

## A Review of Forest Fire Science: Prevention and Detection

Stanley H. Mneney\* and Clinton Shonde

St. Joseph University in Tanzania, P.O Box 7007, Luguruni, Dar es Salaam, Tanzania

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### ABSTRACT

Forest fires have profound effects on both ecosystems and communities, causing immediate destruction and long-term challenges. The impacts on ecosystems include habitat loss, soil degradation, air and water pollution and climate change speedup. The impact on communities include health risks, economic loss, displacement of communities and psychological effects resulting from trauma of losing homes and loved ones. The fight against forest fires involves prevention, early detection and suppression. In this article selected knowledge on forest fires (also known as wildfires) and the strategies and facilities that are available to fight against forest fires are reviewed. The worst scenarios will be highlighted by looking at some of the biggest fires that have happened across the world and the damage they have caused. It is crucial to understand the chemistry of fires (composition and chemical reaction), the causes of fires (natural and human-related), types of fires and the products of fires. These are important for wild fires management using the evolving green technologies. The review will then focus on prevention, early detection and aggressive suppression with a particular focus on the African and Tanzanian scenario. The paper will end by a design of an early detection system to protect a selected conservation area.

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\*Corresponding author's e-mail address: [shmnene@gmail.com](mailto:shmnene@gmail.com) (Mneney, S.H.)

## 1.0 Introduction

Forest fires can be triggered by both natural and human-related causes. Climate change will also intensify forest fires by creating hotter, drier conditions that make forests more vulnerable to burning. Some of the causes of Forest fire trigger, Paton and Shroder (2014) are as follows:

### 1.1 Natural Causes

- i. Lightning strikes: Lightning can ignite dry vegetation, leading to widespread fires. It is one of the most common natural causes of wild fires.
- ii. Extreme Weather Conditions: High temperatures, prolonged droughts, and strong winds create ideal conditions for fires to start and spread.
- iii. Volcanic Eruptions: Lava flows and ash clouds can ignite forests. This is not very common.

### 1.2 Human -related

- i. Agriculture Practices: Farmers often use fire to clear land. These fires can sometimes spread uncontrollably.
- ii. Deforestation and Land Clearing: Large-scale logging and land conversion for farming increase fire risks.
- iii. Negligence: Unsupervised campfires, discarded cigarettes, and sparks from machinery can ignite dry vegetation.
- iv. Arson: Some fires are deliberately set for various reasons, including land disputes or illegal activities.

Some of the worst forest fires across the world in the last 10 years are indicated in table 1 , Weisse and Goldman (2025), . These fires highlight the increasing severity of wildfires worldwide, often fueled by climate change. The damage caused worldwide is in terms of millions of hectares of land burnt, thousands of homes destroyed, deaths of millions of animals and evacuation of a huge number of human beings.

Major recorded forest fires often appears to be concentrated in developed regions. This appears so because of the following reasons:

- i. Developed nations generally have more advanced infrastructure for tracking, reporting and recording wildfires.

- ii. Many developed countries experience climate conditions that make them prone to fires.
- iii. More industrial activity, land development, and tourism in developed nations increase fire risks.

However, this doesn't mean that forest fires are absent in less-developed regions. Fires frequently occur in parts of Africa, Southeast Asia, and South America, especially in places like the Amazon and Congo rain forests, but they might be under-reported or categorized differently.

Forest fires in Africa have been increasing, particularly in regions that were previously considered less fire-prone. Here are some key observations:

- i. Rising Fires in Wet Forests - Fires in Africa's wet, tropical forests, especially in the Congo Basin, have doubled over the past two decades. These fires were historically overlooked because they were smaller compared to savanna fires, but recent studies show they are becoming more frequent due to hotter, drier conditions and deforestation.
- ii. Cyclic Wildfire Patterns - In Sub-Saharan Africa, wildfire occurrences follow cyclic trends, with a five-year oscillation pattern. This means fire activity fluctuates over time, influenced by climate conditions and vegetation changes.
- iii. Impact of human beings - Many fires in Africa are human-induced, often linked to land clearing, agriculture, and deforestation. Fragmentation of forests makes them more vulnerable to burning, especially at the edges.
- iv. Climate Change Effects - Extreme weather events, such as the 2015-2016 el niño, intensified heat and drought conditions, leading to a noticeable increase in fires. Scientists warn that as global temperatures rise, tropical forest fires will likely become more frequent and severe.

### 2.0 CTIF World Fire Statistics Summary

The Center for World Fire Statistics, CTIF Report No.29 (2024), provides comprehensive data on fire incidents, fatalities, and property losses

across selected countries that are willing to provide the required data. Graph in Figure 1 shows cumulative statistics for 50 countries. These graphs give the the number of fires happening in the selected area and the fatalities due to these fires in each year from 2000 to 2022.

Figure 1  
Cumulative Statistics for 50 Countries

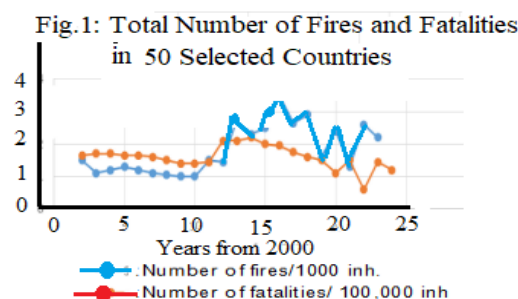


Table 1

*The Worst Fires of the Last Decade 2010-2020 (Weisse, M & Goldman (2025))*

Identity	Date	Damage
1 Australian Bushfire Season "Black Summer"	2019 - 2020	This fire burned 18.6 million hectares, destroyed thousands of homes, and led to the deaths of over 1 billion animals
2 Amazon Rainforest Fires	2019	The amazon forests provides 25% sink of the global CO <sub>2</sub> sink. The fires had big impact on deforestation and climate change. About 970,000 hectares were burned.
3 Siberia Wildfires	2019	These fires burned 2.6 million hectares of forest, aggravated by rising temperatures and dry conditions.
4 Mendocino Complex Fire USA	2018	This was one of California's largest wildfires, burning over 459,000 acres.
5 Camp Fire USA	2018	It caused 85 fatalities, displaced more than 50,000 people, and destroyed more than 18,000 structures. Losses in property is estimated to be about US\$16.5 billion. It was the deadliest and most destructive wildfire in California's history.
6 British Columbia Wildfires, Canada	2017-2018	These fires burned vast areas; about 1.2 million hectares, 1.3 % of area of British Columbia, leading to 65,000 evacuations.
7 Attica Wildfires, Greece	2018	A devastating fire near Athens, killed 102 people, making it one of the deadliest wildfires in Europe.
8 Fort McMurray Wildfires, Canada	2016	This fire led to the evacuation of 88,000 people and caused billions of \$ in damages.

From the extensive CTIF data the following observations can be made, CTIF Report No. 29 (2024).

a) Global Fire Incidents:

- i. Residential fires remain the leading cause of fire fatalities across the world.
- ii. Industrial and transportation-related fires contribute significantly to economic losses.
- iii. Forest fires have increased in frequency and intensity, driven by climate change.

b) Fire Fatalities and Injuries:

- i. Developed countries report lower fire fatality rates due to advanced fire prevention measures.
- ii. Elderly individuals and children are disproportionately affected in fire incidents.

- iii. A significant percentage of fire-related deaths result from human negligence or unsafe behaviour.

c) Economic Impact:

- i. Annual fire-related losses amount to billions of dollars in infrastructure damage and business disruptions.
- ii. The cost of firefighting operations, insurance claims, and healthcare expenses continues to rise.

d) Environmental Consequences:

- i. Large-scale wildfires accelerate deforestation and carbon emissions.
- ii. Toxic pollutants from fire incidents affect air and water quality.
- iii. Climate-related fire patterns indicate worsening risks in arid and drought-prone regions.

### 3.0 The Science of Fires

#### 3.1 The Fire Combustion Process. Spalding, (1979)

Fire is fundamentally a chemical reaction called combustion. It involves the rapid oxidation of a fuel, releasing heat and light. It is an exothermic reaction, meaning it generates energy rather than absorbing it.

Three key elements are essential for fire: fuel (something that burns), heat (to raise the fuel to its ignition temperature), and oxygen (to support combustion). These elements form the "fire triangle," and removing any one of them can extinguish a fire.

The resulting incandescent bloom of gas further heats the fuel, releasing more vapour and perpetuating the cycle. Planet earth is the only known planet where fire can burn. No other planet has the required amount of oxygen to feed a fire. The more oxygen there is, the hotter the fire.

#### 3.2 Types of Fires

Fires are classified based on their fuel source. Below is a UK fire classification chart. The classification will determine the appropriate fire extinguisher. Fire Extinguishers (2023).

**Class A** – Involves fires from burning organic substances like wood, paper, cardboard and textiles.

**Class B** – Flammable liquids such as kerosene, oils, petrol, paints and alcohol.

**Class C** – Fires are caused by combustion of gases such as methane, natural gas, propane, and acetylene.

**Class D** – Fires involve combustible metals such as magnesium, potassium, plutonium, sodium, titanium, lithium and aluminium.

**Electrical** fires involve potentially live electrical equipment.

**Class K** – Combustible oils and fats normally found in kitchens.

In normal circumstances forest fires will fall under type A class of fires.

#### 3.3 Products of Fire Combustion

The main products of fire combustion are carbon dioxide, water vapor, light and heat. Other

potential products include carbon monoxide, nitrogen oxides, sulfur dioxide, particulate matter, and unburnt hydrocarbons. The specific byproducts depend on the completeness of the combustion process and the materials involved.

##### 3.3.1 Complete Combustion

When a fuel burns completely with sufficient oxygen, the primary products are carbon dioxide and water vapor, along with a significant amount of heat and light.

##### 3.3.2 Incomplete Combustion

If oxygen is limited, incomplete combustion can occur. This can lead to the formation of:

**Carbon Monoxide** : A toxic, colorless, and odorless gas.

**Particulate Matter**: Tiny particles of soot, ash, and other materials that can be harmful to health.

**Unburnt Hydrocarbons**: These can include various compounds, some of which may be volatile organic compounds.

**Nitrogen Oxides and Sulfur Dioxide**: These are formed from nitrogen and sulfur compounds present in the fuel or air and can contribute to air pollution.

**Heat**: Heat is always a product of combustion, and the amount varies depending on the fuel and the reaction conditions.

**Light**: Combustion is often accompanied by the emission of light, including visible light and infrared radiation

### 4.0 Forest Fires

#### 4.1 The Impact of Forest Fires, Quranos (2025), Arvin (2024)

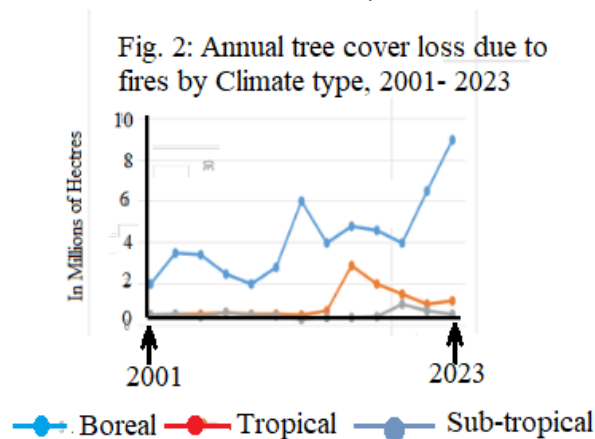
The frequency and severity of forest fires is increasing globally, with a record amount of forest lost in 2024 due to fires. Carbon emissions from these fires have also risen significantly, and the area burned each year has increased over the past two decades. In 2024 tropical forest loss reached 6.7 million hectares, twice as much as in 2023, with fires being the leading cause. In parallel with this, carbon emissions from forest fires globally increased by 60% between 2001 and 2023. About 90% of these fires are caused by human activities.

These changes are happening not only as a result of the growth of the human populations and

expanded agriculture but climate change is primarily to blame for the increasing fire activity. Warmer temperatures leave landscapes drier and more flammable. Drought and heat wave conditions allow fires to burn more completely and more severely, with longer-term impacts on surrounding ecosystems, as well as carbon storage. More burning means more carbon is released from the soil and vegetation into the air, further warming the planet and supporting even more fires.

The graph below, from data collected by the World Resource Institute, shows a brief overview of the impact of forest fires, CTIF (2024). It is a plot of the annual tree cover loss due to fires for the period 2001 to 2023 worldwide. It shows a gradual increase in the boreal forest tree loss with an exponential loss at the end of 2023. The other big loss occurs around 2016 where there is a big loss of the tropical tree cover.

Figure 2  
 Overview of the Forest Fire Impacts CTIF (2024)



#### 4.2 Prevention of Forest Fires

There are strategies that can be used to prevent forest fires, and they often work best when combined. These are initiatives from the local authority, the community and even governments. They include the following:

- i. **Controlled Burns:** Setting small managed fires, helps clear dry vegetation that could fuel larger wildfires.
- ii. **Firebreaks:** Clearing strips of land to stop or slow the spread of flames.
- iii. **Smart Forestry Practices:** Removing dead trees and thinning dense forests reduces fire risk.

- iv. **Public Awareness:** Educating communities about fire safety, like proper disposal of cigarettes and campfire precautions.
- v. **Early Detection Systems:** Using drones, satellites, and AI to monitor fire-prone areas and catch wildfires early.
- vi. **Stronger Policies:** Enforcing regulations on land use, illegal burning, and fire safety measures.
- vii. **Resilient Landscaping:** Encouraging fire-resistant plants and designing defensible spaces around homes and infrastructure.

#### 4.3 Detection Technologies for Forest Fires

##### 4.3.1 General Overview of the Detection Technologies

Early forest fire detection devices use various technologies to identify fires in their initial stages. Here are some common types:

- i. **Optical and Infrared Cameras**
- ii. **Satellite-based Detection Systems.**
- iii. **Smoke and Gas Sensors**
- iv. **Light Detection and Ranging (LIDAR ) Systems**
- v. **AI-Powered Fire Detection Systems.**
- vi. **Drones and Unmanned Aerial Vehicles (UAV)**
- vii. **Acoustic Sensors**
- viii. **Wireless Sensor Networks (WSNs)**

These technologies, when used together, improve the speed and accuracy of wildfire detection, helping prevent large-scale forest fires.

Recent advances in technology has made early detection more efficient—even in remote areas. Here are some more efficient advanced strategies currently in use:

- i. **Satellite Monitoring:** Space-based sensors can detect unusual heat signatures or smoke, helping pinpoint fires in vast, inaccessible forests.
- ii. **AI-Powered Detection:** Machine learning models analyze satellite images and environmental data to predict fire risks and identify early signs of ignition.
- iii. **Drone Surveillance:** Autonomous drones equipped with thermal cameras can scan large areas quickly and report fire risks before they escalate.

- iv. **Ground Sensors:** IoT-enabled sensors placed in forests detect temperature spikes, humidity changes, and even smoke, sending instant alerts to fire management teams.
- v. **Acoustic Sensors:** Listening devices can pick up changes in forest acoustics caused by fire, such as crackling sounds or unusual wildlife movements.
- vi. **Crowd-sourced Detection:** Local communities and park rangers using mobile apps or connected systems can report early smoke sightings, improving response time.
- vii. **IoT-Enabled Forest Fire Detection:** this is selected for a more detailed review in section 4.3.2 below:

#### 4.3.2 IoT-Enabled Forest Fire Detection

IoT-based systems comprise wireless sensor networks, edge devices, and cloud platforms that together collaborate to monitor environmental variables such as temperature, humidity, smoke, and gas concentrations. A typical setup includes sensor nodes deployed across forested areas, gateways for data aggregation, and centralized cloud infrastructure for analysis and alerting. These systems can operate independently using solar power and low-power protocols such as LoRaWAN or Zigbee.

The main advantages of using LoRaWAN for IoT sensors are:

- i. **Security:** LoRaWAN integrates two levels of encryption (network and application) to ensure that transmitted data is protected against interception and tampering.
- ii. **Long range:** LoRaWAN can cover vast geographical areas, with a range of up to 15 kilometers in rural areas and up to 2 kilometers in urban areas.
- iii. **Low power consumption:** The power consumption of LoRaWAN devices is optimized to extend the life of battery-powered sensors for several years.
- iv. **Low cost:** Unlike cellular networks or some Wi-Fi solutions, LoRaWAN operates on free frequency bands (ISM), eliminating the need for subscriptions or data usage costs.
- v. **Scalability:** LoRaWAN can handle thousands of devices with a minimum

number of gateways, enabling large-scale IoT networks to be set up without costly infrastructure.

IoT solutions are cost-effective, modular scalable, and have a localization potential. Their decentralized nature means they can still operate in low-connectivity regions, which is ideal for areas like the Eastern Arc Mountains or Selous Reserve in Tanzania.

Mambile *et al.* (2024) used deep learning with satellite images and IoT data for forest-fire prediction around Kilimanjaro.

#### 4.3.3 Examples of IoT-Based Fire Detection

There are several compelling examples of IoT-based fire detection and environmental monitoring networks. Some examples are shown below:

##### 4.3.3.1 Africa's Largest LoRaWAN Conservation Network – Kenya

- i. Location: Northern Rangelands, Kenya.
- ii. Technology: LoRaWAN, EarthRanger, Cisco gateways.
- iii. Scope: Covers over 3 million hectares across 22 community-led conservancies
- iv. Sensors Used: Wildlife tracking, water levels, vegetation health, and fire risk.

##### 4.3.3.2 Smart Forest Monitoring – Uganda

- i. Partners: Uganda Wildlife Authority, Connected Conservation Foundation
- ii. Technology: LoRaWAN + satellite uplinks
- iii. Applications: Fire detection, anti-poaching, and habitat monitoring in Queen Elizabeth and Murchison Falls National Parks
- iv. Relevance: Highlights hybrid connectivity (LoRa + satellite) for ultra-remote zones

##### 4.3.4 The Proposed IoT-Based Fire Detection Network for Ngorongoro Conservation Area (NCA) in Tanzania

###### 4.3.4.1 Wireless Technology

For the Ngorongoro Conservation Area (NCA) and based on the examples above either LoRaWAN or ZigBee, wireless technology will be used depending on terrain, range, and energy

constraints. The NCA terrain is made up of the following features:

- i. Craters, forests, savannas, and grasslands; leading to varied risk zones for fire.
- ii. Sparse infrastructure; demanding wireless systems with long-range and low power consumption.
- iii. Biodiversity sensitivity, requiring minimal ecological disruption.

#### 4.3.4.2 Sensor Placement Strategy for Effective Coverage

Define Fire Risk Zones

- i. Use historical fire data and vegetation maps to mark hot-spots: dry grasslands, tourist camps, forest fringes, etc.

#### 4.3.4.3 Network Architecture – ZigBee vs LoRaWAN

Feature	ZigBee	LoRaWAN
Range per node	10–100 m	Up to 15 km (line-of-sight)
Power consumption	Low	Very low
Cost	Affordable	Affordable
Mesh networking	Yes (self-healing)	No (star topology)
Ideal terrain	Dense or tree-covered areas	Open, wide terrain with few obstructions
Scalability	Medium	High

- **LoRaWAN:** Ideal for low-power, long-range communication in rural areas.
- **Zigbee:** Shorter range but energy-efficient, good for dense sensor clusters.

Recommendations:

- Use ZigBee in dense forested craters where relay nodes can form a mesh.
- Use LoRaWAN in wide savannas and crater rims where fewer long-range nodes can serve large zones.

Infrastructure Layer

Gateways:

- Install **solar-powered LoRaWAN gateways** on high ground (e.g., observation posts or ranger towers). Each can cover 5–10 km radius.
- For ZigBee, deploy mesh relays with local solar batteries.

Connectivity:

- Gateways can upload to a **central server via 3G/4G, or satellite.**

In the map of Fig. 3 the green forested area around the craters is classified as the High Risk areas and ZigBee technology will be

- ii. Designate three zones: High Risk (crater rim forests), Medium Risk (savanna edges), and Low Risk (wet zones or low activity areas).

Sensor Types & Location

Use multi-sensor nodes combining: Temperature, Smoke, Gas (CO, CO<sub>2</sub>), or/and Infrared / Flame detectors and place them:

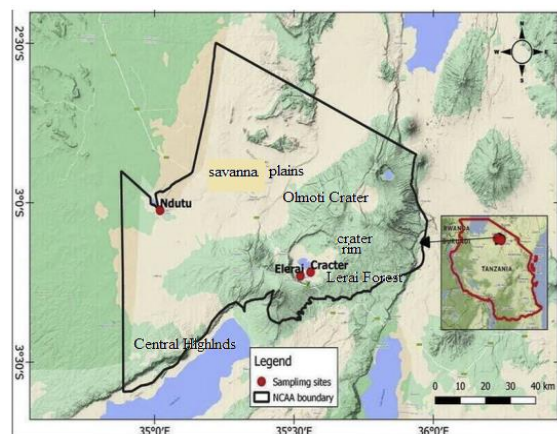
- i. High Risk Zones: sensors every 300–500 m
- ii. Medium Risk Zones: sensors every 800–1000 m
- iii. Low Risk Zones: sensor nodes only at ranger stations or access roads

Mount sensors on existing trees or posts, about 2.5–3 meters high, to avoid wildlife interference and reduce vegetation shadowing.

deployed to form a mesh network. The gray wide area represents the savanna area and the LoRaWAN technology will be deployed.

Figure 3

Conceptual Deployment Zones for the Ngorongoro Conservation Area



## 5.0 Forest Fire Dynamics in Africa (Mkiwa, 2025)

Africa plays a pivotal role in the global landscape of wildfire activity, contributing to approximately

67% of the total area burned worldwide each year. While much of this fire activity is concentrated in savannas and grasslands, recent evidence points to a concerning uptick in fire frequency within tropical and subtropical forest zones—especially in Central and West Africa. Countries such as Angola, the Democratic Republic of Congo (DRC), and Mozambique consistently report the highest fire incidences, largely driven by land-use practices such as shifting cultivation, charcoal production, and deforestation for agriculture.

In Central Africa, the Congo Basin has seen a marked increase in the penetration of fire into historically fire-resistant humid forests, signaling potential shifts in ecosystem resilience under pressures from human activity and changing climate conditions. Similar patterns are observed in parts of Ghana, Cameroon, and Nigeria, where forest edge incursion and fragmentation have elevated fire exposure even during wetter periods, Wimberly, (2024).

In Tanzania, the Miombo woodland, characterized by a pattern of deciduous trees, ground cover grasses, and shrubs, form the dominant forest landscape (Tarimo, 2016). These ecosystems have adapted over centuries to periodic, low-intensity fires. However, contemporary fire patterns in Tanzania reflect both ecological and anthropogenic drivers; annual agricultural burning, and late-season wildfires contribute to increased intensity and frequency, especially in and around protected areas such as the Eastern Arc Mountains and the Selous Game Reserve. Despite their fire-adapted nature, Miombo systems are vulnerable to degradation when exposed to repeated high-intensity burns, leading to biodiversity loss, soil nutrient depletion, and disruption of carbon cycles.

This regional perspective highlights the urgent need for localized forest fire management strategies in tropical Africa that integrate traditional ecological knowledge, early warning systems, and community-centered fire governance where forest-dependent communities are both contributors to and victims of wildfire dynamics.

## **6.0 Conclusions**

Forest fires in tropical regions of Africa represent a complex interplay of ecological processes, human activities, and evolving climate pressures. This review has highlighted the disproportionate share of global burned area attributed to African ecosystems, especially savanna and Miombo woodlands, and underscored the emerging threat of fire incursion into humid tropical forests previously considered resilient.

In the Tanzanian context, fire regimes are shaped by both traditional land-use practices and modern stressors such as shifting agriculture and late-season ignition. While the Miombo woodlands are adapted to fire, increasing frequency and intensity risk degrading biodiversity, carbon stocks, and community livelihoods. Studies from within Tanzania have begun to shed important light on these dynamics, but data fragmentation and limited surveillance capacity remain major barriers to informed response.

Moving forward, an integrated fire management approach is urgently needed; one that combines satellite-based monitoring, local ecological knowledge, and community empowerment. Regional collaboration, open-access data sharing, and policy alignment across conservation and agriculture sectors will be crucial to developing adaptive strategies.

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## **9. Declaration of Conflicting Interests**

The authors declare no conflict of interest.

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