (< 0.1%). The dominance of grassland was associated with the availability and continuity of dry, fine fuels that facilitate fire ignition and rapid spread, particularly during dry periods, while the low incidence of fire in evergreen and Afro-alpine vegetation was associated with higher moisture availability, elevation, environmental conditions, and limited fuel continuity.

The LULC results indicated that the spatial arrangement of forest, grassland, agriculture, bareland, and water influences fire susceptibility and potential fire spread. Agricultural areas may provide potential ignition sources, while grassland may facilitate the spread of fire into adjacent shrubland and woodland. Comparison of pre-fire and post-fire vegetation conditions showed a noticeable short-term decline in vegetation condition within burned areas, reflecting the removal and disturbance of above-ground vegetation biomass. However, the extent and duration of vegetation decline may vary according to vegetation type, fire characteristics, and the capacity of vegetation to recover. The study concludes that fire occurrence on Mount Mulanje is influenced by the interaction of vegetation characteristics, land-cover patterns, climatic conditions, topography, and human activities. The findings highlight the need for targeted fire-management strategies, particularly in grassland areas and at interfaces between agricultural land and natural vegetation. Continued satellite-based monitoring is recommended to assess repeated burning, vegetation degradation, and post-fire recovery and to support sustainable management and conservation of the Mount Mulanje ecosystem.

1. INTRODUCTION

Forest fires are a burgeoning phenomenon on a global scale, as they are responsible for large-scale ecological, biological, environmental, and economic [1][2]. In 2021, global wildfires led to the loss of approximately 7.02 million hectares of tree cover [3]. Consequently, researchers across the globe have devoted considerable efforts to developing strategies for mitigating and managing these challenges, thereby making the investigation of their underlying causes a crucial area of research [4]. These fires can arise from a variety of sources [5] and may be further intensified by environmental conditions such as elevated temperatures, strong winds, and prolonged dry or arid conditions. In addition, topographic

characteristics play a significant role in influencing the propagation of fires [6] [4]. Consequently, topographical factors have increasingly been incorporated as key criteria in various studies, particularly those employing multi-criteria analysis to determine areas that are highly vulnerable to fire occurrence and spread [7] [8].

In montane environments, fire interacts with steep environmental gradients of temperature, moisture, vegetation, and human land use, resulting in considerable spatial variation in fire regimes [9] [10]. Elevation is particularly important because it is associated with changes in climatic conditions, vegetation composition, fuel characteristics, and human accessibility, all of which can influence fire occurrence and behavior. As elevation increases, temperature generally decreases while moisture and precipitation may vary considerably according to local topography and exposure. These environmental gradients can consequently produce distinct vegetation communities and fuel conditions along mountain slopes, potentially resulting in differences in fire frequency, intensity, and spatial distribution. The relationship between elevation and fire occurrence is therefore important for understanding spatial variations in fire regimes within mountainous landscapes.

However, the relationship between elevation and fire occurrence is not necessarily linear or consistent across different environments. Lower-elevation areas may experience greater human influence because of their accessibility and proximity to agricultural land and settlements, increasing the likelihood of anthropogenic ignitions. In contrast, higher elevations may experience cooler and wetter conditions that can reduce fuel flammability during some periods, although prolonged dry seasons can substantially increase the susceptibility of montane vegetation to fire. Topographic characteristics such as slope and aspect can further modify these relationships by influencing solar radiation, moisture retention, wind exposure, vegetation distribution, and the rate and direction of fire spread [6][4]. Thus, understanding fire distribution along elevation gradients requires consideration of the interacting effects of climatic, ecological, topographic, and anthropogenic factors.

Fire is particularly important in African landscapes, where human activities constitute a major source of ignition. In many rural areas, fire is deliberately used for agricultural land preparation, vegetation management, hunting, and other livelihood-related activities. When these fires escape their intended areas, they can spread into natural vegetation and forest ecosystems, particularly during dry periods when fuels become highly flammable. The interaction between human activities and seasonal climatic conditions can therefore produce substantial spatial and temporal variation in fire occurrence. Such patterns are of particular concern in mountainous environments because montane ecosystems frequently contain restricted-range species and provide important ecosystem services, including water regulation, soil protection, and biodiversity conservation.

Malawi is characterized by a strong dependence on natural resources and agriculture, making fire an important component of land-use practices in many parts of the country. Seasonal climatic conditions, particularly the transition from the wet to dry season, can create periods when vegetation becomes increasingly susceptible to burning. Recurrent and uncontrolled fires may contribute to forest

degradation, loss of vegetation cover, biodiversity decline, and changes in ecosystem structure. These concerns are particularly important in protected mountain ecosystems, where natural vegetation is exposed to both anthropogenic pressures and climatic variability. The need to understand the spatial distribution of fire in such landscapes is therefore important for effective conservation and fire-management planning.

Mount Mulanje provides an important case study for investigating the relationship between elevation and fire distribution in Malawi. Located in southern Malawi, Mount Mulanje is a prominent isolated massif that rises from approximately 600 m above sea level to about 3,002 m at Sapitwa Peak [11]. The mountain contains a pronounced elevational gradient associated with considerable variation in climate, vegetation, and habitat types. Its lower slopes include woodland communities, while higher elevations contain Afromontane forest, montane grassland, shrubland, and other specialised habitats. These pronounced ecological gradients make the mountain particularly suitable for examining the spatial distribution of fire across elevation zones.

The ecological significance of Mount Mulanje further increases the importance of understanding fire patterns in the area. The mountain supports high levels of biodiversity and endemism, including the critically endangered Mulanje cedar (*Widdringtonia whytei*), which is recognised as Malawi's national tree [12]. Mount Mulanje is also recognised as a Biosphere Reserve because of its ecological importance and contains a range of habitats extending from lower-elevation woodland to high-elevation montane ecosystems [11]. The mountain's forests are additionally important for watershed protection, with numerous rivers originating from the massif and supplying water to surrounding communities (Mount Mulanje Conservation Trust, 2026). Consequently, disturbances such as recurrent uncontrolled fires may have implications extending beyond the immediate areas that are burned.

Fire is already recognised as a significant threat to the ecosystems of Mount Mulanje. Previous observations have identified several anthropogenic sources of fire in the mountain, including hunting, charcoal production, escaped campfires, and arson [14]. More recent conservation reports have also documented extensive burning during the long dry season and highlighted the impacts of recurrent fires on natural vegetation and restoration efforts, including the loss of young Mulanje cedar trees (BGCI, 2024). These observations demonstrate that fire is not only a theoretical ecological concern on Mount Mulanje but represents an active management challenge. Nevertheless, the spatial distribution of these fires in relation to elevation remains insufficiently quantified.

The influence of elevation is particularly relevant on Mount Mulanje because the mountain encompasses substantial environmental differences over a relatively short horizontal distance. Its steep slopes, plateaus, valleys, and isolated peaks create variations in exposure, moisture, temperature, vegetation, and accessibility. The mountain also supports different vegetation communities at different elevations, ranging from lower-elevation miombo woodland to mid-elevation forests and higher-elevation Afromontane and montane communities [13]. These differences may influence both the probability of fire ignition and the capacity of fires to spread. For instance, lower elevations may be more exposed to

anthropogenic ignition because of their proximity to agricultural land and settlements, whereas higher elevations may contain vegetation communities with different fuel characteristics and varying degrees of exposure to human activities.

Despite the recognised importance of fire on Mount Mulanje, there remains a need for more spatially explicit assessment of how fire occurrence varies along the mountain's elevation gradient. Existing studies and conservation assessments have documented the causes and ecological consequences of fire, as well as the broader environmental and biodiversity characteristics of Mount Mulanje (Warren et al., 2001; [12]. However, comparatively limited attention has been given to quantifying the distribution of fire across discrete elevation zones. Such an assessment is important because identifying elevations with disproportionately high fire occurrence can help reveal areas where fire prevention, monitoring, and ecological restoration should be prioritized.

Remote sensing and geographic information system (GIS) techniques provide effective tools for assessing the spatial distribution, occurrence, and extent of wildfires across complex mountainous terrain [16][17]. Satellite-derived fire products and burned-area datasets can provide spatially explicit information on the occurrence and extent of fire, while digital elevation models (DEMs) can be used to characterize and classify landscapes into elevation zones [18] [19]. Combining these datasets enables researchers to quantify the distribution of burned areas across elevation classes and identify spatial patterns that may be difficult to detect through field-based observations alone. Such approaches have increasingly been applied in wildfire studies to investigate relationships between fire occurrence and environmental factors, including topography, vegetation, climate, and land use [4][7][8].

Therefore, assessing the distribution of fire across elevation zones on Mount Mulanje is important for improving understanding of the spatial characteristics of fire within this ecologically significant mountain ecosystem. Establishing whether fire occurrence is concentrated within particular elevation ranges can provide valuable information for targeted fire management, biodiversity conservation, ecological restoration, and land-use planning. It can also provide a baseline for subsequent investigations into the climatic, topographic, vegetation, and anthropogenic factors responsible for observed patterns.

Accordingly, this study assesses the distribution of fire across elevation zones on Mount Mulanje, Malawi. Specifically, the study examines the spatial extent and distribution of fire across different elevation classes and evaluates the relationship between fire occurrence and elevation. By identifying elevation zones that experience comparatively greater fire occurrence, the study aims to provide spatially explicit evidence that can support the prioritization of fire monitoring and management interventions on Mount Mulanje. The findings are expected to contribute to a better understanding of fire–elevation relationships in tropical montane environments and provide a scientific basis for improving fire management and conservation planning within the Mount Mulanje landscape.

2. METHODOLOGY

2.1 Study Area

The study focuses on the Mount Mulanje Massif and the Mulanje Mountain Forest Reserve, located in the southern region of Malawi, with approximate central coordinates of 15.949°S, 35.582°E. The massif comprises five main elevation zones: Miombo woodland, occurring approximately between 600 and 900 m; evergreen forest, from approximately 900 to 1,600 m; grassland, from 1,600 to 2,200 m; shrubland, from 2,200 to 2,500 m; and alpine vegetation, extending from approximately 2,500 to 3,002 m. The climate is characterised by a pronounced dry season, typically occurring from May to October/November, and a wet season associated with the Inter-Tropical Convergence Zone (ITCZ). The Mulanje cedar (*Widdringtonia whytei*) is predominantly distributed at elevations between approximately 1,800 and 2,550 m.

For the analysis, the study area boundary is defined by the official Forest Reserve boundary, which encompasses the main elevational gradient of the massif. All spatial datasets are projected to a common coordinate reference system appropriate for Malawi, namely WGS 84 / UTM Zone 36S, to ensure consistency and accuracy in spatial analysis.

2.2 Data Sources

Five main categories of spatial data were acquired and processed for this study. All datasets are freely available, with most being obtained from established international data repositories.

2.2.1 Burned Area Products

For higher spatial detail, burned-area scars were mapped using Sentinel-2 MSI imagery obtained from the Copernicus Data Space Ecosystem (<https://browser.dataspace.copernicus.eu/>) and analysed using the Normalised Burn Ratio (NBR). The NBR is a spectral index designed to highlight burned areas, particularly across large fire-affected zones. The index combines near-infrared (NIR) and shortwave-infrared (SWIR) wavelengths.

Healthy vegetation exhibits high reflectance in the NIR region and low reflectance in the SWIR region of the electromagnetic spectrum (Fig. 2). This spectral response is generally reversed in areas affected by fire. Recently burned areas typically exhibit low reflectance in the NIR and high reflectance in the SWIR. Consequently, the spectral difference between healthy vegetation and burned areas is particularly pronounced in the NIR and SWIR regions.

To capture this spectral contrast, the NBR uses the ratio between the NIR and SWIR bands, according to the formula presented below. High NBR values generally indicate healthy, vigorous vegetation, whereas low NBR values indicate burned areas, exposed soil, or other areas with little or no vegetation. Non-burned areas may exhibit NBR values close to zero, although the exact values can vary depending on vegetation type, soil characteristics, moisture conditions, and image acquisition conditions.

$$NBR = \frac{(NIR - SWIR)}{(NIR + SWIR)}$$

2.2.2 Digital Elevation Model and Topographic Derivatives

Elevation data were obtained from the Shuttle Radar Topography Mission (STRM) 1-arc-second (approximately 30m) Digital elevation model. The DEM was used to define elevation zones.

2.2.3 Land Cover Data

Land-cover information was derived from a combination of **ESA WorldCover 10 m** data and supervised classification of selected Sentinel-2 scenes. ESA WorldCover data were obtained from the ArcGIS Living Atlas Land Cover dataset. The major land-cover classes included water, settlements, agriculture, bare rock/soil, and forest. The land-cover layer was used to assess the relationship between vegetation or land-cover types and fire occurrence across different elevation zones.

2.2.4 Ancillary Spatial Data

The official boundary of the Mulanje Mountain Forest Reserve (MMFR) was obtained from the Mount Mulanje Conservation Trust (MMCT) and used to define the core study area. Additional ancillary spatial data included major roads, settlements, and the locations of known Mulanje cedar plots, where available from conservation partners. These datasets supported the interpretation of fire patterns in relation to human accessibility and conservation priorities.

2.2.5 Field Data

For validation purposes, 50 fire hotspot locations were recorded in the field using a handheld Global Positioning System (GPS) device. The geographic coordinates of each observed fire-affected location were collected and subsequently imported into the GIS environment for comparison with the fire hotspot and burned-area datasets derived from remote sensing imagery. The field observations were used to assess the spatial accuracy of the remotely sensed fire detections and to determine whether areas identified as burned corresponded to actual fire-affected locations on the ground. The GPS points were distributed across different elevation zones and vegetation or land-cover types, where accessible, to provide representative ground observations for the validation process. This field-based validation helped improve confidence in the accuracy and reliability of the spatial fire distribution analysis.

2.2.6 Vegetation Indices

The Normalized Difference Vegetation Index (NDVI) was calculated from Sentinel-2 MSI surface reflectance imagery to characterise vegetation greenness and fuel condition across the elevation zones of Mount Mulanje. NDVI was computed using the standard formula:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

where NIR is the near-infrared band and Red is the red band.

Multi-temporal NDVI composites were generated for both the dry season (peak fire period) and the wet season. Mean, maximum and minimum NDVI values were extracted for each elevation zone using zonal statistics. Pre-fire and post-fire NDVI were also compared for selected major fire events to assess vegetation loss and early recovery. NDVI layers were used as an additional biophysical variable in the analysis of relationships between fire occurrence, vegetation condition and elevation.

2.3 Elevation Zonation

Using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), elevation data were extracted and processed in QGIS using the contour extraction tools. Based on the elevation ranges of the Mount Mulanje Massif, five main elevation zones were delineated: Miombo woodland (600–900 m), evergreen forest (900–1,600 m), grassland (1,600–2,200 m), shrubland (2,200–2,500 m), and Afro-alpine vegetation (2,500–3,002 m). These elevation zones were subsequently used to analyse the spatial distribution of fire occurrences and assess variations in fire patterns along the elevational gradient.

3. RESULTS

3.1 Annual Burned Area

The analysis of burned areas on Mount Mulanje showed considerable interannual variation between 2016 and 2025. Over the ten-year period, a total of 10,766 ha was burned, with an average annual burned area of approximately 1,076.6 ha. The annual burned area ranged from a minimum of 192 ha in 2025 to a maximum of 3,022 ha in 2022.

In 2016, approximately 1,298 ha were burned. This increased substantially in 2017, when burned area reached 2,703 ha, representing one of the largest annual burned areas during the study period. Burned area subsequently declined sharply to 477 ha in 2018, followed by a slight increase to 538 ha in 2019. The downward trend continued in 2020, when only 382 ha were burned.

A substantial increase occurred again in 2021, with the burned area rising to 1,214 ha. The highest value of the study period was recorded in 2022, when approximately 3,022 ha were burned. This was followed by a pronounced decline in 2023, with only 386 ha affected. Burned area increased moderately to 554 ha in 2024, before reaching the lowest value of the study period, 192 ha, in 2025.

Overall, the results indicate a highly variable annual fire pattern, with particularly large burned areas occurring in 2017 and 2022, while relatively smaller burned areas were recorded during 2018–2020 and 2023–2025. The burned area in 2022 was approximately 15.7 times greater than that recorded in 2025. Similarly, the burned area decreased by approximately 85.2% between 2016 and 2025, although the intervening years demonstrate that the pattern was not a continuous decline.

3.2 Validation

To validate the fire-occurrence areas identified through remote sensing and the Normalized Burn Ratio (NBR), 50 fire-incidence points were collected using a handheld GPS during field verification as shown in Fig. 4. These GPS points represented locations where evidence of fire occurrence was observed in the field.

The GPS coordinates were then imported into the GIS environment and manually checked against the fire-affected areas identified from the NBR analysis. Each of the 50 validation points was compared with the mapped burned areas to determine whether the remotely sensed results correctly identified locations affected by fire.

Of the 50 GPS validation points, 46 points coincided with areas identified as burned by the NBR analysis, indicating a strong agreement between the field observations and the remotely sensed results. The remaining 4 points did not coincide with the NBR-derived burned areas, which may be attributed to factors such as differences in the timing of field observations and satellite imagery acquisition, spatial resolution, or changes in vegetation and ground conditions after the fire event.

3.3 Fire Occurrences in Different Vegetation Zones

The analysis of fire occurrence across the different vegetation zones of Mount Mulanje over the ten-year study period revealed substantial differences in the extent of burned area among the zones. A total of 10,766 ha was burned across the five vegetation zones, namely miombo woodland, evergreen vegetation, grassland, shrubland, and Afro-alpine vegetation as shown in Figs. 5 and 6. The distribution of burned area was highly uneven, with grassland accounting for the overwhelming majority of the area affected by fire, while the Afro-alpine zone experienced very limited burning.

The grassland zone recorded the largest burned area, with approximately 9,522 ha burned during the study period. This represents about 88.4% of the total burned area recorded across all vegetation zones. The very large proportion of burned area occurring in grassland indicates that this vegetation type was the most frequently or extensively affected by fire during the ten-year period. The dominance of grassland in the burned-area distribution may be associated with the presence of continuous and highly flammable grasses, which can provide sufficient fuel for fire to spread rapidly across relatively large areas, particularly during dry periods. Consequently, grassland fires may account for much of the extensive fire activity observed on Mount Mulanje.

The shrubland zone recorded the second-largest burned area, with approximately 642 ha affected by fire over the study period. This accounts for approximately 6.0% of the total burned area. Although substantially lower than the area burned in grassland, the extent of burning in shrubland indicates that fires also affected areas dominated by woody shrubs. The occurrence of fire in these areas may depend on the availability and continuity of dry vegetation and fuel conditions, as well as the spread of fires from adjacent vegetation types.

The Miombo zone recorded approximately 346 ha of burned area, representing about 3.2% of the total area burned during the ten-year period. Fire occurrence in miombo vegetation was therefore considerably lower than in grassland and shrubland. The relatively smaller burned area may reflect differences in vegetation structure, fuel continuity, and moisture conditions compared with grass-dominated areas. Nevertheless, the occurrence of burned areas within the miombo zone demonstrates that woodland vegetation was also exposed to fire during the study period.

Approximately 254 ha were burned in the evergreen vegetation zone, accounting for about 2.4% of the total burned area. This relatively small proportion suggests that evergreen vegetation experienced considerably less fire activity than grassland. The lower occurrence of fire in this zone may be related to the generally higher moisture content and less continuous availability of dry, easily combustible fuels compared with grassland. However, the presence of burned areas indicates that fire was not completely absent from evergreen vegetation.

The Afro-alpine zone recorded the smallest burned area, with only approximately 2 ha burned over the ten-year study period. This represents less than 0.1% of the total burned area. The extremely limited occurrence of fire in this zone suggests that Afro-alpine vegetation was comparatively resistant or less exposed to fire during the study period. Its higher elevation, environmental conditions, and potentially limited fuel availability may contribute to the very low extent of fire occurrence observed.

3.4 Land Use and Land Cover of Mount Mulanje

Land-cover classification was conducted to identify the major land-cover types within the Mount Mulanje Forest Reserve. As shown in Fig. 7. The analysis produced four main land-cover classes: vegetation, cultivated land, buildings, and grassland. Grassland constitutes a substantial proportion of the study area, particularly across the higher and more open parts of the landscape. Vegetation is distributed mainly across forested areas, while cultivated land is concentrated around the accessible margins of the reserve. Buildings occur in relatively smaller and more localized areas. The resulting land-cover map was used to examine the spatial relationship between land-cover types, elevation zones, and fire occurrences, thereby helping to determine whether particular land-cover classes are more frequently affected by fire.

3.5 Vegetation Condition Before and After Fire

The assessment of vegetation condition before and after fire was conducted to determine how fire occurrence influenced the vegetation status of Mount Mulanje. Vegetation condition was evaluated by comparing the vegetation characteristics observed before fire with those observed following fire occurrence. This comparison provides an indication of the extent to which vegetation cover and condition changed after areas were affected by fire.

Before fire occurrence, the affected areas generally exhibited relatively higher vegetation conditions, characterized by greater vegetation cover and stronger vegetation responses as shown in Fig. 8. The pre-fire condition provides a baseline against which changes following fire can be assessed. Areas with

healthy and continuous vegetation cover are expected to show stronger vegetation-index responses than areas with sparse or degraded vegetation.

Following fire occurrence, a noticeable reduction in vegetation condition was observed in the burned areas, as shown in Fig. 9. Fire removes above-ground vegetation biomass and can temporarily reduce vegetation cover, resulting in lower vegetation index values immediately after burning. The magnitude of this change may vary depending on fire intensity, vegetation type, the season in which the fire occurs, and the ability of the vegetation to recover following fire.

4. DISCUSSION

The study recorded a total of 10,766 ha of burned area across the five vegetation zones during the ten-year period. However, the distribution was highly uneven. Grassland accounted for approximately 9,522 ha (88.4%), meaning that nearly nine out of every ten hectares burned occurred within the grassland zone. In contrast, shrubland, miombo woodland, evergreen vegetation, and Afro-alpine vegetation collectively accounted for only about 11.6% of the burned area. This pronounced difference suggests that vegetation type and associated fuel characteristics play an important role in determining the spatial distribution of fire on Mount Mulanje.

The grassland zone was clearly the most fire-prone vegetation type. Its dominance in the burned-area distribution can largely be attributed to the characteristics of grass-dominated ecosystems. Grasslands commonly contain continuous layers of fine, dry fuels that can ignite easily and allow fire to spread rapidly, particularly during the dry season. Once grasses become sufficiently dry, even relatively small fires can spread over extensive areas where fuel is continuous. The large area burned in grassland may therefore reflect both the high flammability of dry grasses and the ability of fire to spread across relatively open landscapes. In addition, repeated burning can maintain grass-dominated conditions by suppressing the establishment of woody vegetation, potentially creating a feedback in which grasslands remain particularly susceptible to subsequent fires.

The shrubland zone, with approximately 642 ha (6.0%) burned, experienced substantially less fire than grassland but was still the second most affected vegetation type. This indicates that shrub-dominated areas can support fire when sufficient dry fuel is available. However, unlike grasslands, shrublands may have a more discontinuous fuel structure, which can restrict fire spread. Fire in shrubland may also be influenced by its proximity to grassland, since fires originating in highly flammable grasslands can spread into neighbouring shrub-dominated areas under favourable weather conditions. Therefore, the relatively moderate burned area in shrubland may reflect both its own fuel characteristics and its connectivity with surrounding fire-prone vegetation.

The miombo woodland recorded approximately 346 ha (3.2%) of burned area. Although this represents a relatively small proportion of total burning, it demonstrates that woodland vegetation is not immune to fire. The lower burned area compared with grassland may be associated with differences in fuel continuity and moisture availability. In woodland ecosystems, vegetation is generally more structurally

complex, and fuels may be less continuous at ground level than in grasslands. Nevertheless, dry leaf litter, grasses beneath the tree canopy, fallen branches, and other combustible materials can provide sufficient fuel to carry fires. The occurrence of fire in miombo therefore suggests that fire management on Mount Mulanje should not focus exclusively on grassland areas.

The evergreen vegetation zone experienced approximately 254 ha (2.4%) of burning, making it one of the less affected vegetation types. The relatively low burned area is consistent with the expectation that evergreen vegetation generally maintains greater moisture availability than seasonally dry grasslands. Moist vegetation is less readily ignited and can interrupt the continuity of dry fuels required for rapid fire spread. The comparatively small extent of burning therefore suggests that the evergreen zone may provide some degree of natural resistance to fire. Nevertheless, the occurrence of burned areas within this zone is important because even relatively infrequent fires can have significant ecological consequences in vegetation communities that are not well adapted to recurrent burning.

The Afro-alpine zone was the least affected, with only approximately 2 ha burned, representing less than 0.1% of the total burned area. This extremely small contribution indicates that fire occurrence at the highest elevations was negligible compared with the lower vegetation zones. Several factors could explain this pattern. The Afro-alpine environment has distinctive climatic and ecological conditions, including low temperatures, high elevation, and potentially limited continuity of combustible fuels. Its relatively isolated position may also reduce exposure to fires spreading from lower elevations. The result suggests that elevation and associated environmental conditions may act as important constraints on fire occurrence. However, the very small burned area should not necessarily be interpreted as complete fire resistance, since rare fires can still occur under unusually dry or favourable conditions.

The LULC results provide an important framework for interpreting the observed fire patterns on Mount Mulanje. The previous fire analysis showed that grassland accounted for approximately 88.4% of the total burned area, whereas vegetation types such as evergreen vegetation and Afro-alpine vegetation experienced considerably less burning. This suggests that the characteristics and spatial distribution of land-cover types are important factors in determining fire susceptibility.

In particular, grassland appears to represent the land-cover type most conducive to extensive fire spread, mainly because of the presence of continuous dry fuels. Forest, particularly moist evergreen forest, is likely to be less frequently affected because of higher moisture levels and less continuous availability of easily ignitable fine fuels. However, forest edges and areas adjacent to grassland may remain vulnerable, especially during periods of prolonged dryness. Agricultural areas may also contribute to fire occurrence through human activities and their proximity to natural vegetation.

The LULC pattern therefore indicates that fire occurrence on Mount Mulanje should not be viewed solely as a natural phenomenon. Rather, it is likely to result from an interaction between vegetation characteristics, climatic conditions, topography, and human land-use activities. The conversion or fragmentation of natural vegetation through agriculture may modify fuel continuity and create locations where human ignition sources interact with highly flammable vegetation.

Following fire occurrence, a noticeable reduction in vegetation condition was observed in burned areas. Fire removes above-ground vegetation biomass and can temporarily reduce vegetation cover, resulting in lower vegetation-index values immediately after burning. The magnitude of this change may vary depending on fire intensity, vegetation type, season of burning, and the ability of the vegetation to recover following fire.

The comparison between pre-fire and post-fire conditions therefore indicates that fire had an immediate negative effect on vegetation conditions in the affected areas. Burned areas generally showed a reduction in vegetation condition after fire compared with their condition before burning. This reduction reflects the removal or disturbance of vegetation caused by fire. However, the post-fire condition does not necessarily represent permanent vegetation loss, because some vegetation types may recover through regeneration and resprouting after the fire.

Differences in vegetation response were also expected among the different vegetation zones. Grassland areas, which accounted for the largest proportion of the burned area on Mount Mulanje, may show relatively rapid recovery where grasses regenerate after burning. In contrast, vegetation types such as miombo, evergreen vegetation, and shrubland may exhibit different rates and patterns of recovery depending on their species composition and ecological characteristics. The Afro-alpine zone, which experienced very limited fire occurrence during the study period, contributed comparatively little to the overall change in vegetation condition.

Overall, the comparison of vegetation condition before and after fire demonstrates that fire caused a short-term decline in vegetation condition within burned areas. The extent and duration of this decline, however, depend on the characteristics of the fire and the subsequent recovery of vegetation. Therefore, changes in vegetation conditions should be considered both in terms of the immediate effects of fire and the longer-term capacity of vegetation communities to recover.

The results highlight the importance of monitoring vegetation conditions following fire events on Mount Mulanje. Repeated assessment using satellite-derived vegetation indices can help identify areas experiencing substantial vegetation degradation and can also provide information on the rate and extent of post-fire recovery. Such monitoring is particularly important in areas with frequent or extensive burning, where repeated fires may reduce the capacity of vegetation to recover fully between fire events.

5. CONCLUSION

This study concludes that fire occurrence on Mount Mulanje is highly unevenly distributed across vegetation zones and is strongly associated with land-cover characteristics and environmental conditions. Over the ten-year study period, a total of 10,766 ha was burned across the five vegetation zones. Grassland was by far the most affected vegetation type, accounting for 9,522 ha (88.4%) of the total burned area, followed by shrubland with 642 ha (6.0%), miombo woodland with 346 ha (3.2%), evergreen vegetation with 254 ha (2.4%), and Afro-alpine vegetation with approximately 2 ha (< 0.1%).

This pattern demonstrates that grassland is the dominant fire-prone vegetation zone on Mount Mulanje, while Afro-alpine vegetation experienced very limited fire activity.

The high incidence of fire in grassland is largely associated with the abundance and continuity of dry, fine fuels, which facilitate ignition and rapid fire spread during dry periods. The relatively lower levels of burning in shrubland, miombo, and evergreen vegetation suggest that differences in vegetation structure, fuel continuity, and moisture availability influence fire susceptibility. The very limited burning in the Afro-alpine zone further indicates that elevation, climatic conditions, and limited fuel availability may constrain fire occurrence at higher elevations. Nevertheless, the occurrence of fire in all vegetation zones demonstrates that no vegetation type can be considered completely free from fire risk.

The study also establishes that land use and land cover provide an important framework for understanding the spatial distribution of fire on Mount Mulanje. The interaction between grassland, forest, agricultural land, bareland, and water influences the availability and continuity of fuels and consequently affects the potential for fire ignition and spread. In particular, the proximity of agricultural areas to natural vegetation may increase the potential for human-related ignition, while grassland can facilitate the spread of fire into adjacent shrubland and woodland. Therefore, fire occurrence on Mount Mulanje is not solely a natural ecological process but is likely influenced by the combined effects of vegetation characteristics, climatic conditions, topography, and human land-use activities.

The findings further demonstrate that fire has an immediate negative effect on vegetation conditions. Burned areas generally showed reduced vegetation-index values following fire, reflecting the removal and disturbance of above-ground vegetation biomass. However, the observed decline should not necessarily be interpreted as permanent vegetation degradation because vegetation communities differ in their capacity and rate of post-fire recovery. Grasslands may recover relatively quickly through grass regeneration, whereas miombo woodland, shrubland, and evergreen vegetation may require longer periods depending on species composition, fire intensity, and environmental conditions. The limited fire occurrence in the Afro-alpine zone means that its contribution to overall post-fire vegetation change was minimal.

Overall, the study demonstrates that fire is an important factor influencing vegetation conditions and landscape dynamics on Mount Mulanje. The concentration of burning in grassland, combined with the observed decline in vegetation condition following fire, highlights the need for targeted fire-management interventions. Particular attention should be given to grassland areas and the interfaces between grassland, agricultural land, shrubland, and forest, where fire ignition and subsequent spread may be more likely.

Finally, the study highlights the value of remote sensing and satellite-derived vegetation indices for monitoring fire impacts and post-fire vegetation recovery. Continued monitoring can help identify areas experiencing repeated burning, assess the severity of vegetation disturbance, and determine whether vegetation is recovering or undergoing longer-term degradation. Such information is essential for

developing effective fire-prevention and management strategies and for supporting the long-term conservation and ecological integrity of the Mount Mulanje ecosystem.

STATEMENTS

Declarations

Author Contributions

LM: Methodology, Software, Investigation, Writing – original draft, Writing – review & editing, Conceptualization, Visualization, Formal analysis, Validation, Data curation.

Acknowledgements

The authors would like to thank the Mount Mulanje Conservation Trust (MMCT) for providing institutional support. We also acknowledge the contributions of colleagues who provided informal feedback during the preparation of this manuscript.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

References

1. Sachdeva S, Bhatia T, Verma AK (2018) GIS-based evolutionary optimized Gradient Boosted Decision Trees for forest fire susceptibility mapping. *Nat Hazards* 92:1399–1418. <https://doi.org/10.1007/s11069-018-3256-5>
2. Van Le H, Hoang DA, Tran CT, Nguyen PQ, Tran VHT, Hoang ND, Amiri M, Ngo TPT, Nhu HV, Van Hoang T, Bui DT (2021) A new approach of deep neural computing for spatial prediction of wildfire danger in tropical climate areas. *Ecol Inf* 63:101300. <https://doi.org/10.1016/j.ecoinf.2021.101300>
3. Dos Reis M, Graça PMLA, Yanai AM, Ramos CJP, Fearnside PM (2021) Forest fires and deforestation in the central Amazon: Effects of landscape and climate on spatial and temporal dynamics. *J Environ Manage* 288:112310. <https://doi.org/10.1016/j.jenvman.2021.112310>
4. Paudel G, Pandey K, Lamsal P, Bhattarai A, Bhattarai A, Tripathi S et al (2024) Geospatial forest fire risk assessment and zoning by integrating MaxEnt in Gorkha District. *Nepal Heliyon* 10(11):e31305. <https://doi.org/10.1016/j.heliyon.2024.e31305>
5. Tout F, Rebouh N, Benzid Y, Zouak Z, Zeghmar A, Bourecherouche M, Dinar H, Keblouti S (2025) GIS-Based Analysis of Wildfire Distribution Across Slopes in the Wadi Safsaf Watershed, Northeastern Algeria. *Banko Janakari* 35(2):45–54. <https://doi.org/10.3126/banko.v35i2.73366>

6. Makumbura RK, Dissanayake P, Gunathilake MB, Rathnayake N, Kantamaneni K, Rathnayake U (2024) Spatial mapping and analysis of forest fire risk areas in Sri Lanka – Understanding environmental significance. *Case Stud Chem Environ Eng* 9:100680. <https://doi.org/10.1016/j.cscee.2024.100680>
7. Talukdar NR, Ahmad F, Goparaju L, Choudhury P, Arya R, Qayum A, Rizvi J (2024) Forest fire estimation and risk prediction using multispectral satellite images: Case study. *Nat Hazards Res* 4(2):87–96. <https://doi.org/10.1016/j.nhres.2024.01.007>
8. Vergara AJ, Valqui-Reina VS, Cieza-Tarrillo D, Munoz-Astecker LD, Ocaña CL, Cubas J, Auquiñivín-Silva EA (2024) Integration of the AHP Method and GIS Techniques for Mapping Areas Susceptible to Forest Fires in the Southern Amazon Region (Peru). *Int J Des Nat Ecodyn* 19(3):769–778. <https://doi.org/10.18280/ijdne.190307>
9. Bekker MF, Taylor AH (2001) Gradient analysis of fire regimes in montane forests of the southern Cascade Range, Thousand Lakes Wilderness, California, USA. *Plant Ecol* 155:15–28. <https://doi.org/10.1023/A:1013263212092>
10. Gill L, Taylor AH (2009) Top-down and bottom-up controls on fire regimes along an elevational gradient on the east slope of the Sierra Nevada, California, USA. *Fire Ecol* 5(3):57–75. <https://doi.org/10.4996/fireecology.0503057>
11. United Nations Educational, Scientific and Cultural Organization (UNESCO) (2025) Mount Mulanje Cultural Landscape. UNESCO World Heritage Centre
12. Bayliss J, Makungwa S, Hecht J, Nangoma D, Bruessow C (2007) Saving the Island in the Sky: The plight of the Mount Mulanje cedar *Widdringtonia whytei* in Malawi. *Oryx* 41(1):64–69. <https://doi.org/10.1017/S0030605307001548>
13. Dowsett-Lemaire F (1988) The forest vegetation of Mt. Mulanje (Malawi): A floristic and chorological study along an altitudinal gradient (650–1950 m). *Bull du Jardin Botanique Natl de Belgique* 58(1–2):77–107. <https://doi.org/10.2307/3668402>
14. NASA Earth Observatory (2014), October 10 *The forests of Mulanje*. NASA Earth Observatory
15. Warren A, Kosonen J, Katundu M, Matinga B (2001) *Causes and consequences of anthropogenic fire in Mulanje Mountain Forest Reserve, Southern Malawi: Report following Mulanje Fire Research Expedition, 2001*
16. Li X et al (2024) Application of Remote Sensing and Explainable Artificial Intelligence (XAI) for Wildfire Occurrence Mapping in the Mountainous Region of Southwest China. *Remote Sens* 16(19):3602. <https://doi.org/10.3390/rs16193602>
17. Nelson DM, He Y, Moore GW (2024) Trends and applications in wildfire burned area mapping: Remote sensing data, cloud geoprocessing platforms, and emerging algorithms. *Geomatics* 4:100008. <https://doi.org/10.1016/j.geomat.2024.100008>
18. Giglio L, Boschetti L, Roy DP, Humber ML, Justice CO (2025) The NASA VIIRS burned area product, global validation, and intercomparison with the NASA MODIS burned area product. *Remote Sens Environ* 328:115006. <https://doi.org/10.1016/j.rse.2025.115006>

19. Boschetti L, Roy DP, Giglio L, Huang H, Zubkova M, Humber ML (2019) Global validation of the collection 6 MODIS burned area product. Remote Sens Environ 235:111490.
<https://doi.org/10.1016/j.rse.2019.111490>

Figures

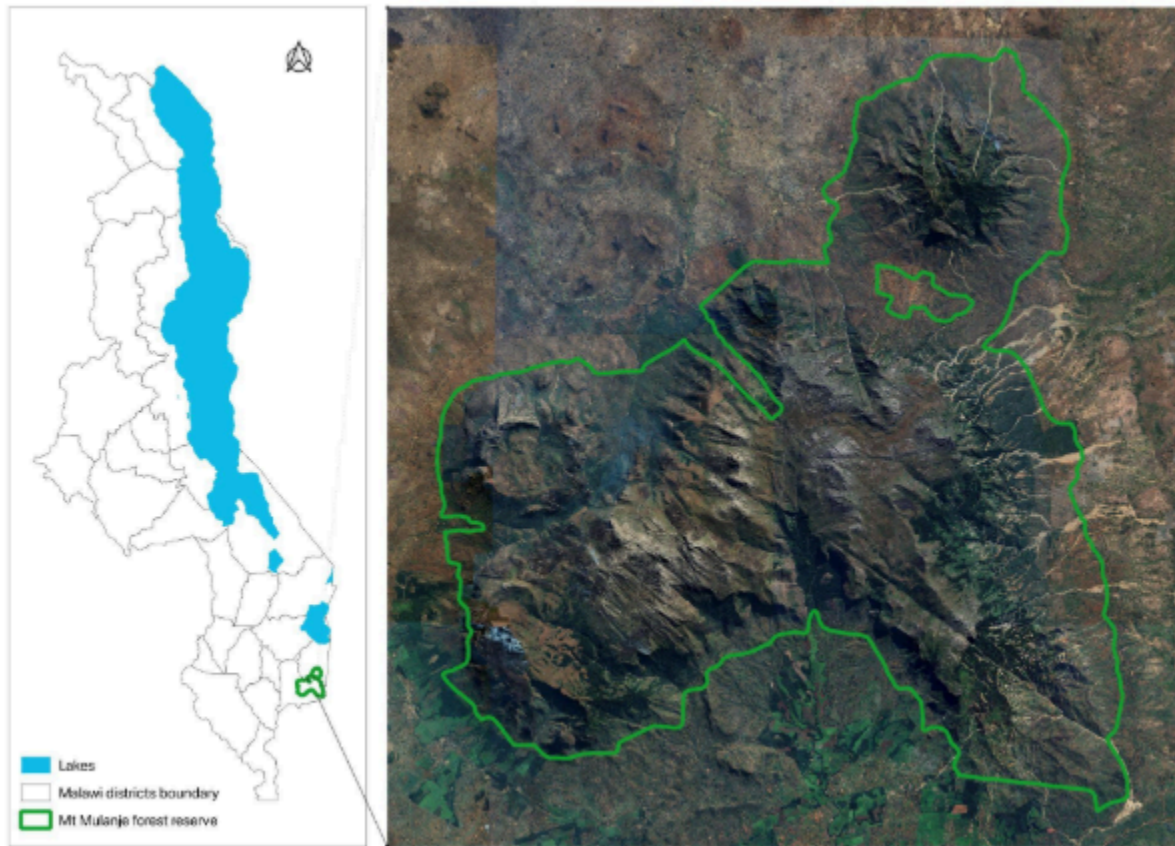


Figure 1

Mount Mulanje

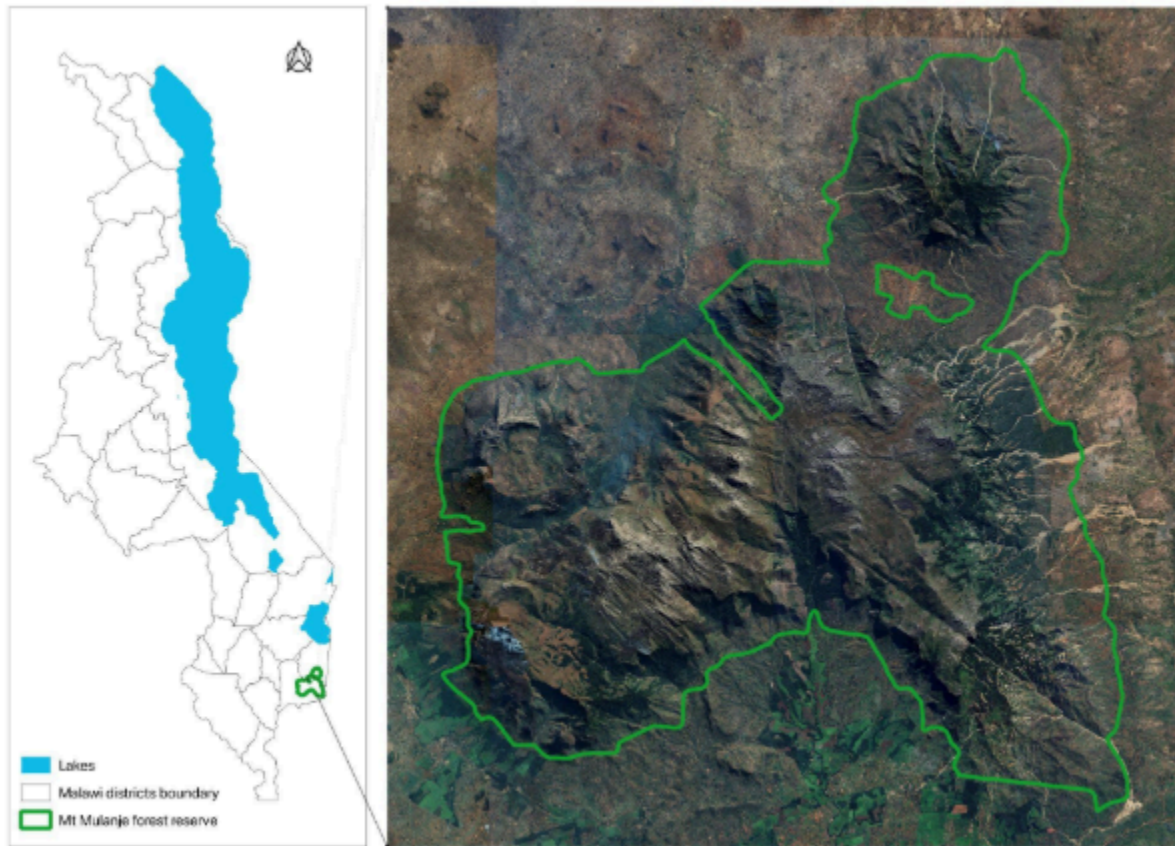


Figure 1

Mount Mulanje

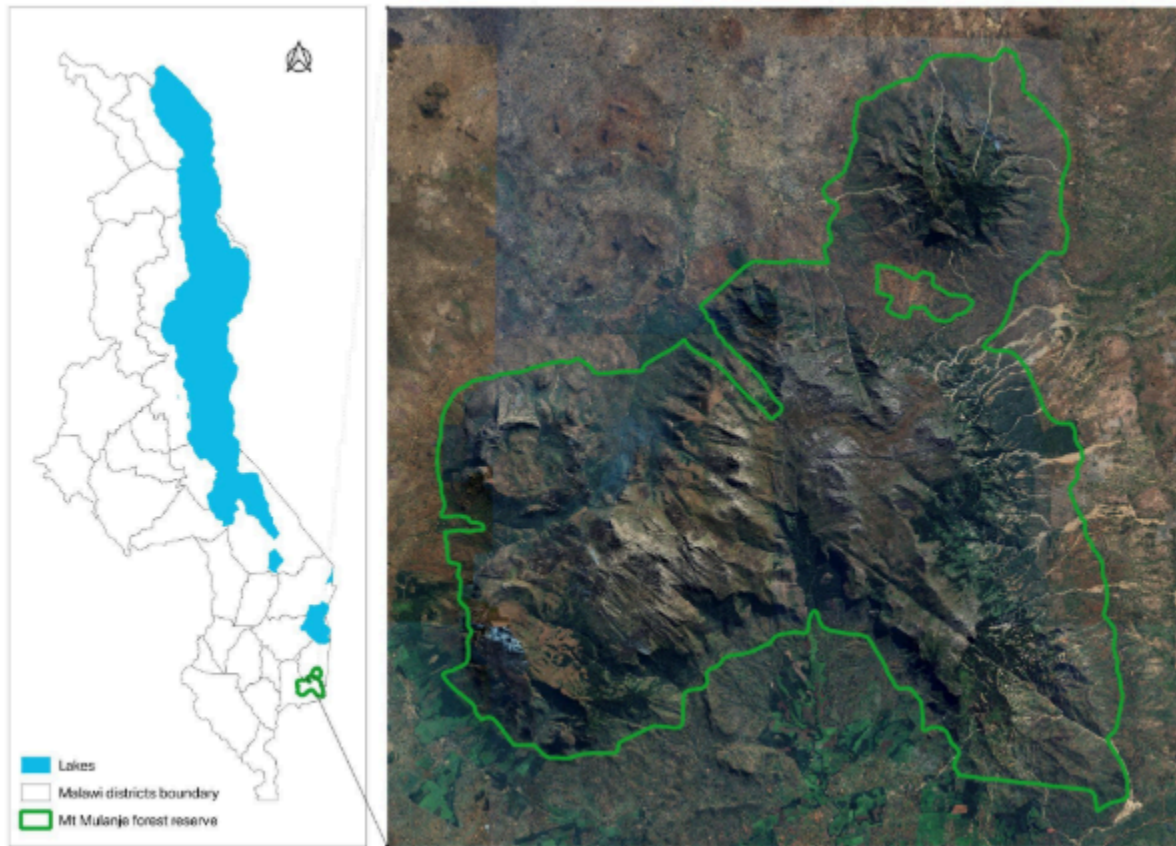


Figure 1

Mount Mulanje

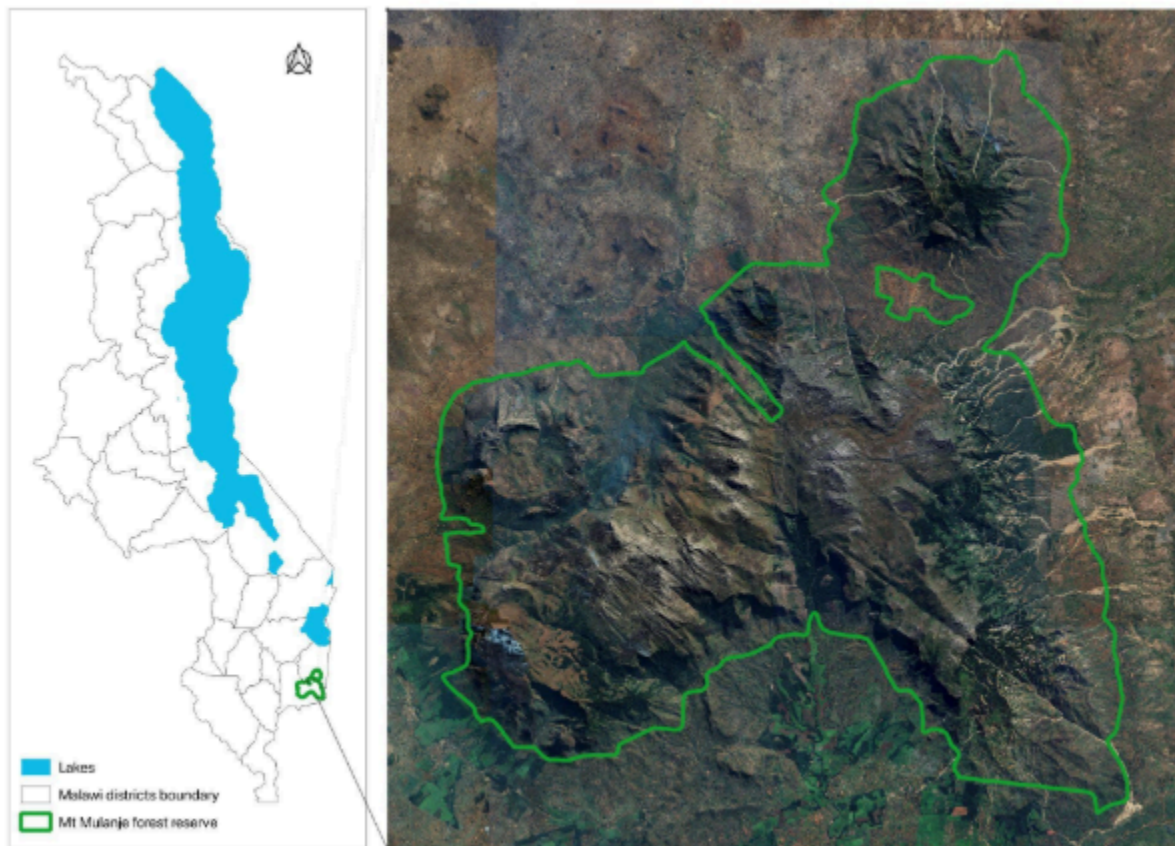


Figure 1

Mount Mulanje

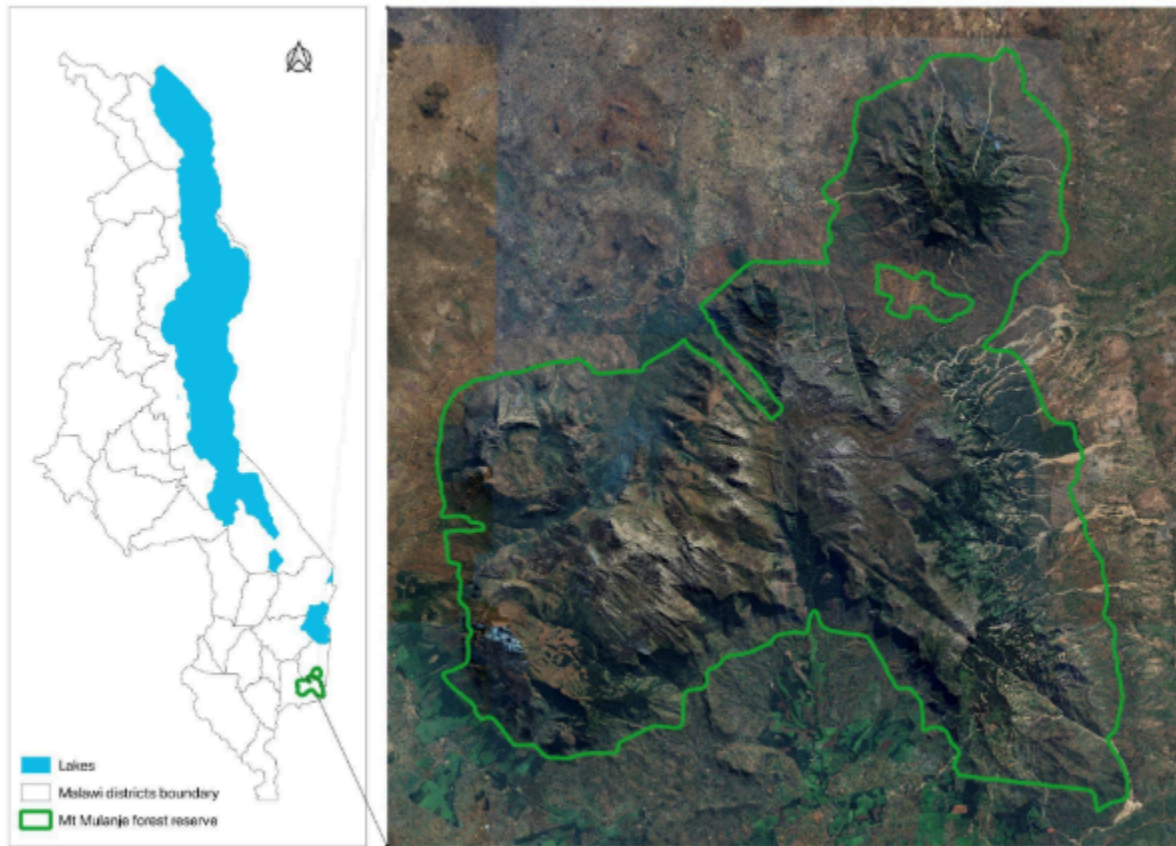


Figure 1

Mount Mulanje

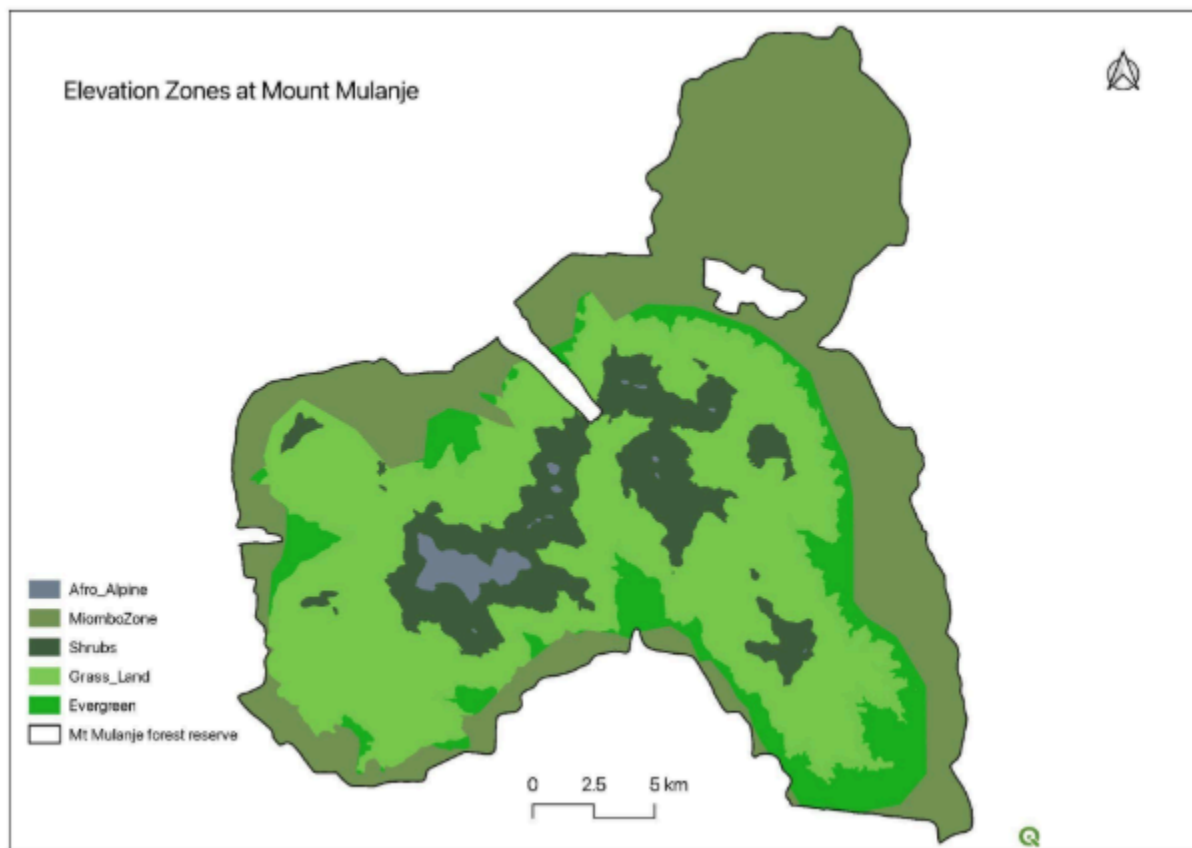


Figure 2

Elevation Zones at Mount Mulanje

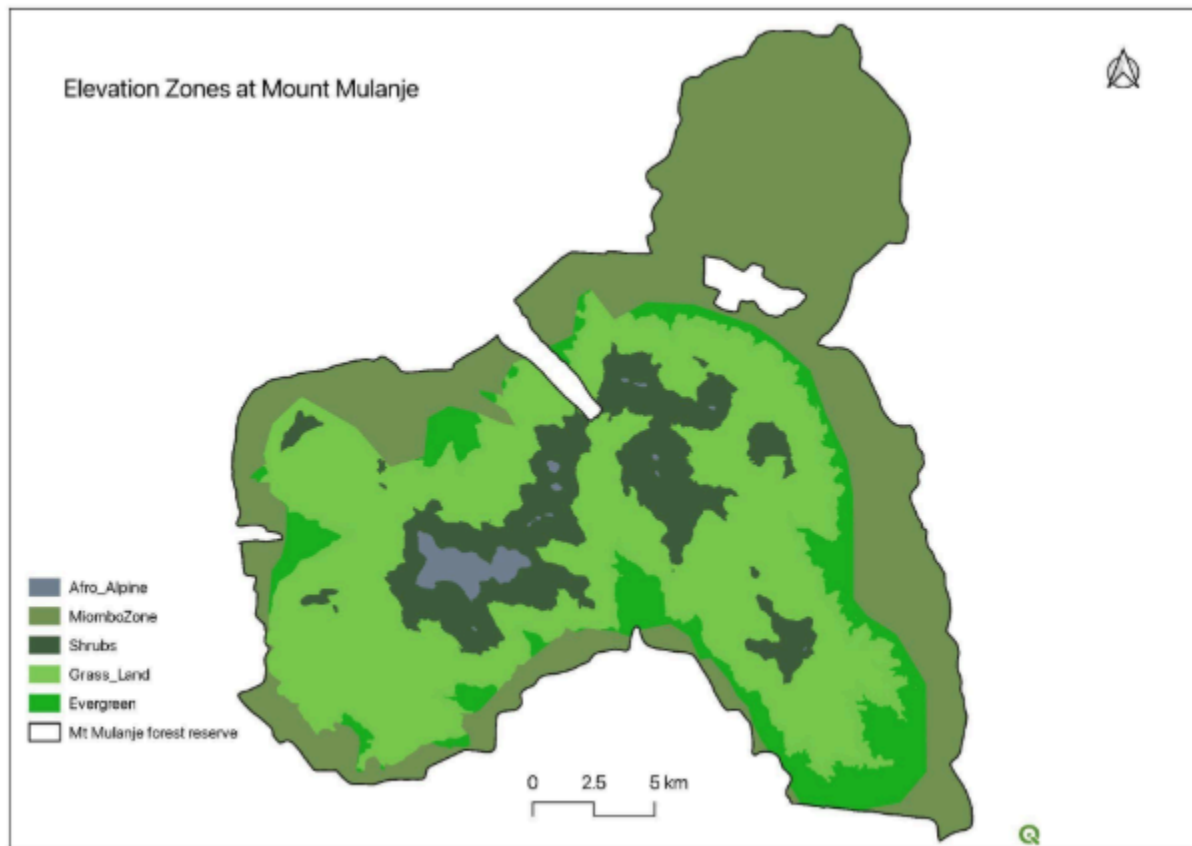


Figure 2

Elevation Zones at Mount Mulanje

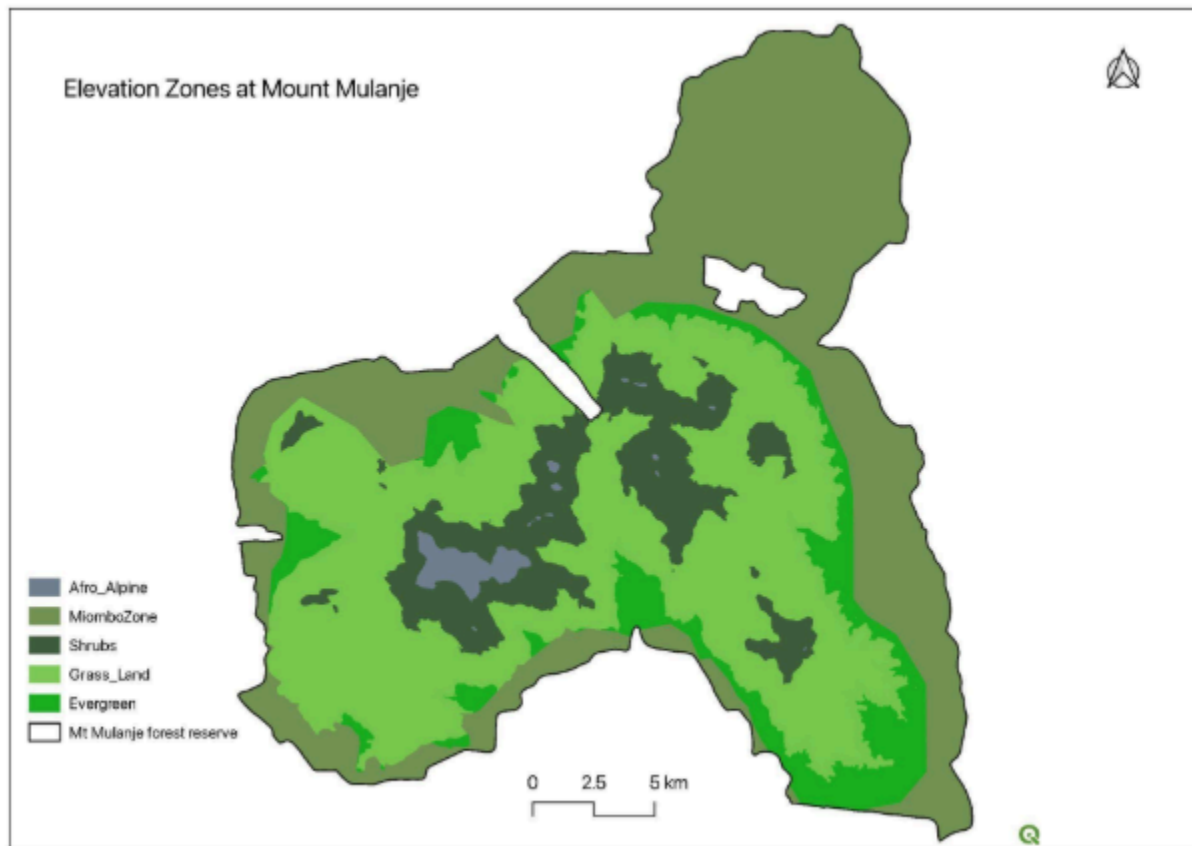


Figure 2

Elevation Zones at Mount Mulanje

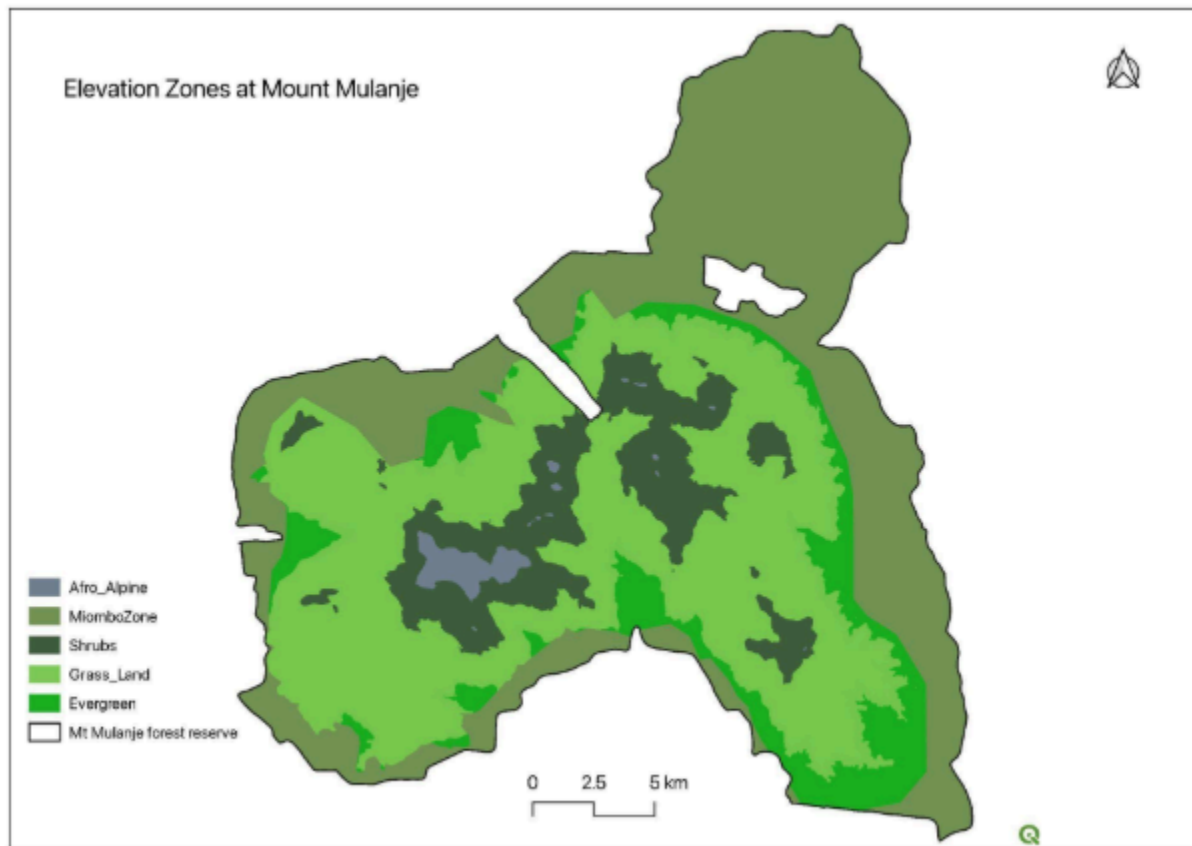


Figure 2

Elevation Zones at Mount Mulanje

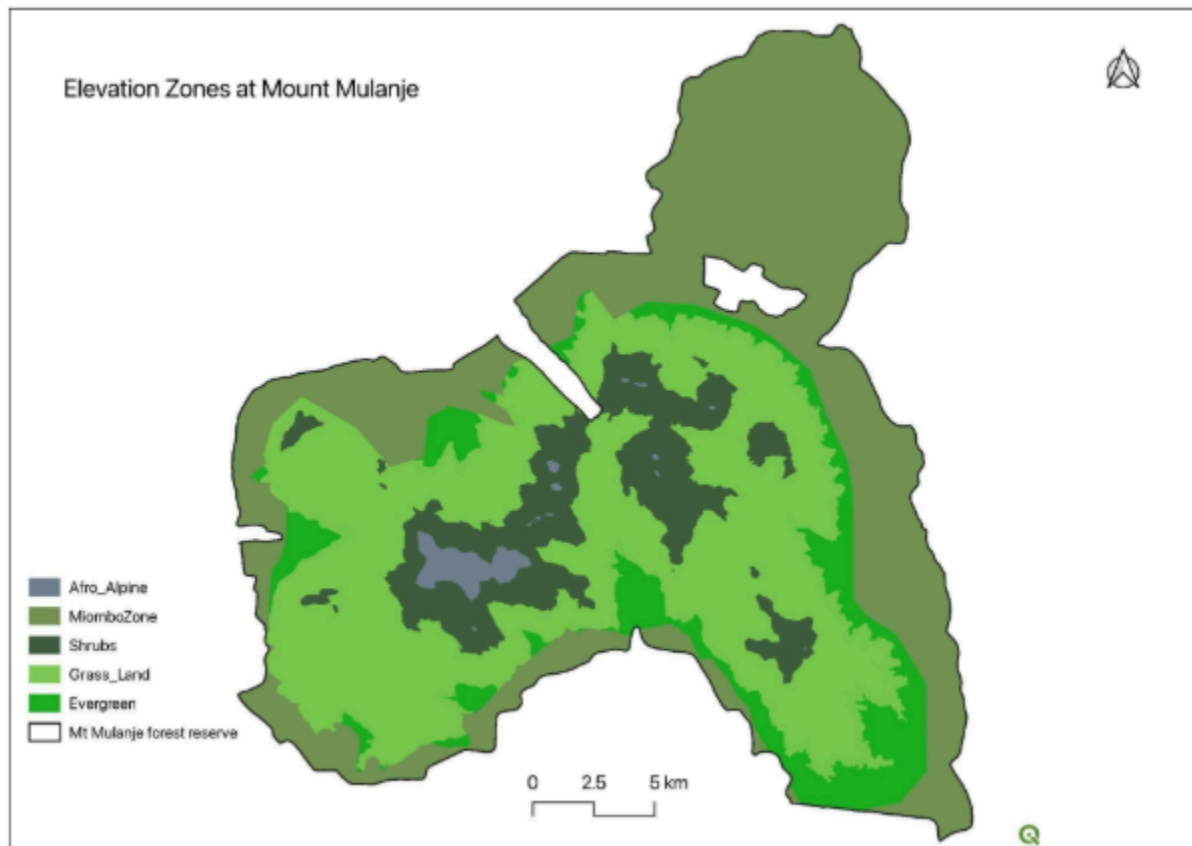


Figure 2

Elevation Zones at Mount Mulanje

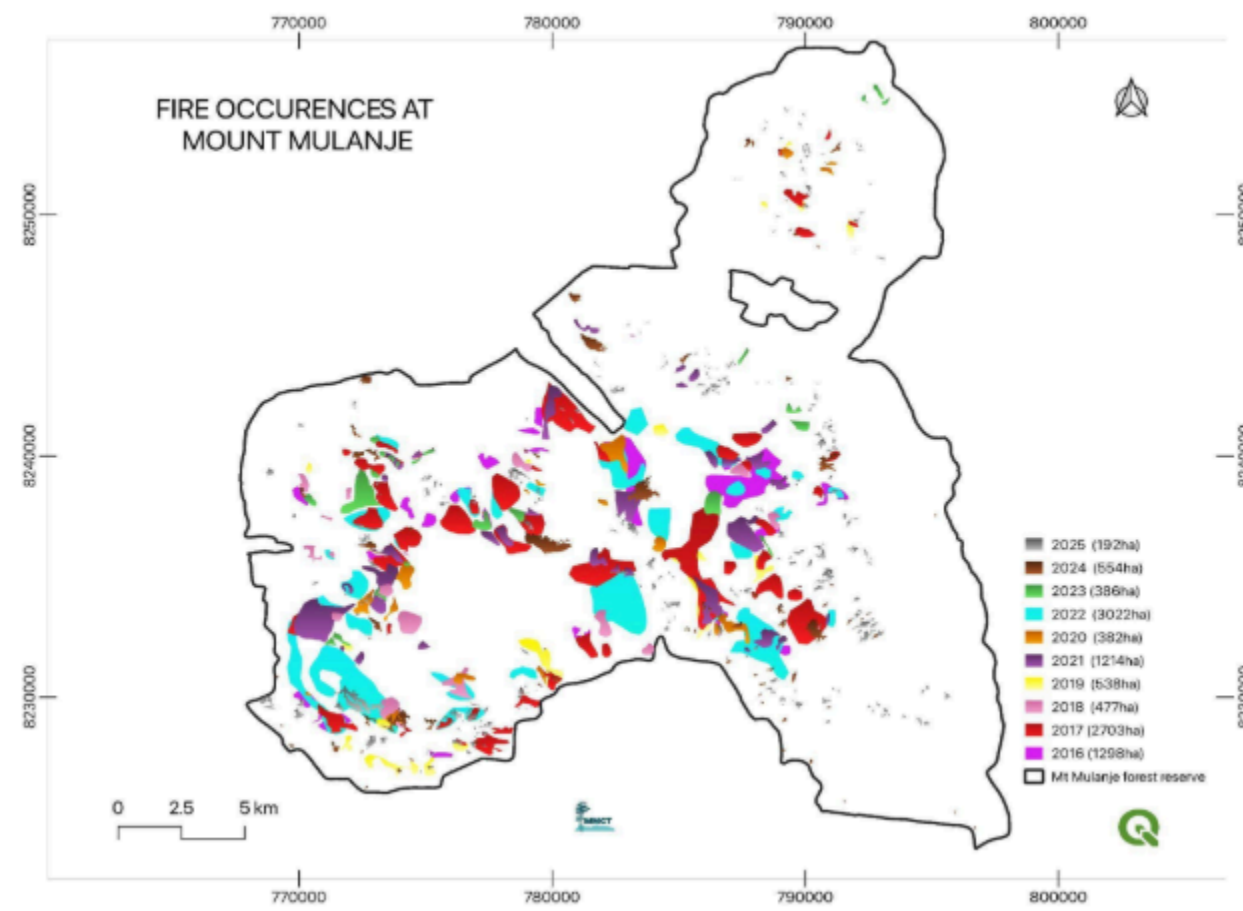


Figure 3

Annual burned area

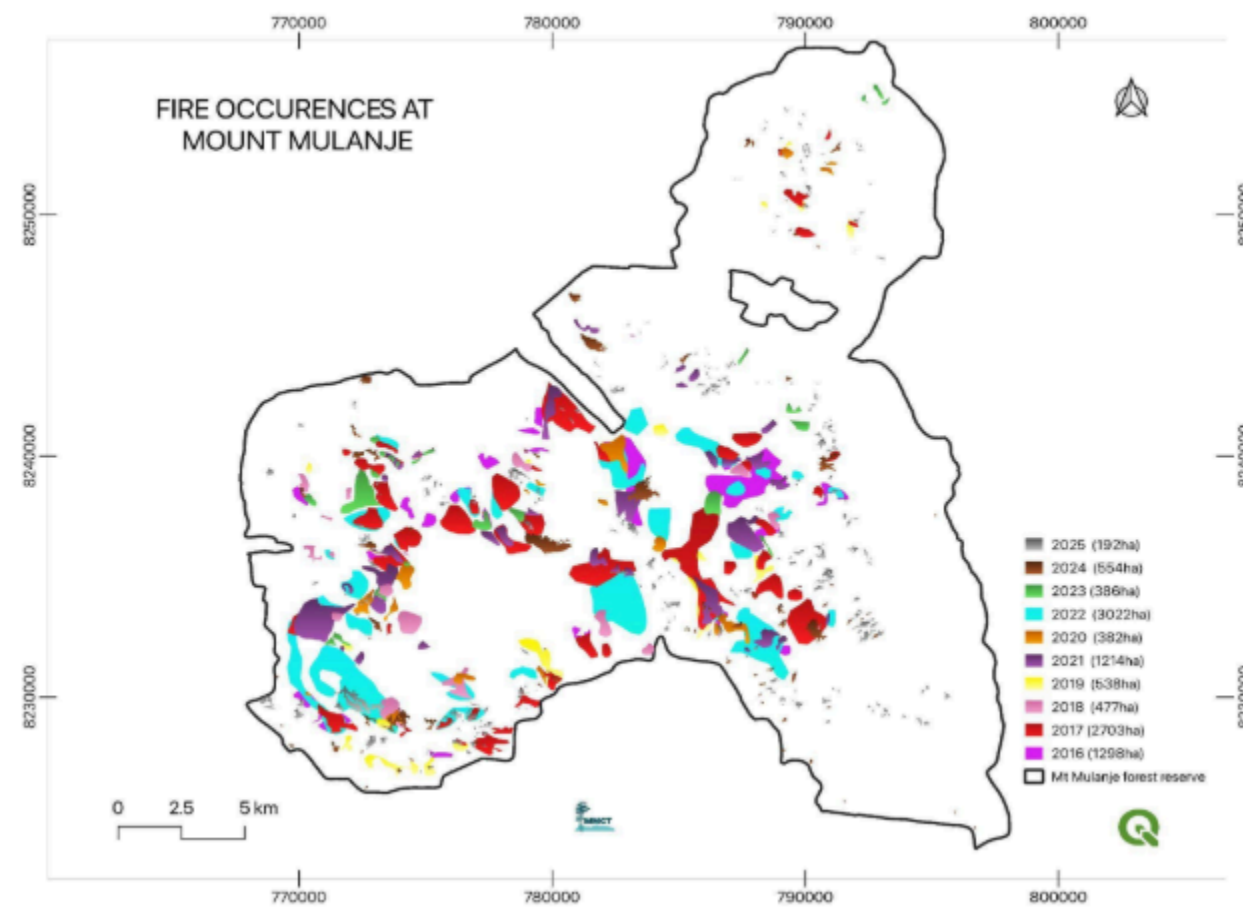


Figure 3

Annual burned area

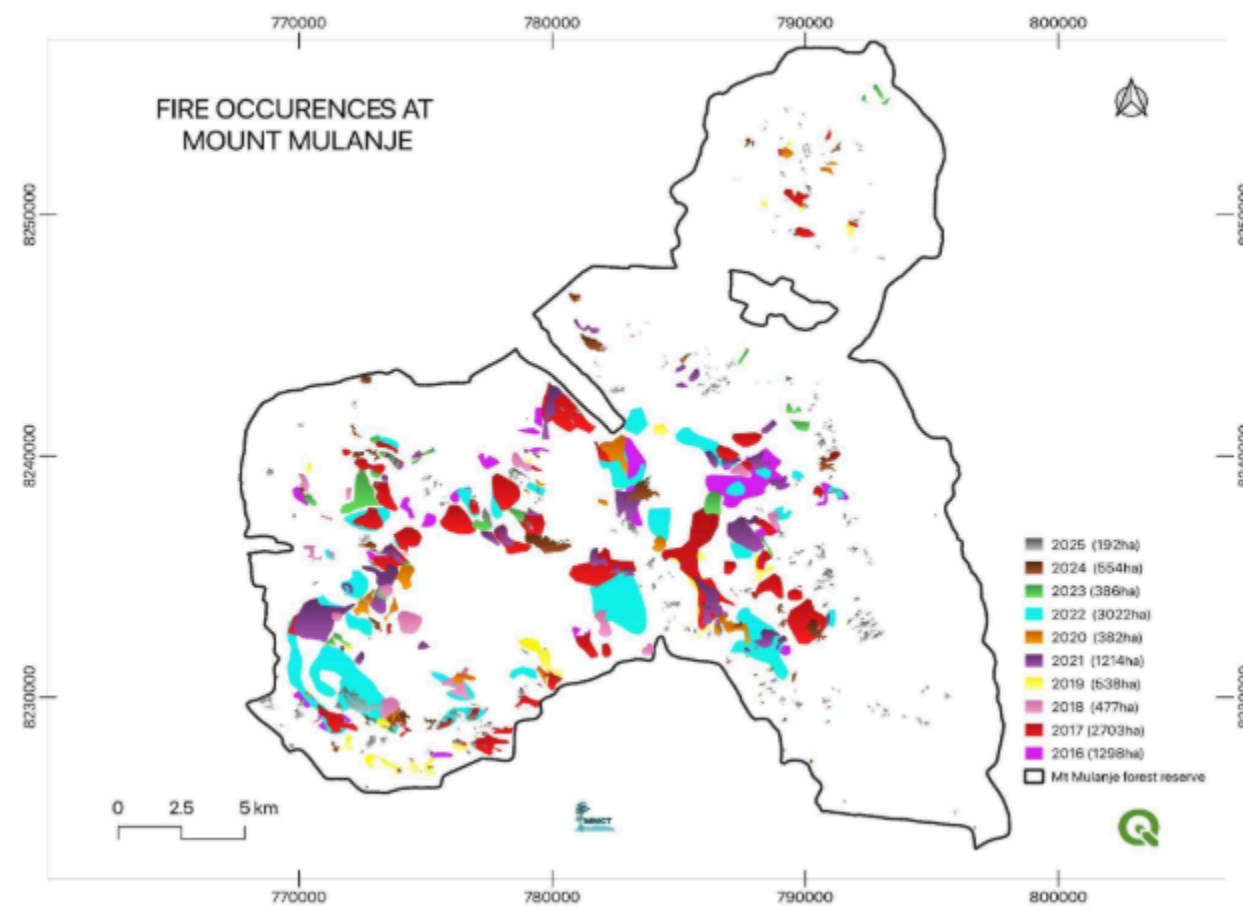


Figure 3

Annual burned area

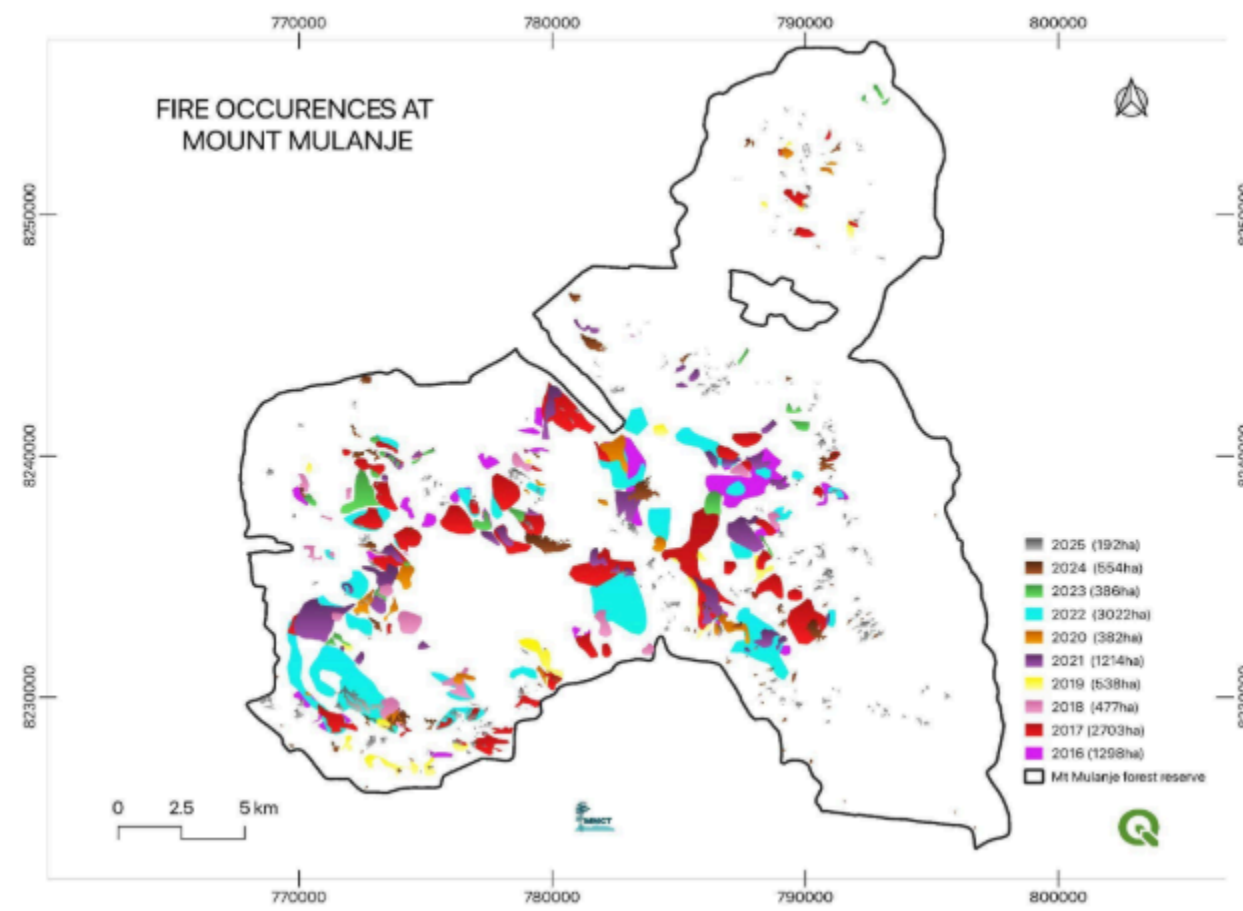


Figure 3

Annual burned area

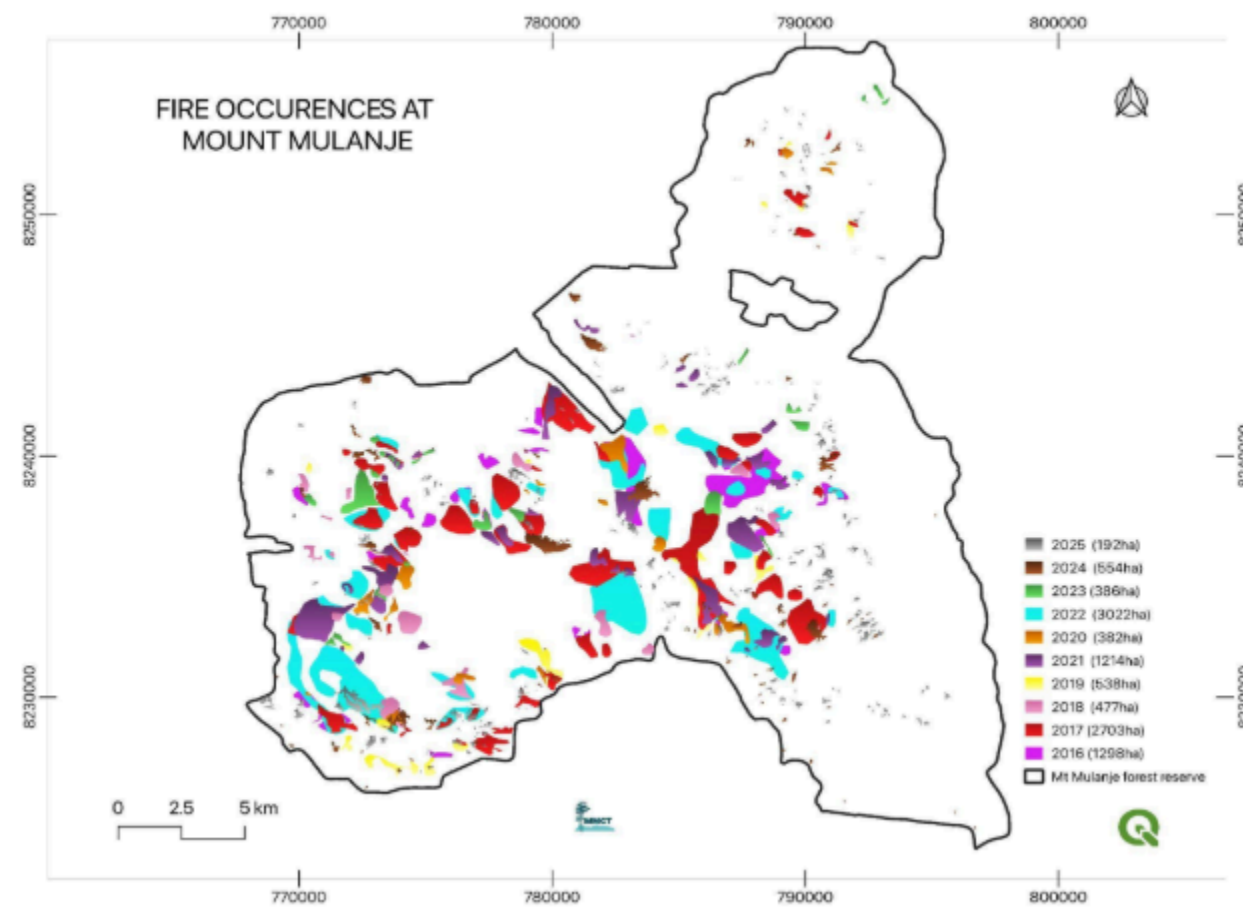


Figure 3

Annual burned area

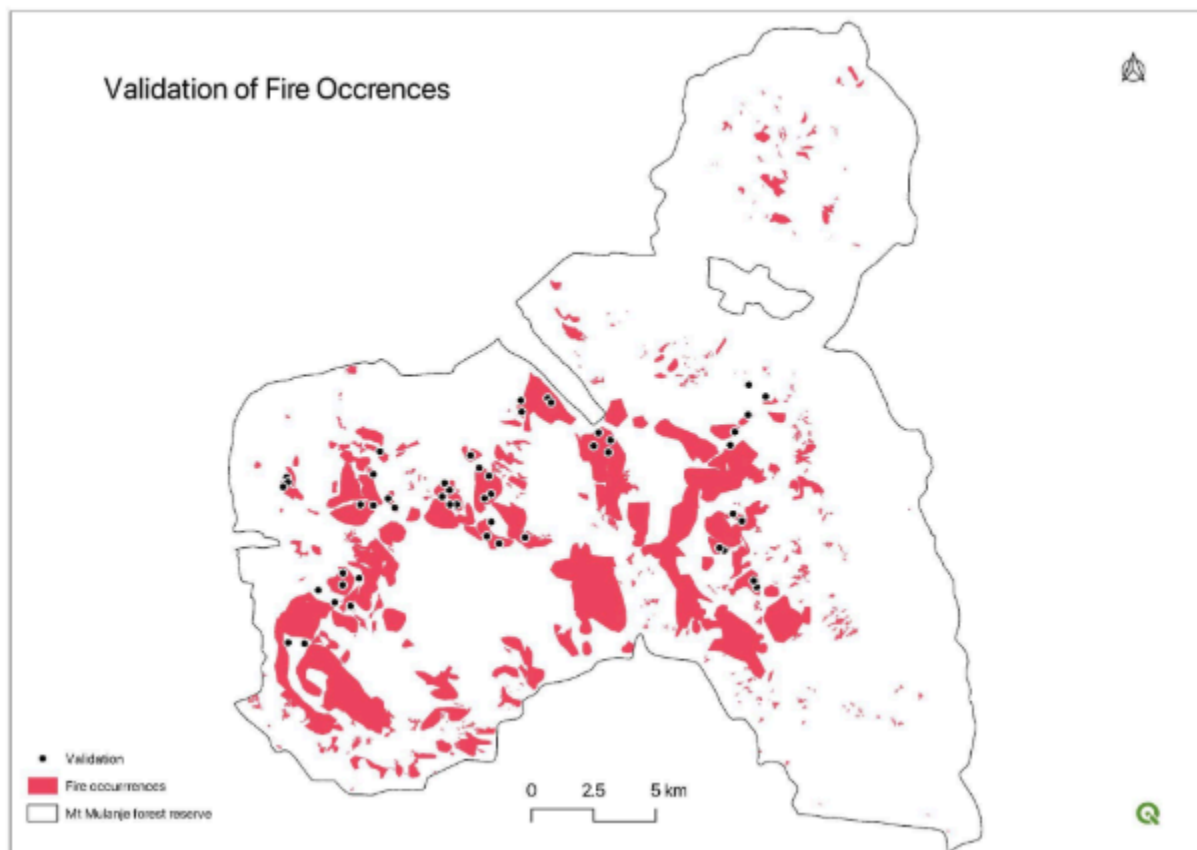


Figure 4

Validation of burned area

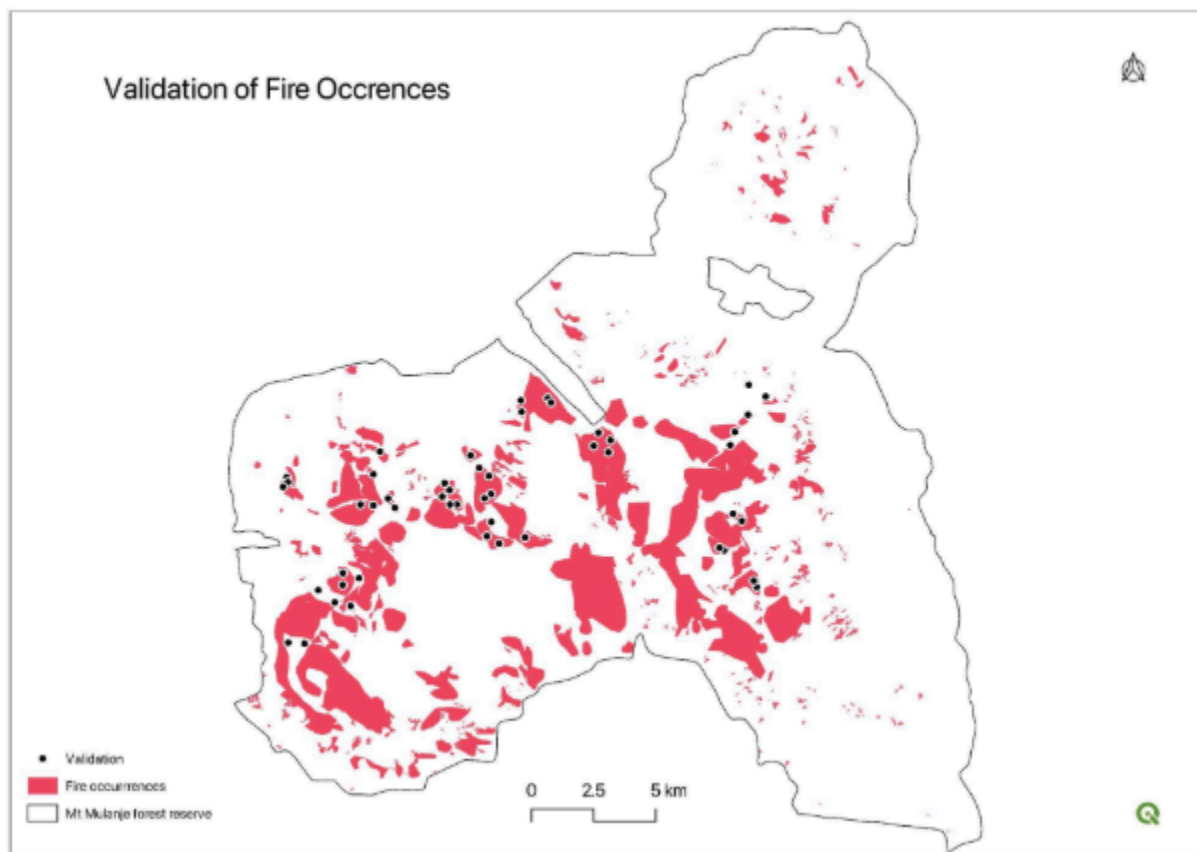


Figure 4

Validation of burned area

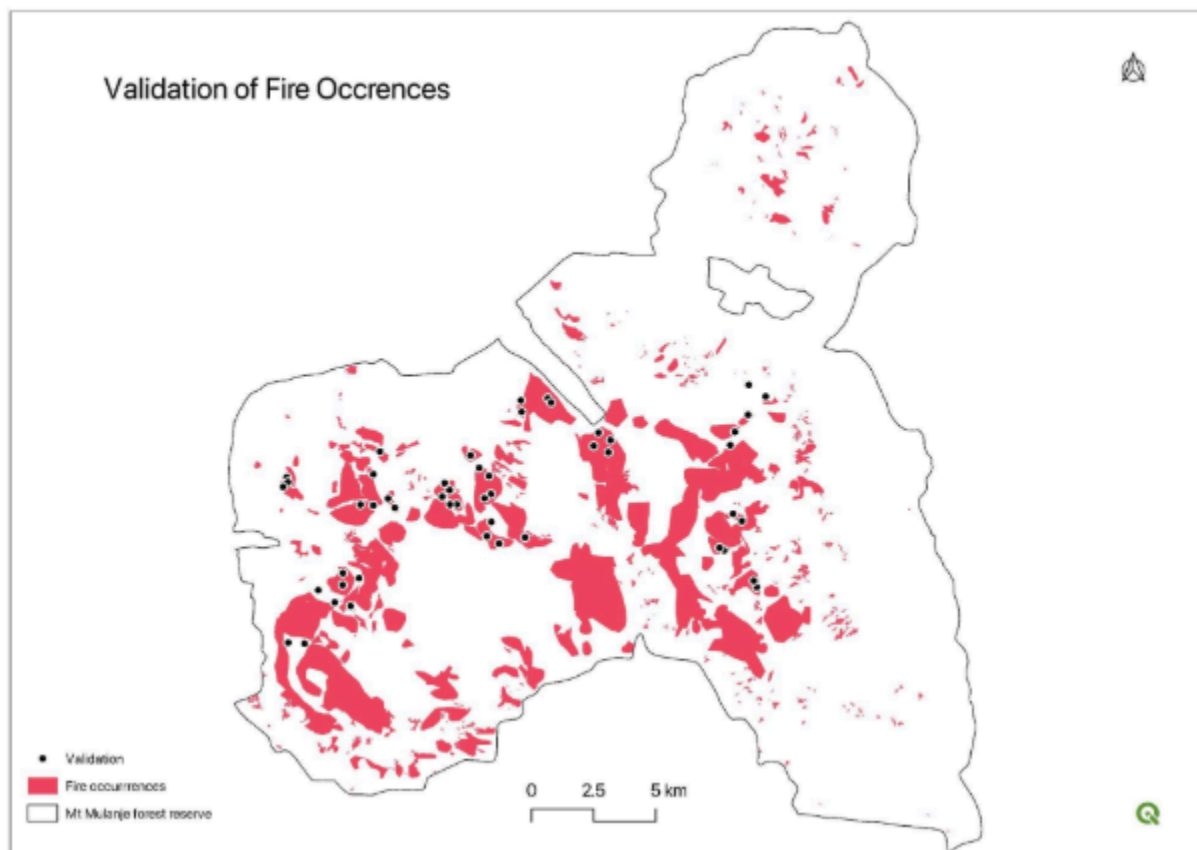


Figure 4

Validation of burned area

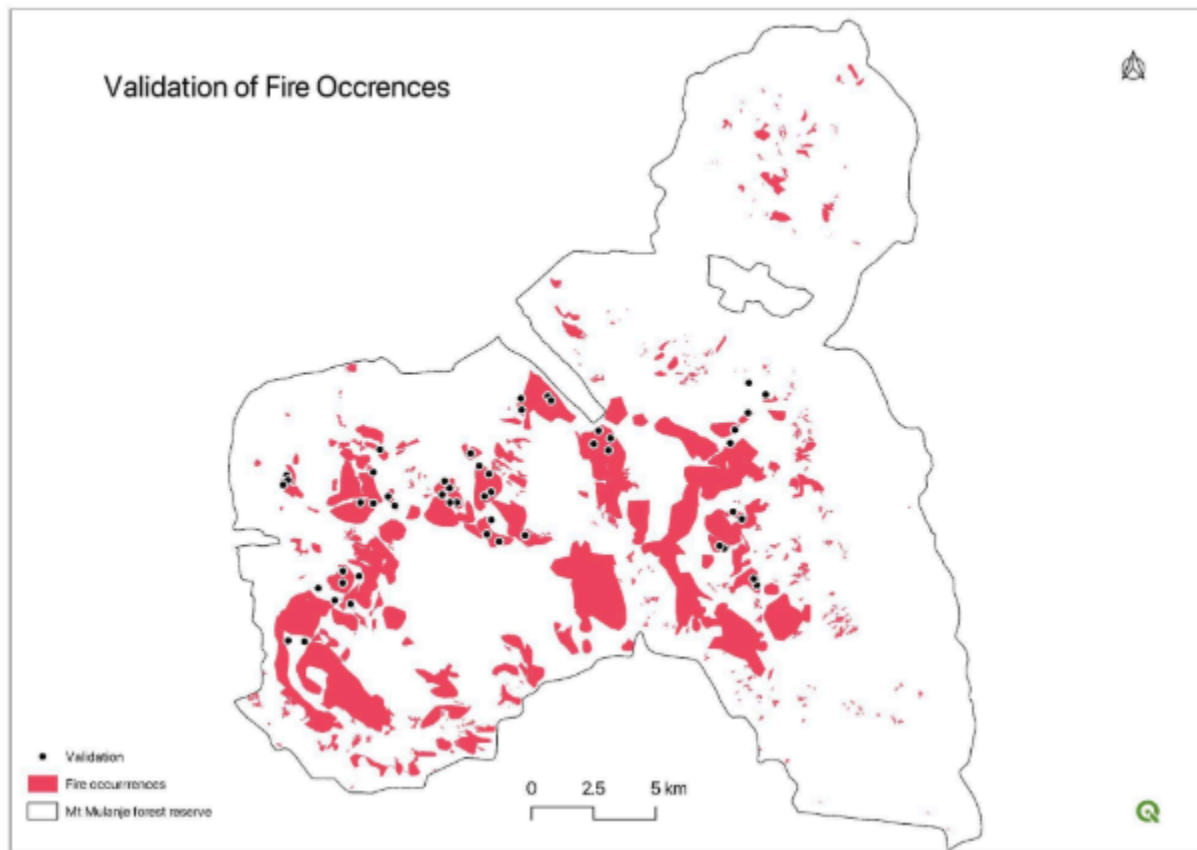


Figure 4

Validation of burned area

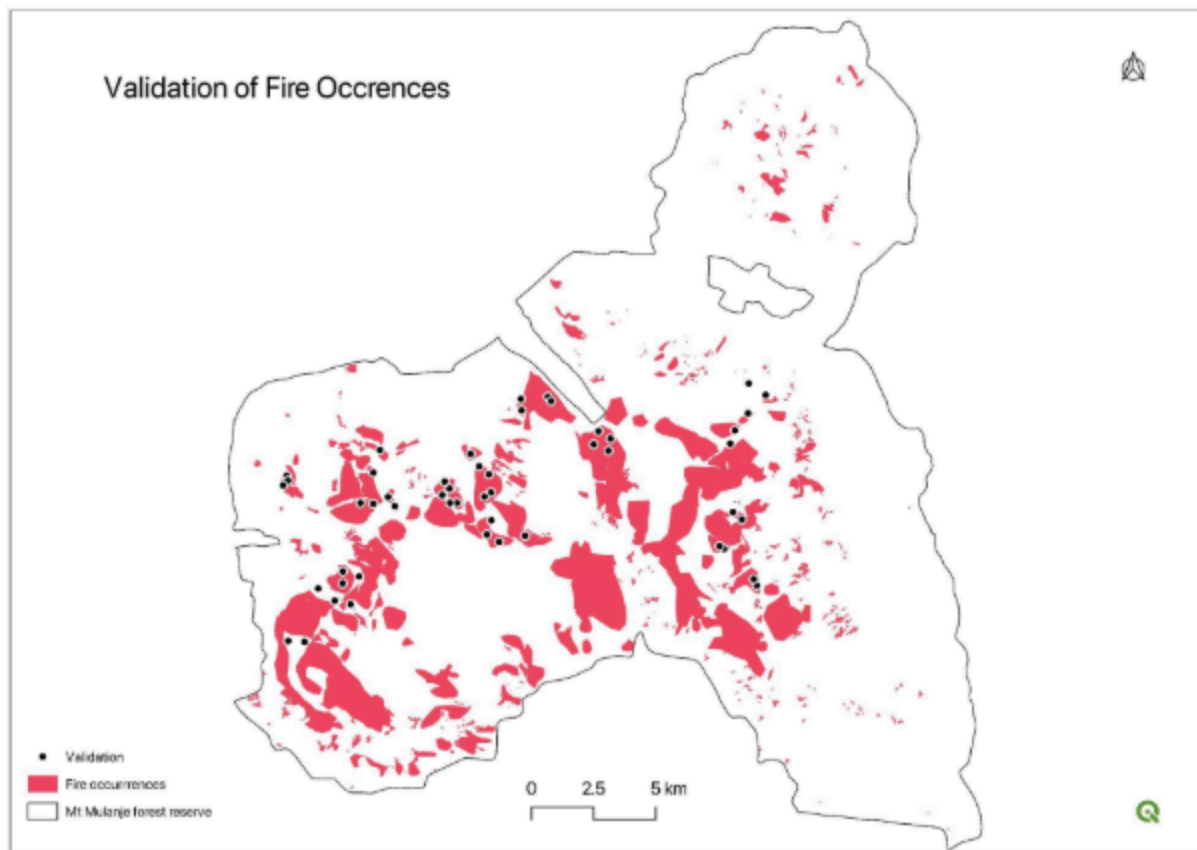


Figure 4

Validation of burned area

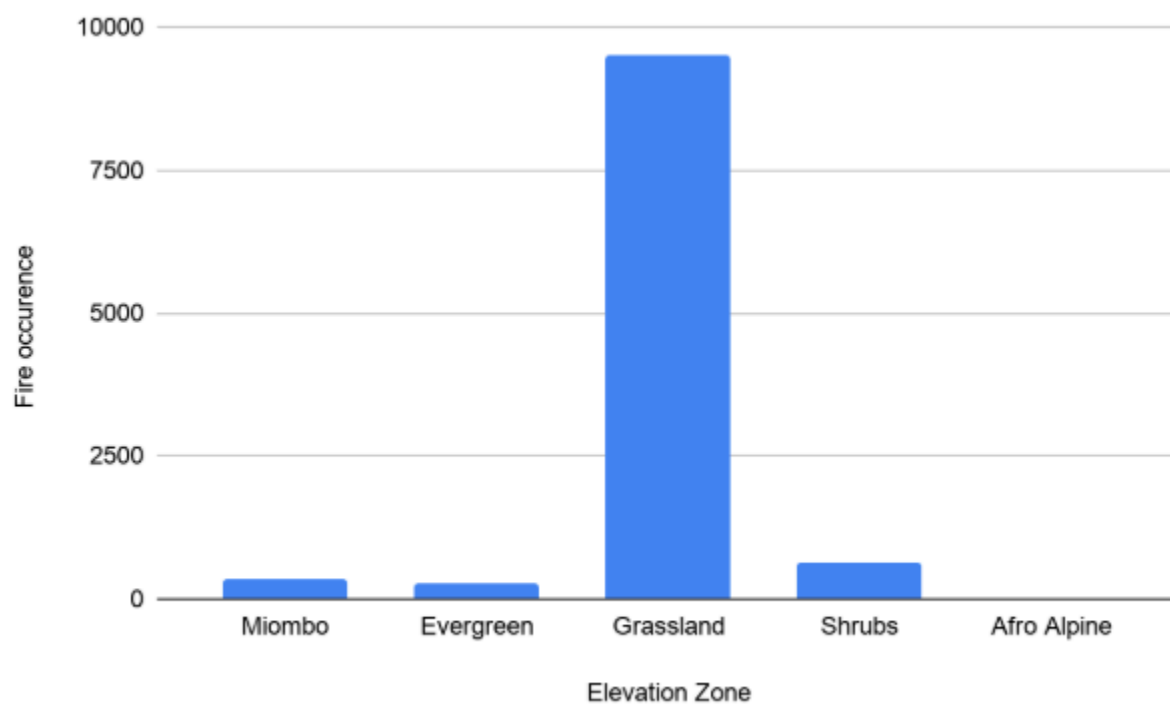


Figure 5

Fire occurrence in each Zone

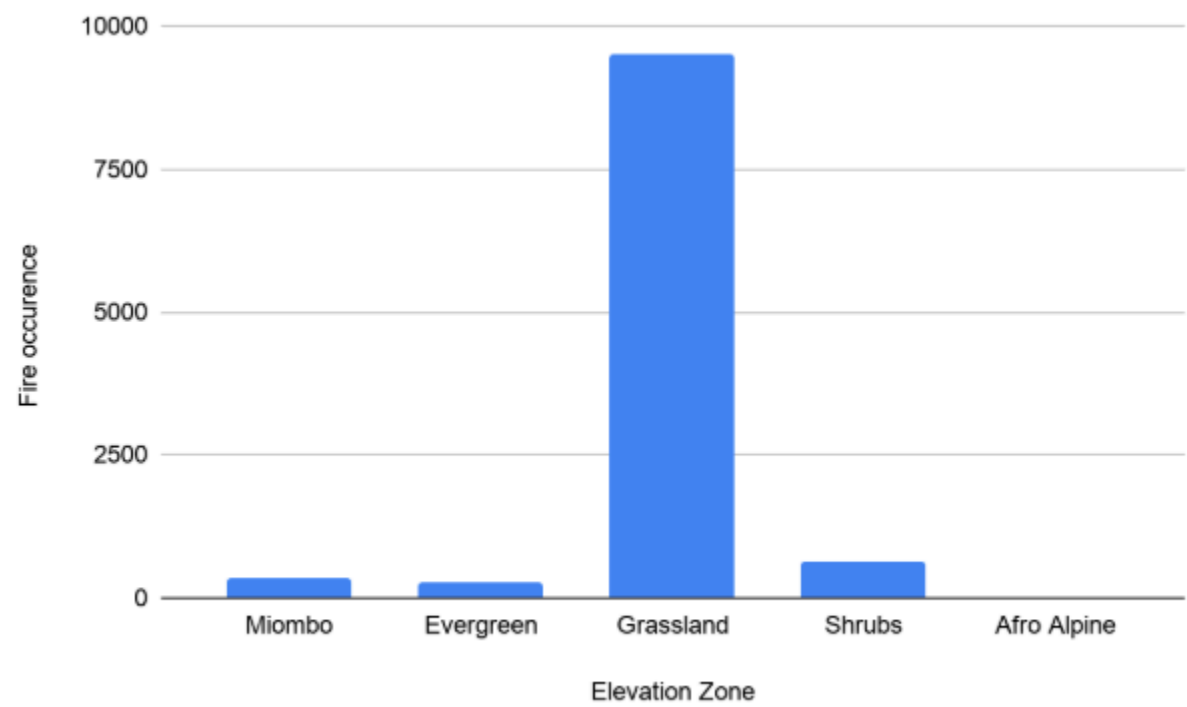


Figure 5

Fire occurrence in each Zone

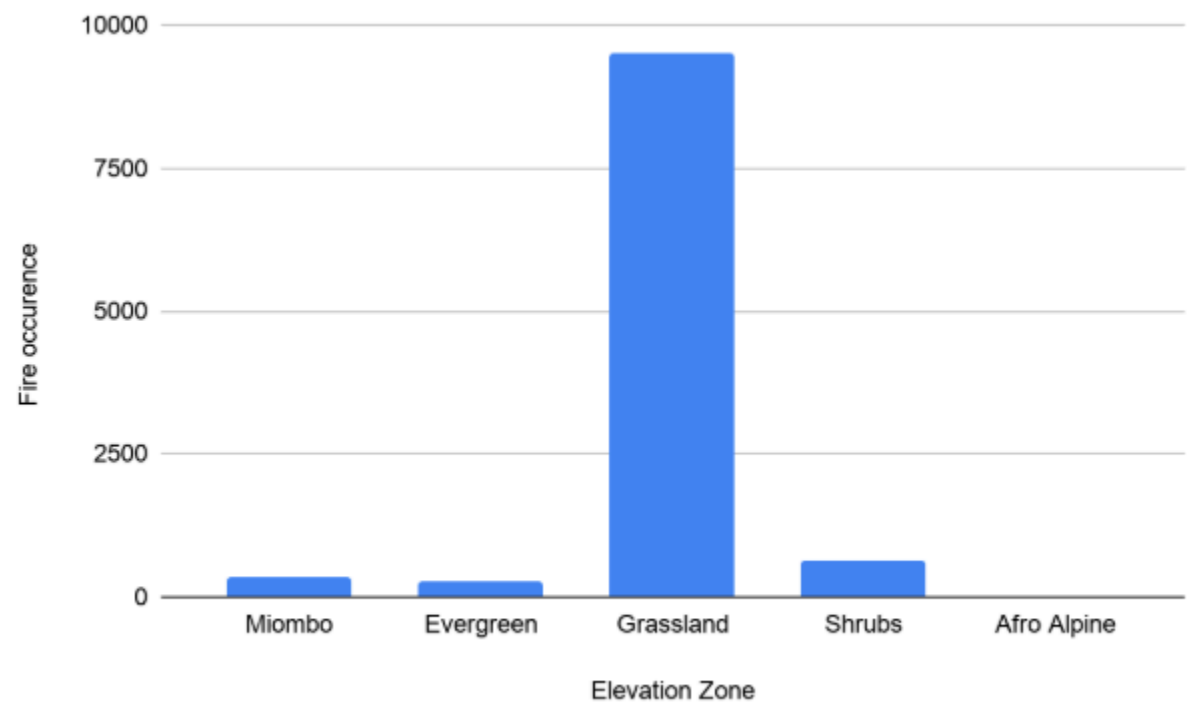


Figure 5

Fire occurrence in each Zone

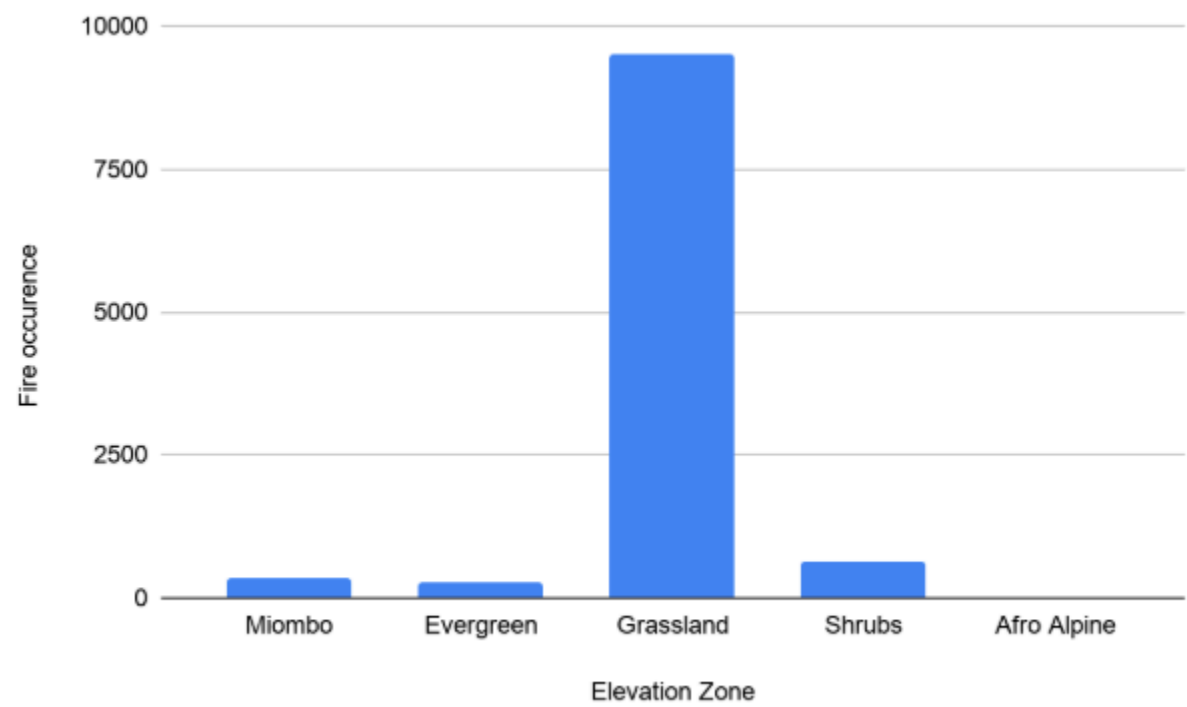


Figure 5

Fire occurrence in each Zone

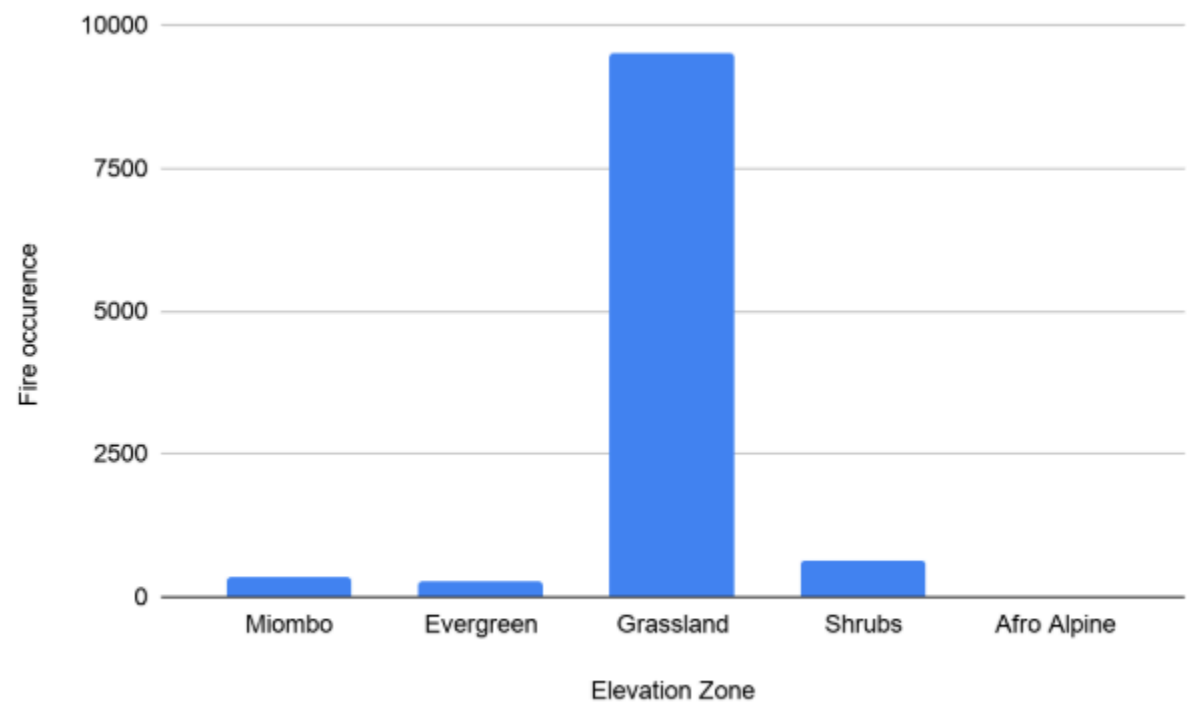


Figure 5

Fire occurrence in each Zone

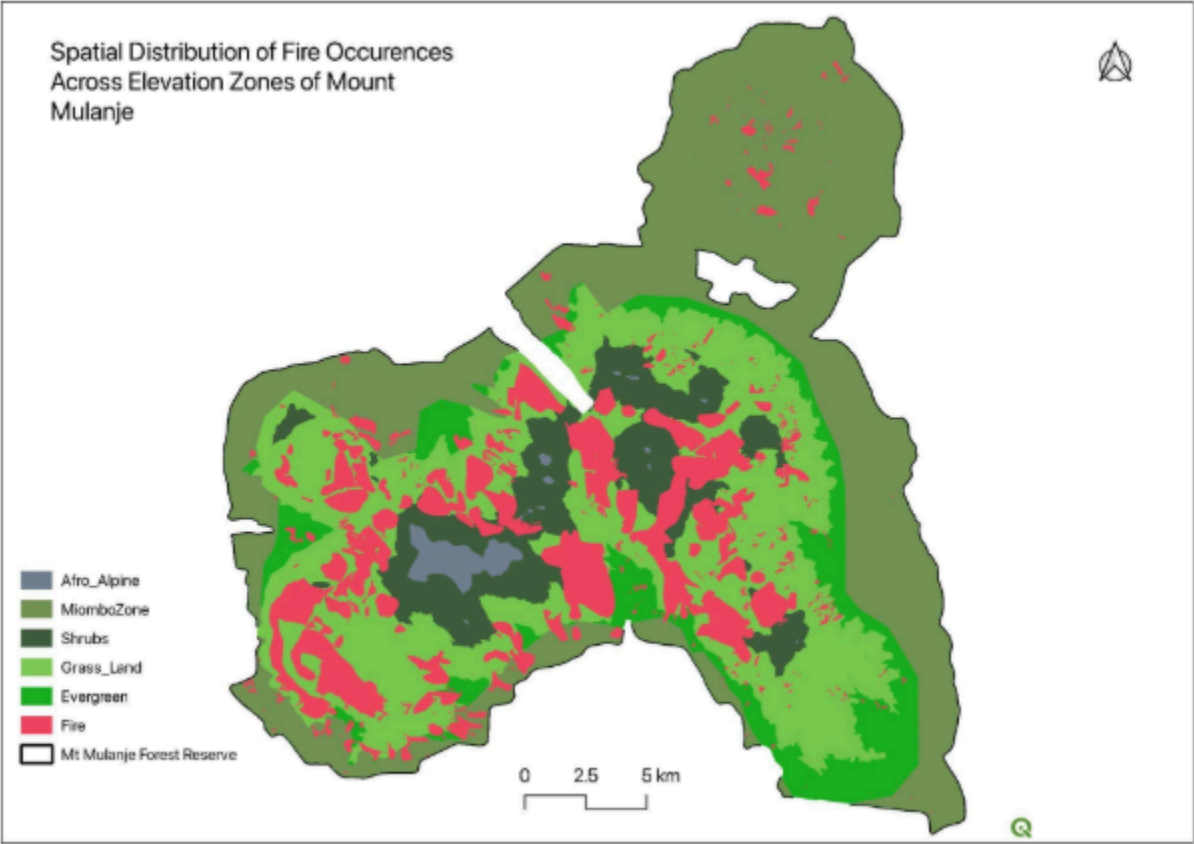


Figure 6

Spatial distribution of fire occurrences across elevation zones of Mount Mulanje

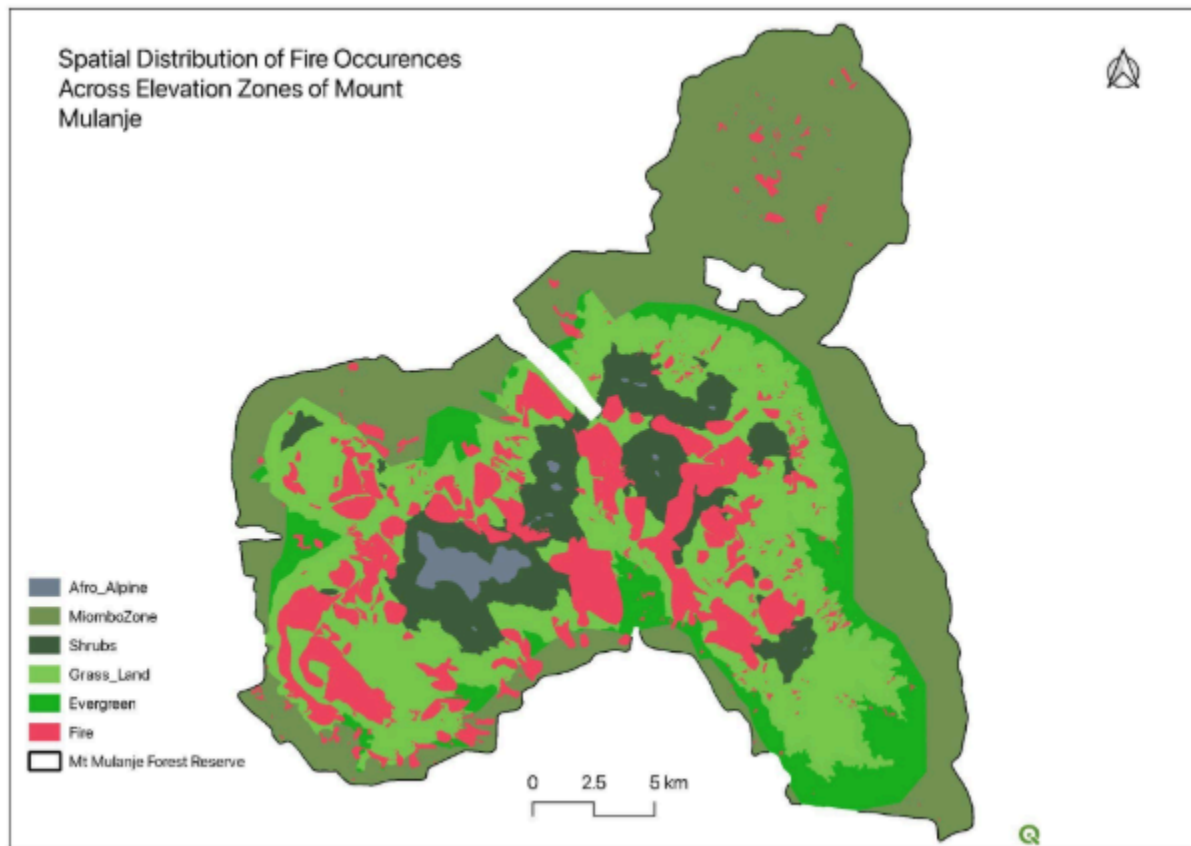


Figure 6

Spatial distribution of fire occurrences across elevation zones of Mount Mulanje

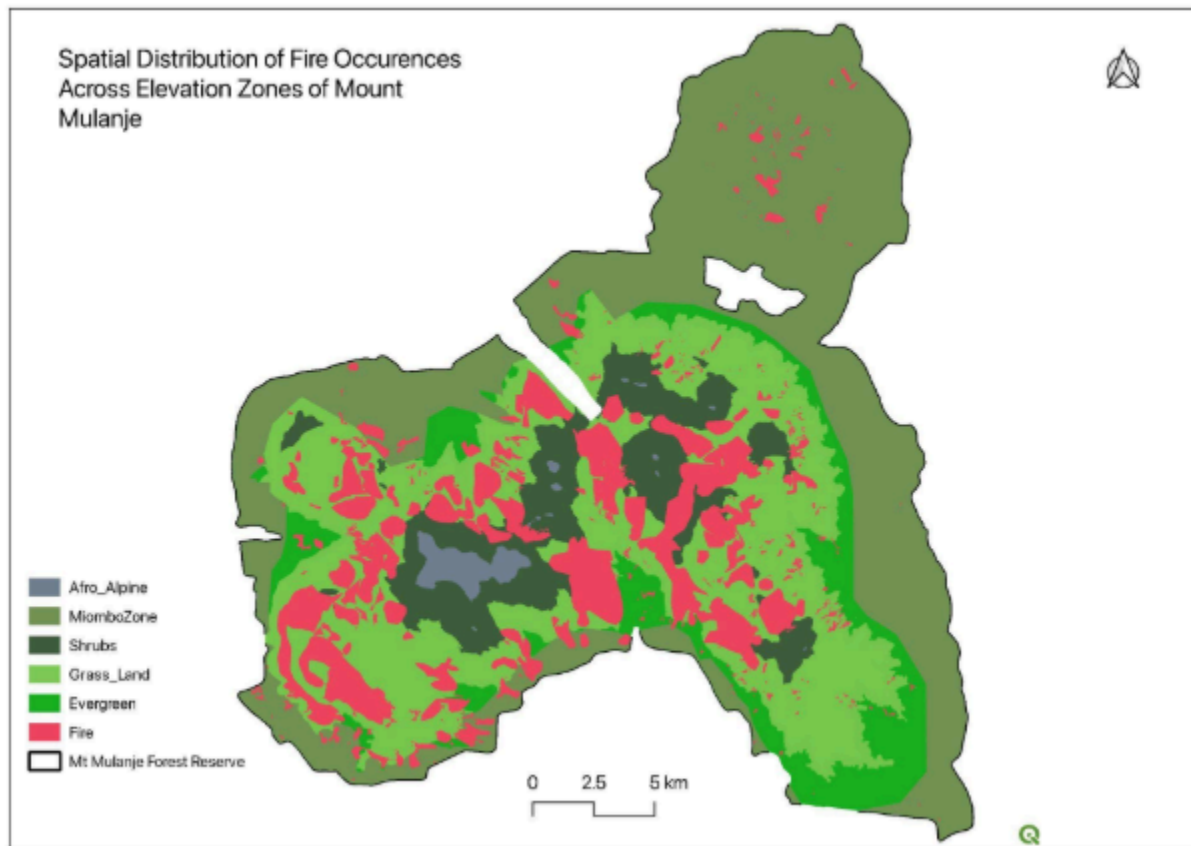


Figure 6

Spatial distribution of fire occurrences across elevation zones of Mount Mulanje

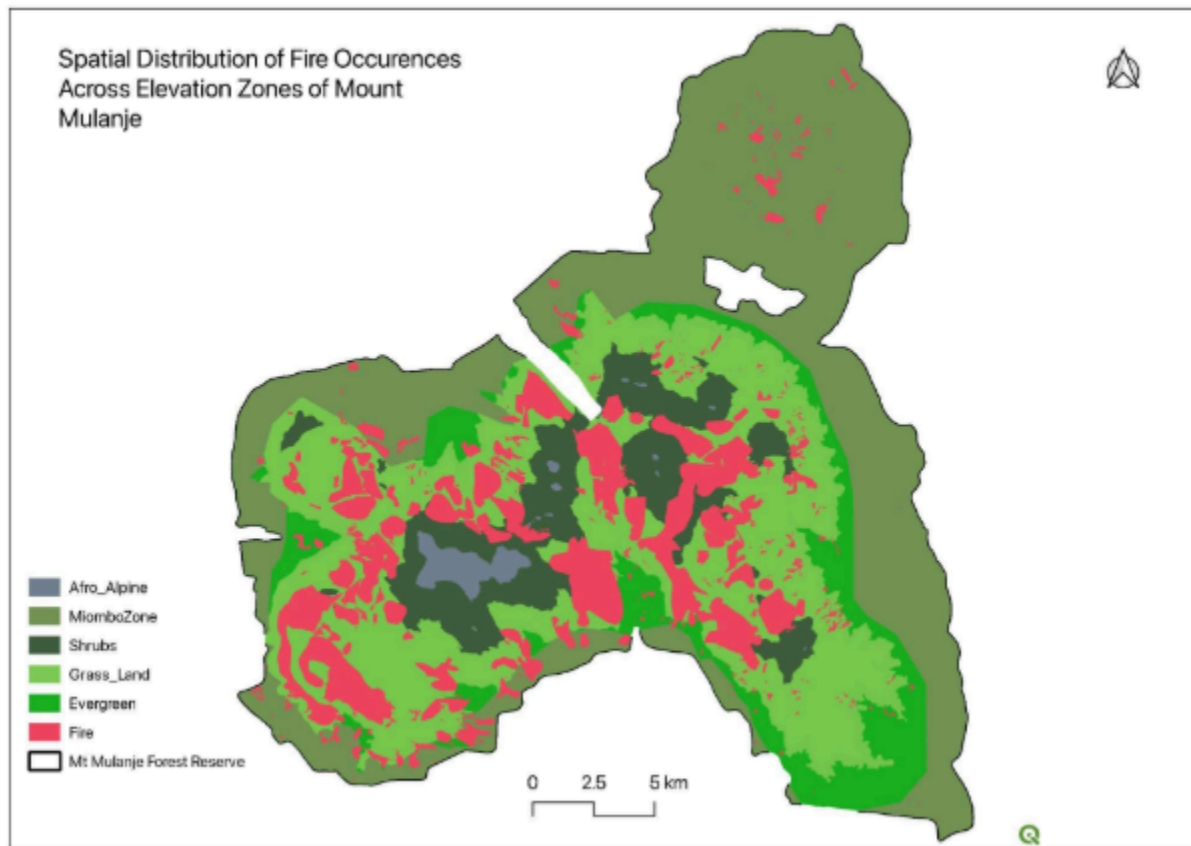


Figure 6

Spatial distribution of fire occurrences across elevation zones of Mount Mulanje

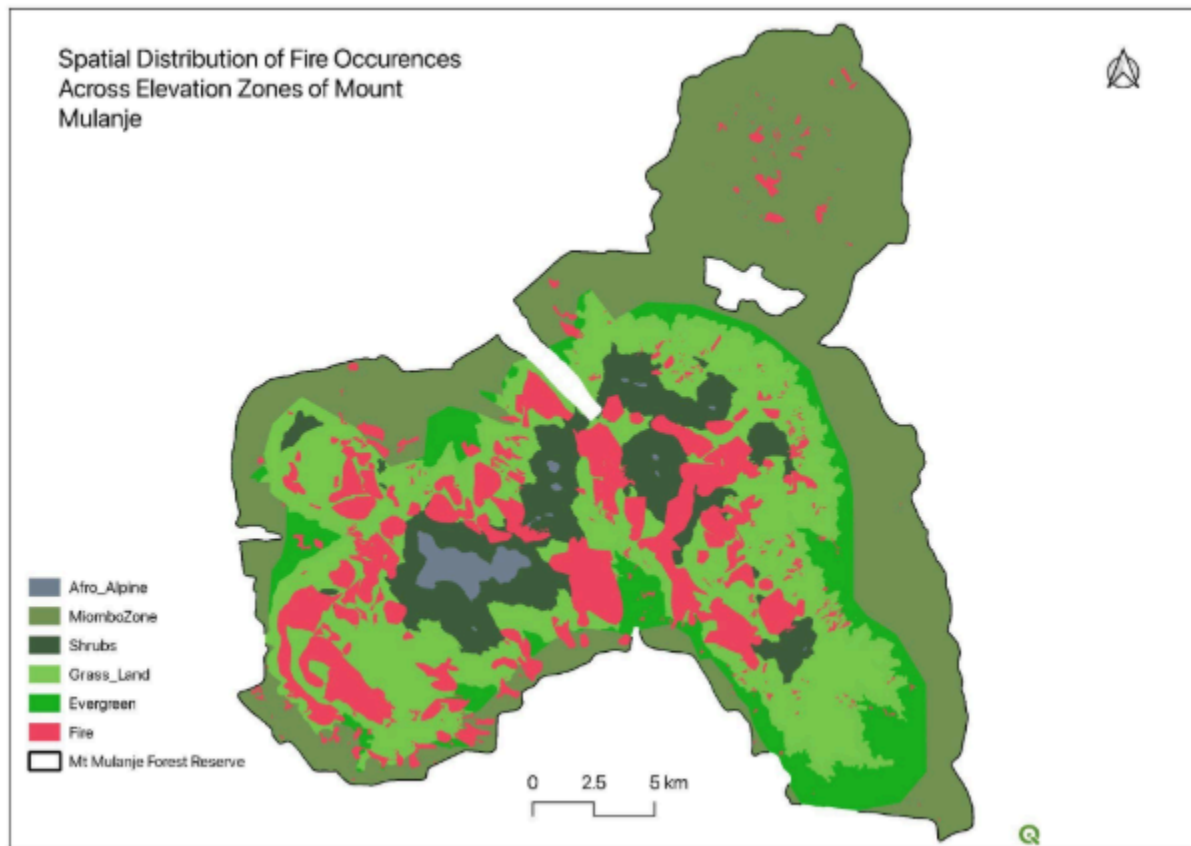


Figure 6

Spatial distribution of fire occurrences across elevation zones of Mount Mulanje

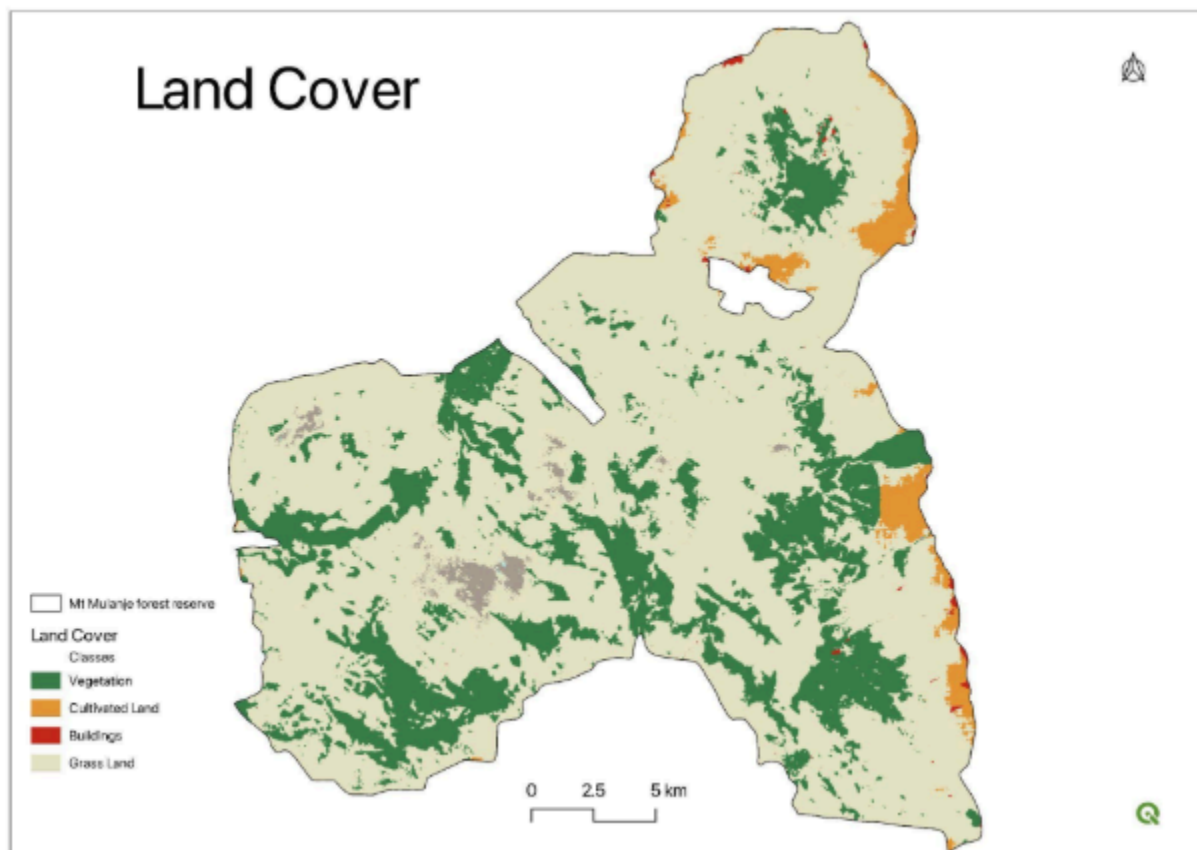


Figure 7

Land cover map for Mount Mulanje

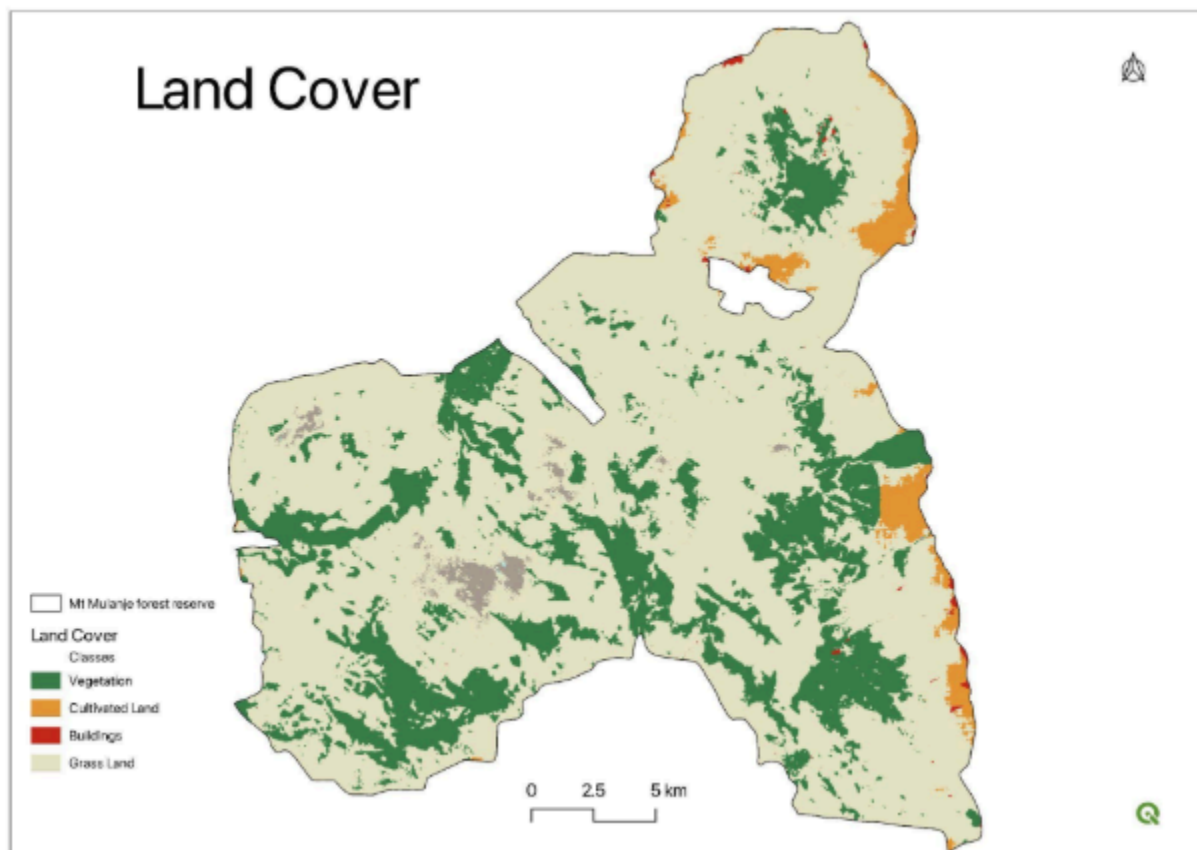


Figure 7

Land cover map for Mount Mulanje

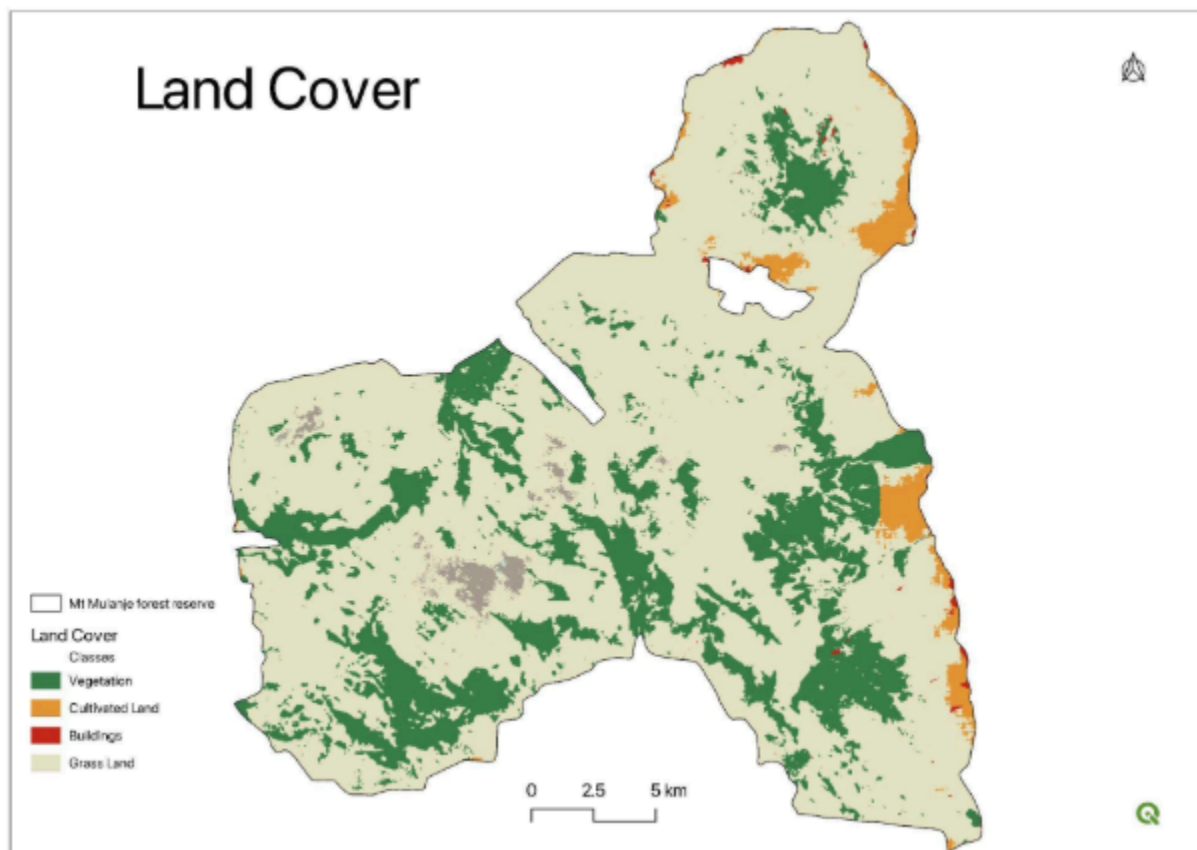


Figure 7

Land cover map for Mount Mulanje

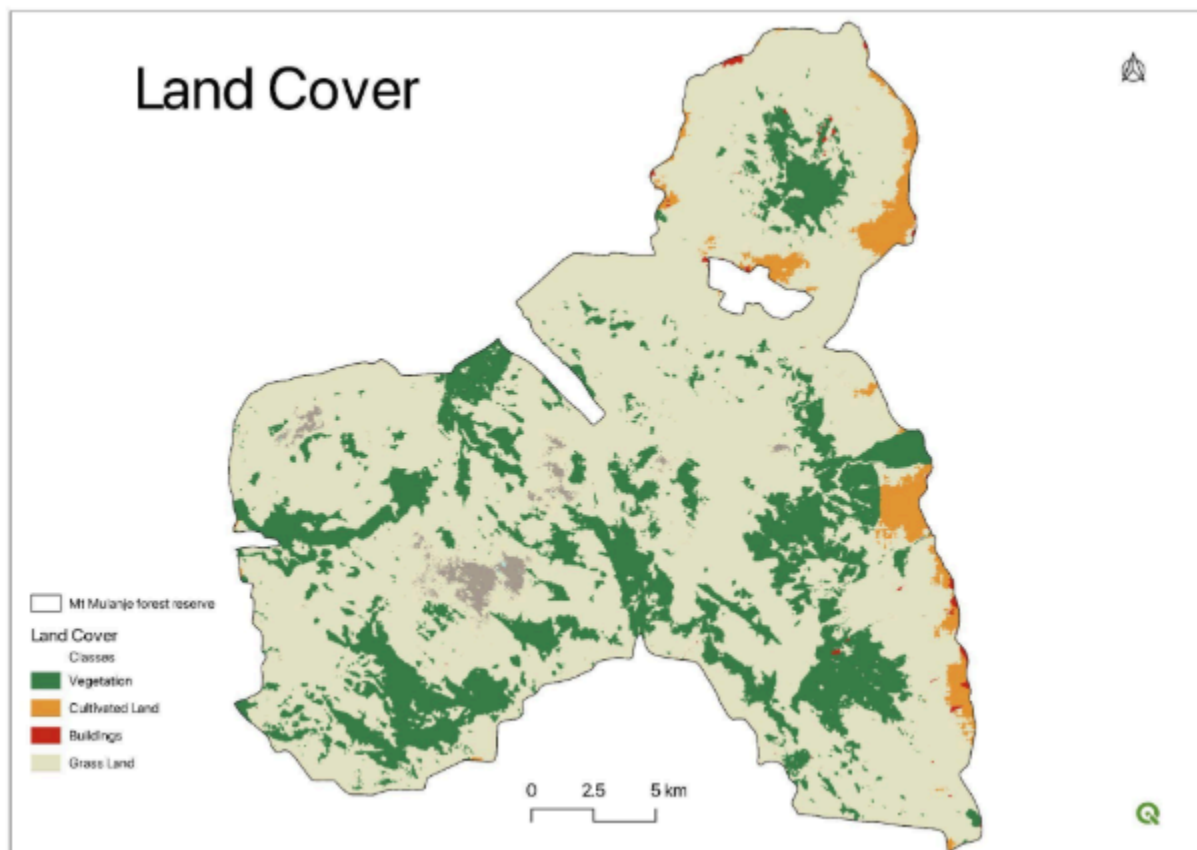


Figure 7

Land cover map for Mount Mulanje

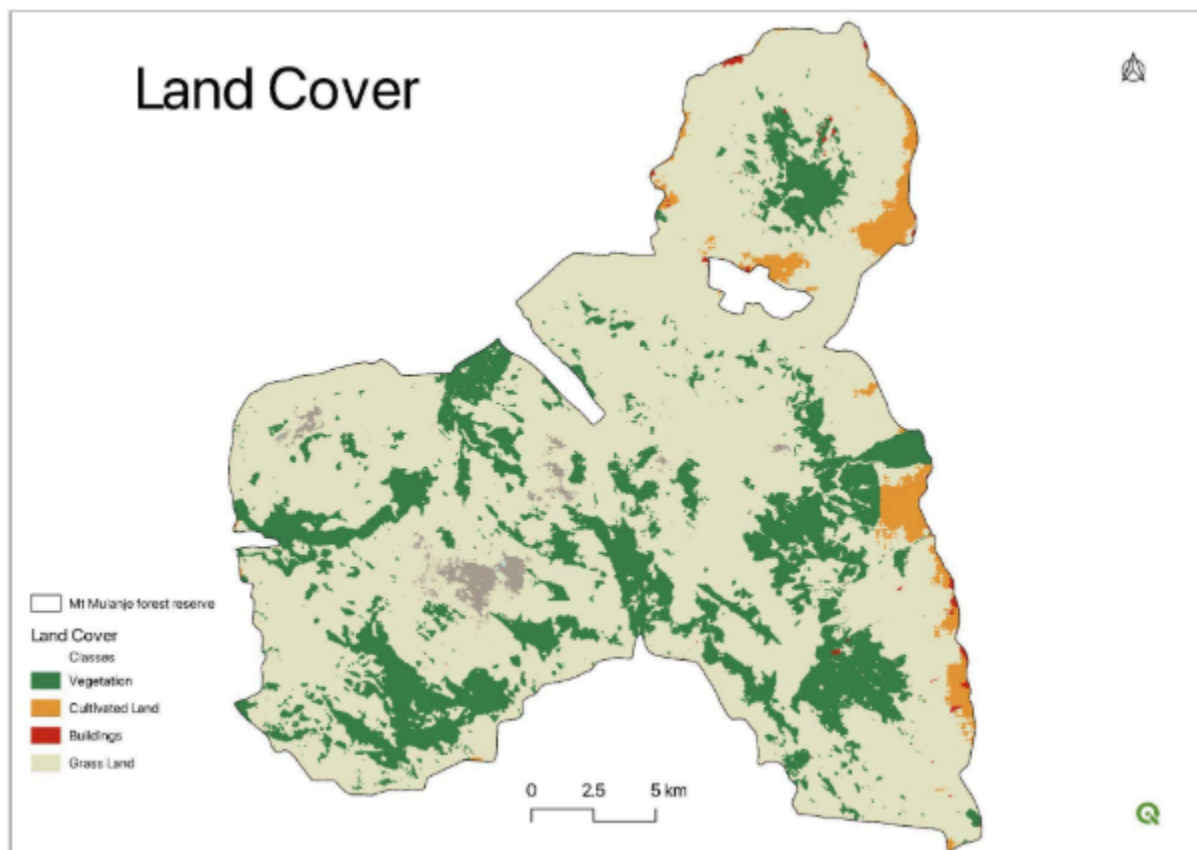


Figure 7

Land cover map for Mount Mulanje

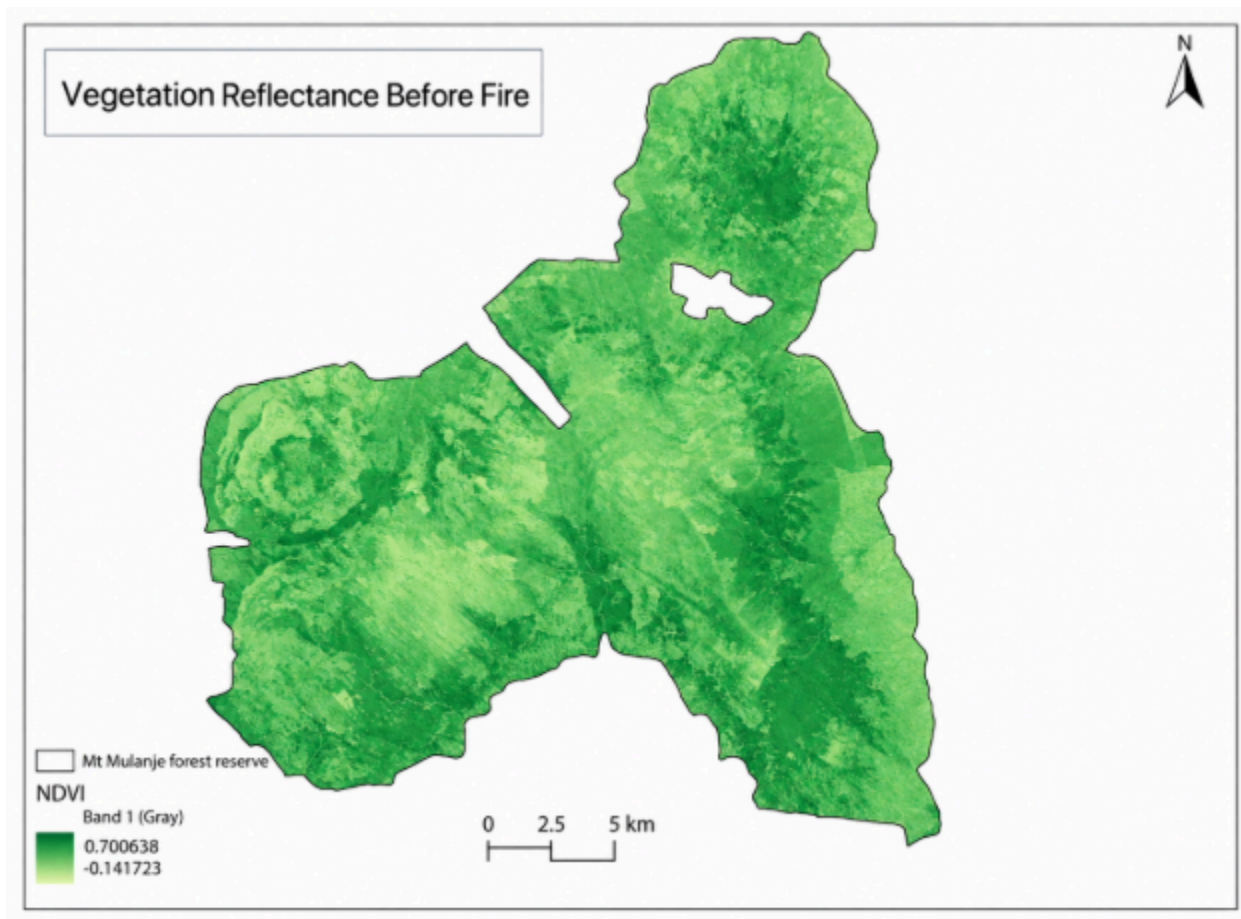


Figure 8

Vegetation reflectance before fire

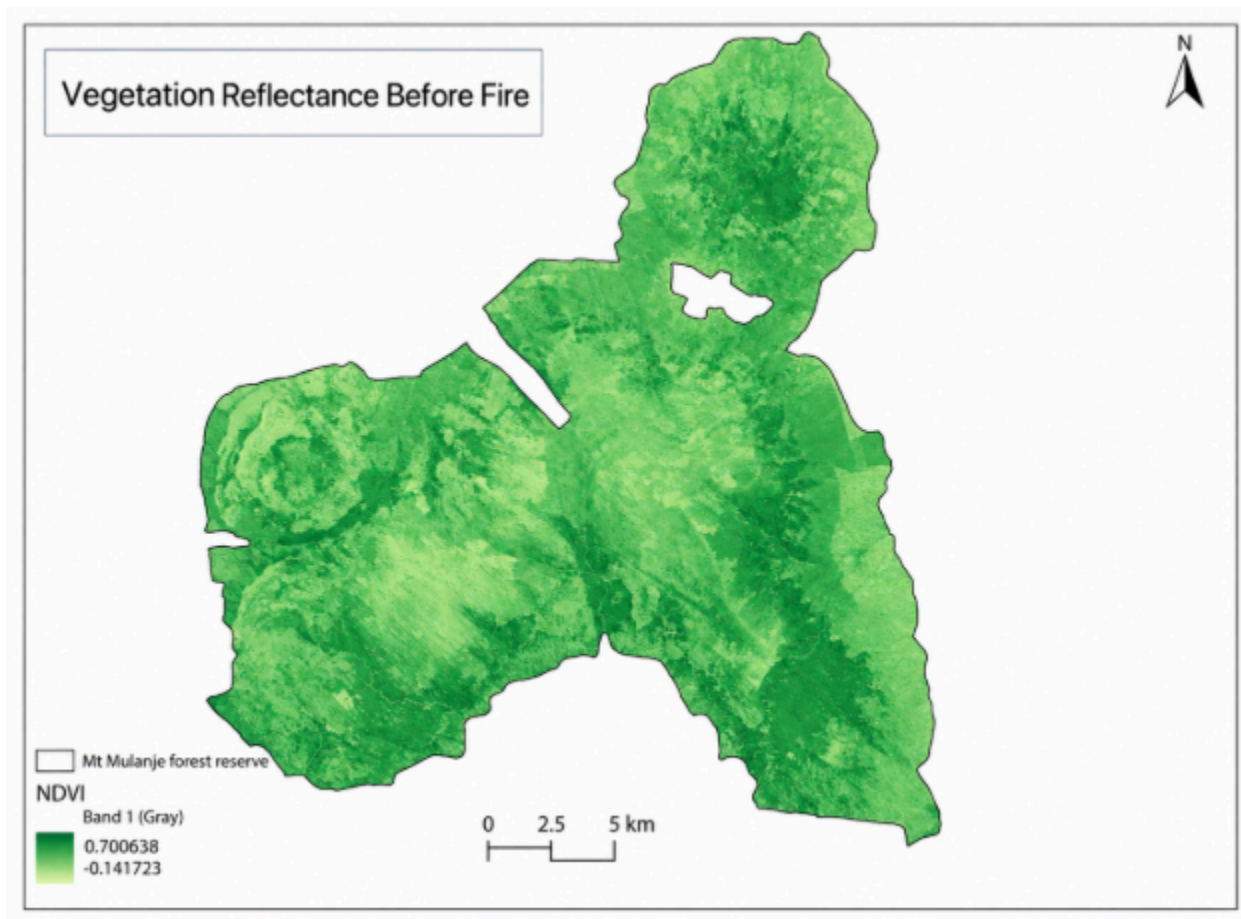


Figure 8

Vegetation reflectance before fire

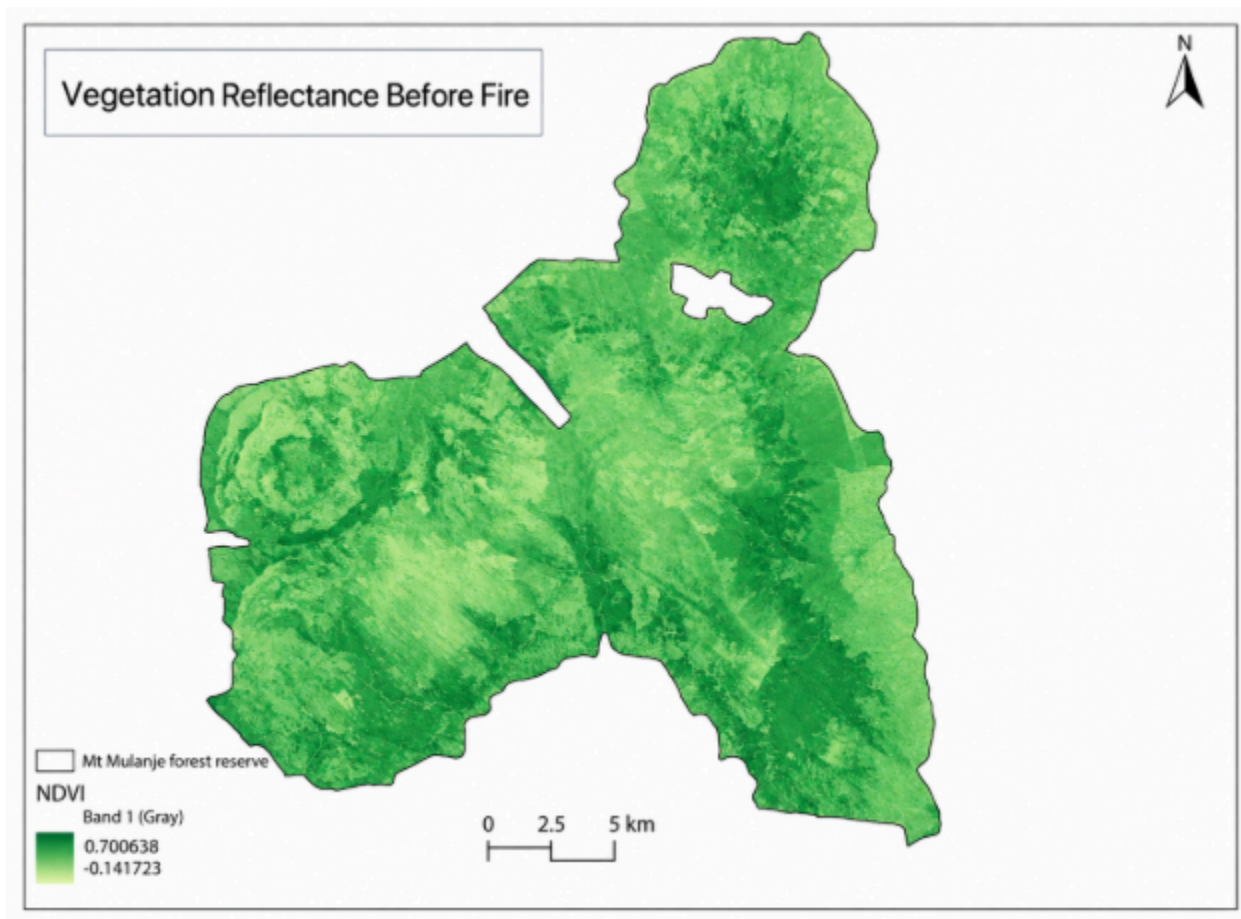


Figure 8

Vegetation reflectance before fire

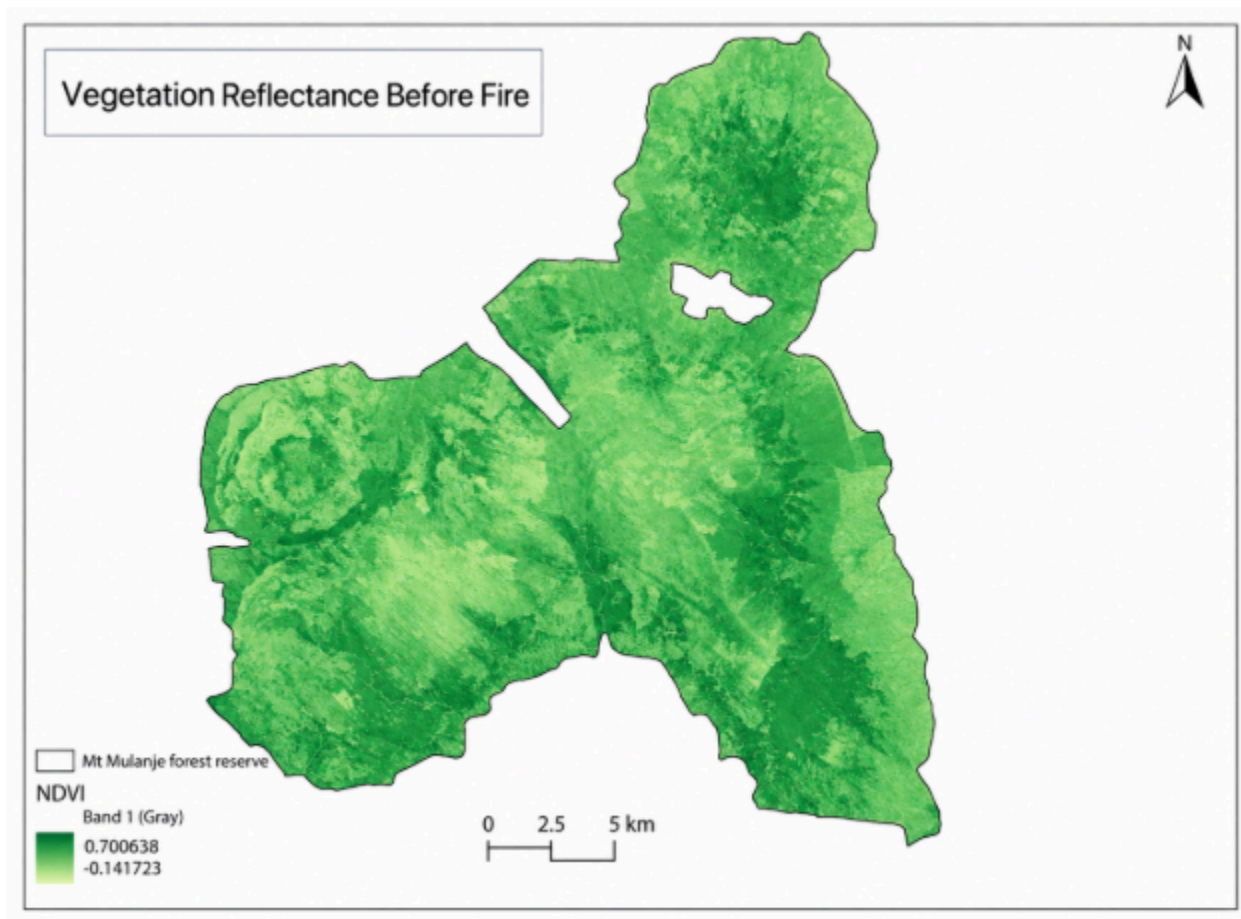


Figure 8

Vegetation reflectance before fire

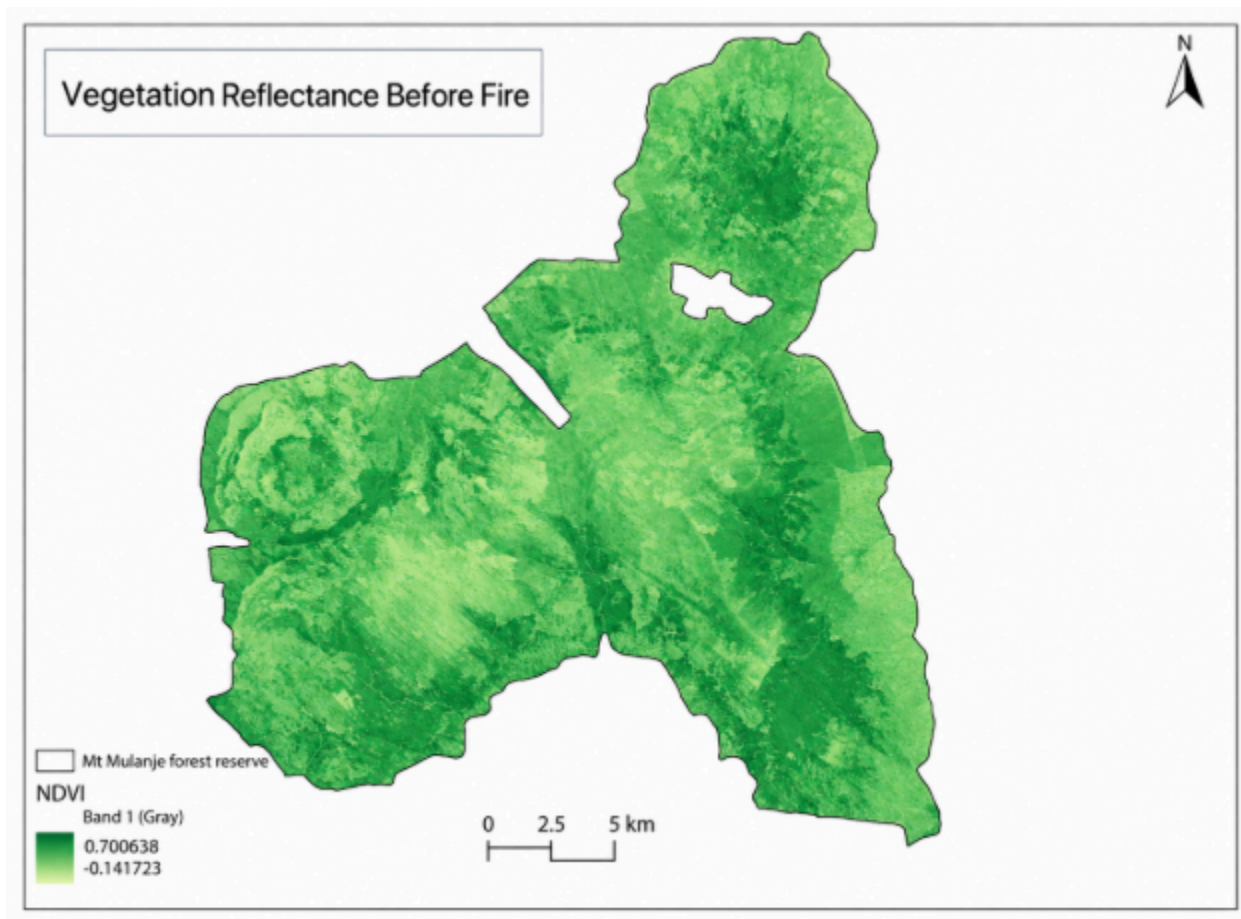


Figure 8

Vegetation reflectance before fire

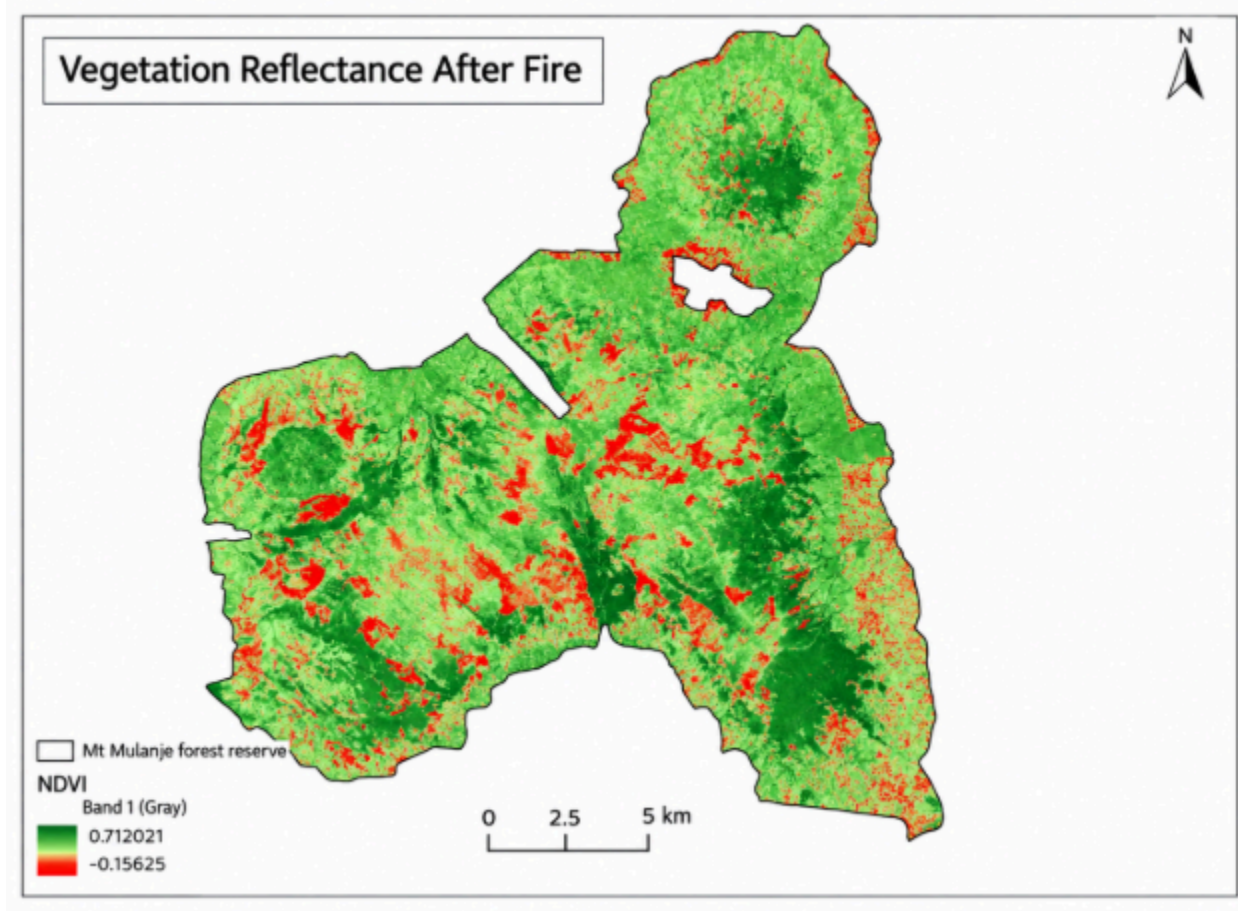


Figure 9

Vegetation reflectance after fire

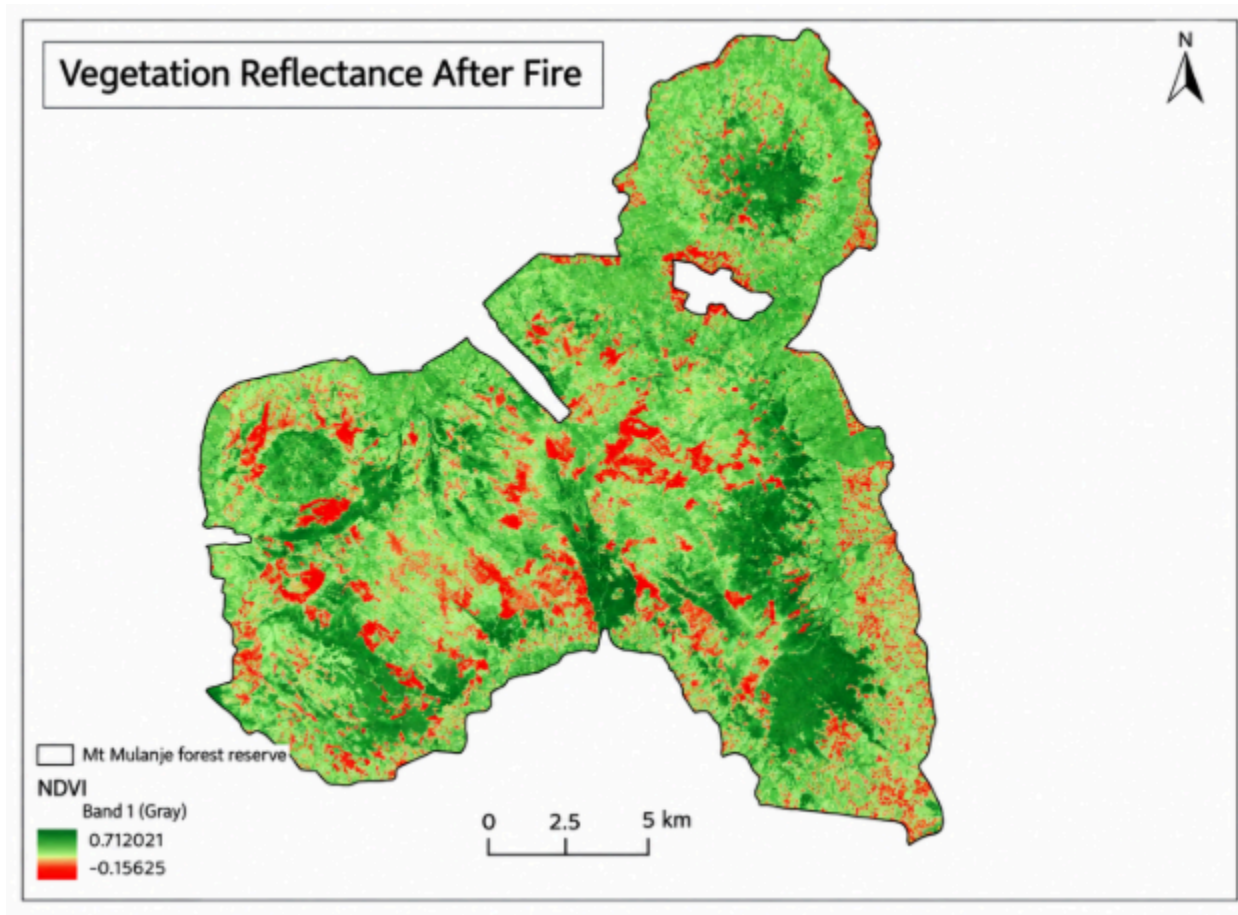


Figure 9

Vegetation reflectance after fire

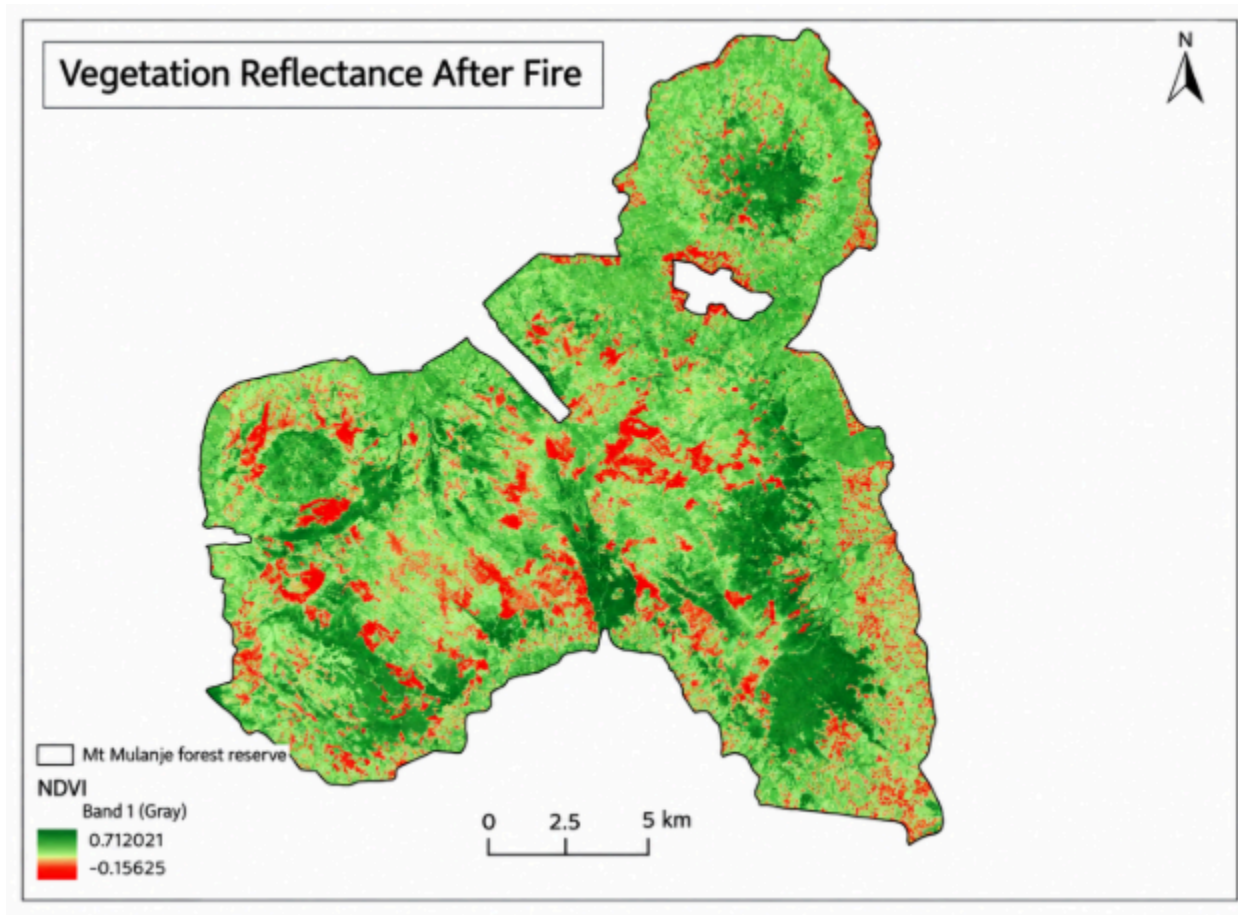


Figure 9

Vegetation reflectance after fire

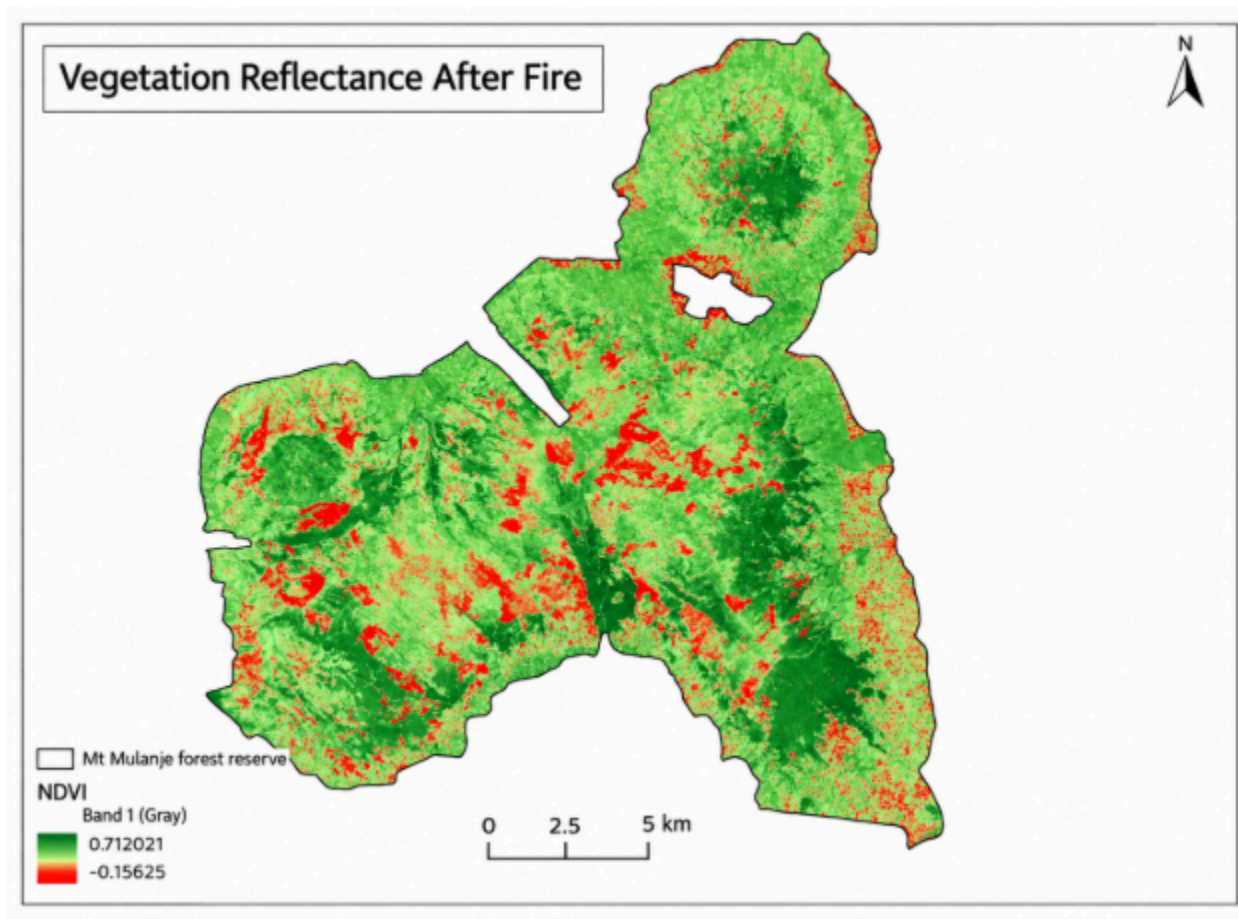


Figure 9

Vegetation reflectance after fire

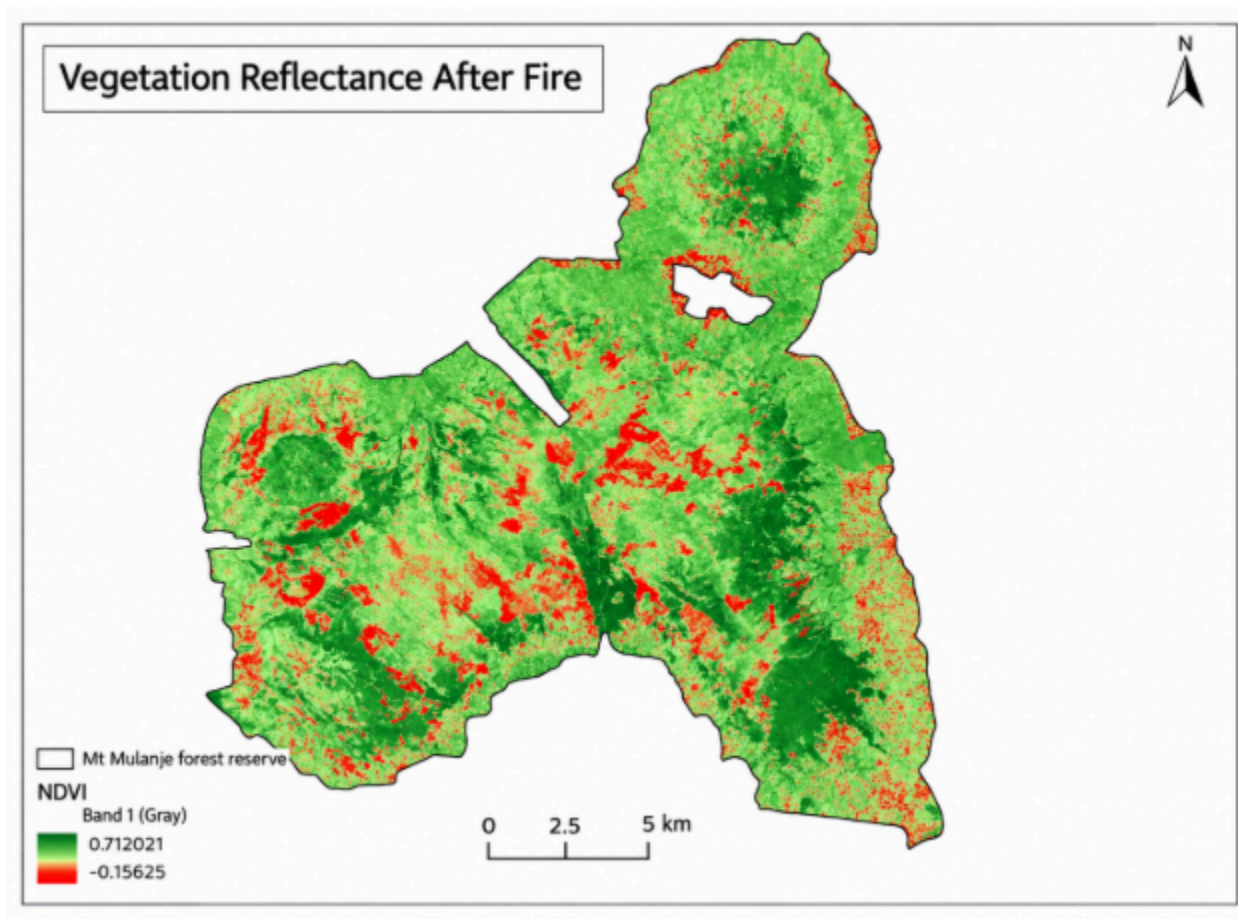


Figure 9

Vegetation reflectance after fire