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Unveiling the Impact of Climate Variability on Forest Fire Occurrence in Namibia: A Modelling Study

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Abstract

Background

Forest fire is the primary disturbance affecting the structure and composition of many forest ecosystems worldwide. Forest fires caused severe destruction to forest ecosystems in Namibia (South West Africa) during the period of 2011–2021. The aim of this paper is to assess the impacts of climate variability on forest fire occurrence in Namibia.

Results

A total of 38.184 Mha of forests was burned during the study period. Forest fire occurrence fluctuated in response to changes in climate variability (temperature, precipitation, and wind speed). Using linear regression models, ranked according to the Akaike information criterion (AIC), we found a combination of average wind speed in the 3-month period of July, August, September, and average monthly wind speed in January, May July, and August, to be the most important drivers of forest fires.

Conclusions

Forest fire occurrences are highly concentrated in the north-eastern and north-central regions. Forest fire occurrence is not limited to climate variability. There is little scientific evidence about other factors influencing forest fire occurrence in Namibia, in addition to climate variability.

1. Introduction

Forest fire is the primary disturbance affecting the structure and composition of many forest ecosystems worldwide (Liu et al., 2010). The frequent forest fires in recent years are believed to be attributed to the changing climate conditions. In other words, climate determines the spatiotemporal distribution, intensity, and patterns of forest fires by affecting vegetation and the extent of drought (Zeng et al., 2022).

Studies have established that climate change is increasing forest fire occurrence due to extreme temperatures, projected impacts on plant biomass accumulation, and socioeconomic factors (Camia et al., 2017; Gebeyehu, 2019; Girardin et al., 2013). Predictive studies indicate that if climate change continues, it will likely increase the fire season environments, that are more likely to incur large forest fires (Anoszko et al., 2022; Davis et al., 2017). Future projections based on historical records, current trends, and simulation modelling indicate that prolonged warmer and drier conditions will lead to lower fuel moisture and longer fire seasons, thus likely increasing the frequency and intensity of future fire, compared to that of the twentieth century (Halofsky et al., 2020).

In forest ecosystems, climate conditions are one of the central drivers of forest fires worldwide (Angra and Sapountzaki, 2022; Aponte et al., 2016). Changing climate makes forest ecosystems vulnerable to wildfires (Heidari et al., 2021) and leads to adverse forest ecosystem destruction (Holden et al., 2018; Juárez-Orozco et al., 2017). The effects include disturbance of wildlife habitat, acceleration of nutrient cycling, and mortality of individual trees (Dale et al., 2001; Hutchinson et al., 2019; Jhariya and Raj, 2014). Additionally, forest fires can reduce precipitation by releasing substantial amounts of smoke into the atmosphere, thus promoting more drought and fires (Kirsanov et al., 2020). Consequently, the precipitation regime significantly impacts the number of fires and areas burned (Chen et al., 2014). These events can thus affect forest ecosystem services and biodiversity.

Despite the impacts of fire on the ecological aspect of forest ecosystems (Chuvieco et al., 2014; Pereira et al., 2021), it also affects the socio-economic sphere (Chinamatira et al., 2016; Román et al., 2013)]. Wildfires also have direct economic costs, such as property losses and firefighting costs (Lang and Moeini-Meybodi, 2021). Firefighting costs can potentially affect the economic performance of the forestry sector. Fire costs are measured through prevention and suppression measures, and direct and indirect costs (Stougiannidou et al., 2020).

On the regional level, in Europe, for example, the frequency of heat-induced fire is predicted to increase significantly, especially in the southern part of Eastern Europe (Carnicer et al., 2022). Representing the Mediterranean region, another climate change-prone country, Greece, experienced increased temperature, decreased precipitation, and a high frequency of forest fires (Angra and Sapountzaki, 2022). Similarly, increased temperatures in Canada are associated with extended burned areas (Mukhopadhyay, 2009).

In Southern Africa, forest fires are predominantly evident during the dry season, typically from May to October, while few fires occur during the wet season, mainly from November to April (De Sales et al., 2019). In the same view, in South Africa, where a total of 15 Kha of forest was burned in 2017, it has been highlighted that wildfire was preceded by a prolonged drought, which is also associated with temperature rise (Kraaij et al., 2018).

Regarded as the driest country in sub-Saharan Africa (Mupambwa et al., 2019), Namibia is characterised by high temperatures, with mean annual temperatures ranging from 14.3 to 24. 2°C (Lisao et al., 2017; World Bank Group, 2021). Changing climatic conditions have resulted in prolonged dry summer seasons in Namibia (Keja-Kaereho et al., 2019; Liu and Zhou, 2021), where summer months are generally warmer and persistently dry. Warmer and dry conditions also create favourable fire environments (Seidl et al., 2017); hence, the trends in fire occurrence are primarily a response to changes in vegetation biomass during dry seasons (Lenihan et al., 2003).

Studies have predicted that climate change will continue to significantly influence fire behaviour and cause destruction to forest ecosystem services in Namibia (Kapuka et al., 2022; Keja-Kaereho et al., 2019; Nikodemus et al., 2022; Reid et al., 2007). This phenomenon has already started to manifest in most parts of the country (Kapuka and Hlásny, 2020), which is prone to forest fires due to the dry conditions (Mwansa, 2018). Hence, forest ecosystems are vulnerable to forest fires in the increasingly changing climate (Kazapua et al., 2009; Mayr et al., 2018).

Forest fires play an essential role in the Namibian ecosystems and economies, and provide vital ecological functions (Sheuyange et al., 2005). More than one million hectares of forest and grasslands are burned every year in Namibia. In 2022 alone, burned areas accounted for 920,944 ha in various regions between April and September (Ministry of Environment and Tourism, 2022). Most of the fires in Namibia occur in the northern regions of the country (van Wilgen, 2009), where most of these fires are human-induced; for example, as a result of some agriculture practices such as slash-and-burn, that often leads to the uncontrollable spread of fire (Ministry of Environment and Tourism, 2016; Verlinden and Laamanen, 2006), or it is started unintentionally (Sheuyange et al., 2005). In Namibia, most fires occur during the periods of May-July, the dry and windy seasons (early dry season: low-intensity fires), and August-September (late dry season: high-intensity fires) (Kazapua et al., 2009; Siljander, 2009). The most fire-prone areas are the communal lands in the north-central and northeastern parts of the country (Verlinden and Laamanen, 2006). Depending on the intensity and timing, Forest fires may cause environmental damage and loss of biodiversity, which impact the livelihood of local people, and regional economies (Pricope et al., 2015).

A better understanding of forest fire trends can increase predictive capacity regarding the long-term consequences of global change on forest ecosystems in dry and highly climate change-vulnerable developing countries like Namibia. However, assessments of forest fire occurrence trends and intensity in correlation with climate variables, such as precipitation, temperatures, and wind speed are not sufficiently addressed on the national level in Namibia. Therefore, this paper aims to assess the impacts of climate variability on forest fire occurrences in that country.

2. Materials And Methods

2.1 Study area

Namibia is located in the southwestern part of the African continent, between the Namib Desert and the Kalahari Desert (Liu and Zhou, 2021). It is bordered by Angola and Zambia to the north, Botswana to the east, and South Africa to the south (Fig. 1). Covering a total surface area of 825,615 km^2, Namibia has a population of 2.5 million (Kapuka and Hlásny, 2020).

The vegetation types of Namibia are characterised by its geographical location, situated between the Namib Desert stretching along the coast on the west, and the Kalahari Desert which borders its eastern and southern neighbours, Botswana and South Africa, respectively (Bliss, 2018; Nikodemus et al., 2022; Radatz, 2003). The dry climatic conditions have a significant influence on its vegetation types. Hence, the three main vegetation types in Namibia can be classified as woodlands, savannas (grass cover, trees, and shrubs), and deserts (Namib grassland) [(Bhardwaj, 2019; Giess, 1986)].

2.2. Meteorological data

Our climate variables include wind speed, temperature, and precipitation. Future fire regimes were estimated using climate conditions to calculate future fire weather (de Groot et al., 2013). We used the average monthly and annual (Figs. 2, 3) temperature (°C) and precipitation (mm), as well as average monthly and clustered (in three-month periods) (Fig. 4) wind speed (m/s) per region for 12-year time series (2010–2021). The Namibia Meteorological Service Head Office in Windhoek (capital of Namibia) provided meteorological data, which were available for 269 weather stations in different regions across the country with varying climatic conditions.

In addition to temperature and precipitation, wind is another atmospheric factor that plays a huge role in the spread of fire (Purificação et al., 2022). In other words, the wind's intensity determines the fire's intensity and spread (Evers et al., 2022). Wind also determines fire direction (Sanjuan et al., 2014). However, it is noteworthy that other factors, such as tree density, determine the wind's influence on fire. For example, low tree densities need extreme wind to transfer fire between widely-spaced trees, whereas, at high tree densities, fire spreads quickly regardless of the strength of the wind (Song and Lee, 2017). As a result, we focused mostly on seasonal wind speed as a focal variable to test our model (Fig. 4).

2.3. Forest fire data

We obtained the forest fire area data from the Remote Sensing and Mapping Section of the Directorate of Forestry (DoF) of the Ministry of Environment, Forestry, and Tourism (MEFT) Head Office in Windhoek. We used fire (burned areas) data per region for 12-year time series (2010–2021).

We further mapped the distribution of forest fire across the country. The maps were produced with ArcGIS Desktop version 10.8. The shapefiles of Namibia - Subnational Administrative Boundaries - were downloaded from the freely-available database at the Humanitarian Data Exchange of the United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA) (https://data.humdata.org/).

2.4. Statistical analyses and model selection

Before the analysis, data were checked for outliers and collinearity. We plotted the response variable with each covariate during data exploration to check their relationship. Based on the data exploration, the relationship between tree loss and the explanatory variables was analysed using linear regression (Zuur et al., 2010). A set of a priori [1] models (Dochtermann and Jenkins, 2011; Rosen, 2016) was selected prior to analysis (Table 2) in order to test which model would best explain the loss of forested areas. These models were constructed using previously known variables that were identified as important for forest fire development dynamics, mainly climatic variables. The information-theoretic analysis approach (Burnham et al., 2011) was used to assess competing models. Models were ranked according to the Akaike information criterion (AIC); and the most parsimonious model was selected based on the lowest AIC value. We also calculated Akaike weights to arrange candidate models in order of parsimony, where Akaike weight is a number from 0 to 1, providing a measure of the relative likelihood of each model, given the data and candidate model set (Burnham et al., 2011).

We tested the correlation between changes in annual area affected by forest fire in a particular year, and changes in annual area affected by forest fire in previous years, by calculating the autocorrelation function (ACF). Because we used previous year forest fire area as an explanatory variable in our analysis, the sample size changed from 12 (2010–2021) to 11 years (2011–2021). All data cleaning, plotting, calculations, and statistical analysis were conducted in VSCode 1.73.1 using Python programming language (Rossum and Drake, 2010) version 3.8.5, and using statsmodels 0.13.5, scikit-learn 1.1.2 (Pedregosa et al., 2011), pandas 1.5.0 and Matplotlib 3.6.0 (Trubin et al., 2022).

3. Results

3.1. Burned areas

Total area affected by forest fire, considering all 12 years from 2010 to 2021, amounted to 38.184 Mha (Fig. 5). Forest fire area was above zero for all years, with the lowest damage of 0.179 Mha in 2019.

Forest fire occurrences have been fluctuating since 2010. However, the highest forest fire occurrence was in 2011 (6.6 Mha) and 2012 (7.1 Mha), respectively. The lowest forest fire occurence was recorded in 2018 (0.2 Mha) and 2019 (1 Mha), respectively. There was an increase in forest fire occurrences in 2020 (3.5 Mha), and a slight decline was recorded in 2021 (3 Mha).

3.2. Forest fire distribution

Forest fire is predominantly concentrated in the north-eastern regions throughout the period of 2011–2021 (Fig. 6).

Our results show that forest fire occurs mainly in the forested areas according to the vegetation distribution of Namibia (Fig. 1). The most affected regions were the Zambezi, Kavango East and West, and some parts of the Oshikoto, Oshana, and Omusati regions. Relatively smaller patches of forest fire occurrence were also recorded in the central regions, the Khomas and Otjozondjupa regions, as well as some parts of the Erongo, Omaheke, and Hardap regions.

3.3. Annual burned area

We tested the data on damage by forest fire throughout our study period for autocorrelation; the ACF function did not reveal trends between damage caused by forest fire in a given year and the previous year. Linear regression was used further to investigate the relationships between burned area and meteorological variables. The a priori set of competing models that differ by a combination of predictor variables is given in Table 1.

Table 1
Proposed models to study annual changes of forest fire areas for a 12-year period.

Model	Variables
1	Annual burned area = AugW + JAS_W +
2	Annual burned area = JulW + AugW +
3	Annual burned area = JanW + MayW +
4	Annual burned area = MayW + JulW +
5	Annual burned area = FebP + JulP +
6	Annual burned area = JanW + AugW +
7	Annual burned area = JulW + AMJ_W +
8	Annual burned area = AprT + DecW +
9	Annual burned area = MarP + JFM_P +
10	Annual burned area = FebP + MarP +
11	Annual burned area = MayW + AMJ_W +
12	Annual burned area = MayW + JFM_W +
13	Annual burned area = AugW + JFM_W +
14	Annual burned area = FebW + AMJ_T +
15	Annual burned area = SepW + AMJ_T +
16	Annual burned area = Y_P(t-1) + JulT +
17	Annual burned area = JunP + JulP +
18	Annual burned area = AprT + SepW +
19	Annual burned area = JunT + SepW +
20	Annual burned area = MayW + JAS_W +

Notes: Annual burned area is the yearly change according to Eq. 1 (is random error).

Table 2

Akaike's information criterion (AICc) values for a small sample dataset (ΔAIC values and Akaike weights (AIC weight) for the competing models are listed in Table 1). The model with the lowest ΔAIC is the most parsimonious, given the data. Models with ΔAIC < 2 may be considered as good as the best, while models in the ΔAIC range of 2–7 are also plausible. The AIC weight is a value between 0 and 1, with the sum of all models in the candidate set being 1. This weight can be considered the probability that a given model is the best-approximating model.

Model	AIC	ΔAIC	AIC weight
1	25.669	0.000	0.051
2	26.637	0.968	0.031
3	27.605	1.936	0.019
4	28.687	3.018	0.011
5	28.808	3.139	0.011
6	29.689	4.020	0.007
7	30.191	4.522	0.005
8	30.260	4.591	0.005
9	30.273	4.604	0.005
10	30.306	4.637	0.005
11	30.339	4.669	0.005
12	30.422	4.753	0.005
13	30.519	4.850	0.005
14	30.547	4.878	0.004
15	30.560	4.891	0.004
16	30.691	5.022	0.004
17	30.703	5.034	0.004
18	30.862	5.193	0.004
19	30.871	5.202	0.004
20	30.923	5.254	0.004

The most parsimonious model, according to AICc, was Model 1 (Table 2). Our model revealed (Table 4) that August average wind speed in a given year (AugW) and average wind speed in the period of July, August, and September in a given year (JAS_W) had a greater effect on forest fire area change from 2011–2021 (Table 4 and Fig. 4). Higher average wind speed in August of any given year resulted in more burned areas. On the other hand, higher average wind speed in the period of July, August, and September in a given year resulted in less area affected by forest fires.

The rest of the explanatory variables (Table 1) were not included in the most parsimonious models although, according to ΔAIC, Model 2 and Model 3 can also have strong explanatory power, because their ΔAIC < 2. These two models contain variables related to average monthly wind speed. The rest of the models tested, in the range of ΔAIC 2–7, may have biological meaning, although they are not considered optimal in our study period and area. These models represent different combinations of various wind speed (more often), precipitations, and temperature and underscore the tree loss change, although they have a much smaller probability of being the best model (AIC weight).

Table 3
Linear model equation estimating the alteration in annual area change (see Eq. 1) by forest fires as a function of the August average wind speed in a given year (AugW), and average wind speed in the period of July, August, and September in a given year (JAS_W) during the period of 2011–2021 in Namibia.

Parameter	Estimate	p-value	Model values
Intercept	0.4155	0.012 *	
AugW	0.4155	0.0038 **	Adjusted R-squared: 0.541
JAS_W	-0.4094	0.37	

4. Discussion

4.1 Summary of the results

Forest fires have become more severe in recent years in Africa due to prolonged fire seasons, due to changing climate scenarios (Siljander, 2009). Studies in other parts of the world have raised the same concern (Stougiannidou et al., 2020). In the case of Namibia, forests have been subjected to large-scale fire outbreaks in recent years. However, although fire is a vital ecosystem process in savannas (van Wilgen, 2009), to the best of our knowledge research in this area is limited.

Our study examined forest fire occurrence in areas with forests across Namibia from 2010 to 2021 (Fig. 6). A total of 38.184 Mha of forests were burned during the study period. Forest fires were highly concentrated in the north-eastern region. However, the north-central and central regions also experienced fire, but in relatively more minor measures. Fire intensity was the highest between 2010 and 2012. During this period, Namibia experienced severe droughts. However, an increase in forest fire occurrence has been witnessed recently, since the period of 2019–2021.

Our results showed that forest fire occurrence fluctuated in response to changes in climate variability (temperature, precipitation, and wind speed) over the study period (Fig. 5). We further identified that forest fires are most frequent during dry seasons. In Namibia, the dry season is between August and October. During this season, the wind speed, which is one of the leading climate variables, is stronger (Kazapua et al., 2009). In the case of forest fire, wind speed is considered the most critical weather parameter (Beer, 1991).

The occurrence of forest fires during the summer season is not only limited to Namibian conditions. A similar study in the United States also highlighted that forest fire occurrence was high during summer (August – December) (Heidari et al., 2021). In south-central Chile too, a study on socio-economic and land-cover drivers of wildfire activity and its spatiotemporal distribution also showed that forest fire occurred mostly during summer (Pozo et al., 2022).

There is a link between climate variability and forest fire. For example, if climate change leads to increased air temperature, reduced humidity, and stronger winds, we can expect larger fires (Lohmander et al., 2022). Our results show that the average annual temperature has risen since 2010 (Fig. 2). However, there was a decline in the average annual temperature in 2017 (16.7°C) and 2018 (16.2°C). As a result, the average annual precipitation has been affected, although it fluctuated during the period of 2010–2021 (Fig. 3). Similar trends have been noted in forest fire occurrence.

However, we discovered that although a relationship between climate variability and forest fire occurrence exists, it is complex due to other factors (Tomašević et al., 2022), such as socio-economic factors (Pozo et al., 2022), human behaviours, and forest ecosystems management practices. For example, in 2017, the annual average precipitation was the highest (1.08 mm), with a relatively small burned area (2.0 Mha). Conversely, in 2019, there was relatively the lowest rainfall of 0.4 mm, and at the same time, an insignificant number of forest fires occurred (1.0 Mha) (Figs. 3 and 5). Therefore, our results show that forest fire occurrence is not limited to climate variability. However, to the best of our knowledge, there is little scientific evidence about other factors influencing forest fire occurrence in Namibia, in addition to climate variability.

As well as the effects on forest ecosystems, forest fires can have significant economic and social consequences for local communities, and can be harmful or even fatal for humans living in the regions close to the burning areas (Kirsanov et al., 2020; Ntinopoulos et al., 2022). Although it is not comprehensively investigated, the effects of forest fires in Namibia have severely affected economic, social, and environmental spheres in recent years.

4.2 Limitations of study

For the creation of the dataset with average climate variables, data from all of the weather stations were aggregated, despite the relatively large size of the study area with different landscape and climate patterns. Input variables did not demonstrate correlation with the target variable. However, during the examination for multicollinearity, it was found that the variables in Model 1 exhibited a high degree of correlation (0.906). The decision to retain this combination of variables was made to include as much information as possible. Other best models had correlation between variables less than 0.7. Additionally, the dataset's small sample size precluded the use of a variance inflation factor (VIF) in linear regression modelling.

To further investigate the relationships between forest fire areas and meteorological variables, a set of generalised additive models (GAM) were also tested, with the assumption of non-linear relationships. The best GAM models of the set remained identical to those during linear modelling.

To our knowledge, this study is one of the pioneer studies on the impact of climate variability on forest fire in Namibia and the Southern African region. Hence, we experienced several limitations, including a lack of historical data, monthly fire data, and research papers in the body of literature. Furthermore, Namibia's conditions, ranging from forestry to climate variability, are unique. Therefore, the results cannot be confidently extrapolated to other parts of the world. However, comparative research on a regional level is encouraged.

5. Conclusions

Our study provides novel and timely insights into the impact of climate variability on forest fire occurrence in Namibia during the period of 2010–2021. The results of our study prove that climate change significantly influences forest fire occurrence. A total of 38.184 Mha of forests were burned during the study period. During this period, Namibia has experienced an increase in temperature, fluctuating precipitation, and strength of wind speed. However, although forest fires in the changing climate have attracted considerable attention in recent decades, huge research gaps remain in Southern Africa.

Our paper was limited to assessing the impact of climate variability on forest fire occurrence across Namibia. Climate variables in this study included wind speed, precipitation, and temperature. We identified a positive correlation between climate variability and forest fire occurrence. Our results coincide with the body of literature at firming a link between climate change and the emergence of new fire regimes (Aponte et al., 2016). For example, our best model revealed a positive relationship between windspeed and forest fire. Wind speed is the main climate variable that drives forest fire.

Namibia has no complete historical records for forest fire and climate variability. There is also a lack of monthly forest fire data. However, it should be emphasised that modelling forest fire and climate change, including remote sensing, can provide forest managers, fire protection agencies, and policy-makers with empirical estimates of how much, and where, climate change might affect the geographic distribution of large fires and alter the frequency of their occurrence (Davis et al., 2017). Therefore, we propose continuous research on this subject whereby assessments can focus on predictive analysis of future forest fire trends and climate variability, excluding non-forested areas such as coastal/non-vegetation areas.

Declarations

Declaration of Competing Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions: Conceptualisation, Andreas Nikodemus, Aleksei Trubin, Miroslav Hájek, and Ratna Chrismiari Purwestri; methodology, Andreas Nikodemus and Aleksei Trubin; software, Andreas Nikodemus, Aleksei Trubin, and Diana Carolina Huertas Bernal; validation, Miroslav Hájek; formal analysis, Andreas Nikodemus and Aleksei Trubin; investigation, Andreas Nikodemus, Aleksei Trubin, and Miroslav Hájek; resources, Andreas Nikodemus and Miroslav Hájek; data curation, Andreas Nikodemus; writing original draft preparation, Andreas Nikodemus, Aleksei Trubin, and Alpo Kapuka; writing review and editing, Andreas Nikodemus and Albertina Ndeinoma; visualization, Andreas Nikodemus, Aleksei Trubin and Diana Carolina Huertas Bernal; supervision, Miroslav Hájek; project administration, Miroslav Hájek; funding acquisition, Miroslav Hájek. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the ethical conduct of the National Commission on Research Science and Technology (NCRST), approved on 19 October 2022, and the ethical clearance by the Ministry of Environment, Forestry and Tourism (MEFT) of Namibia, and approved by the Directorate of Forestry (DoF), dated 18 August 2022.

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Figures

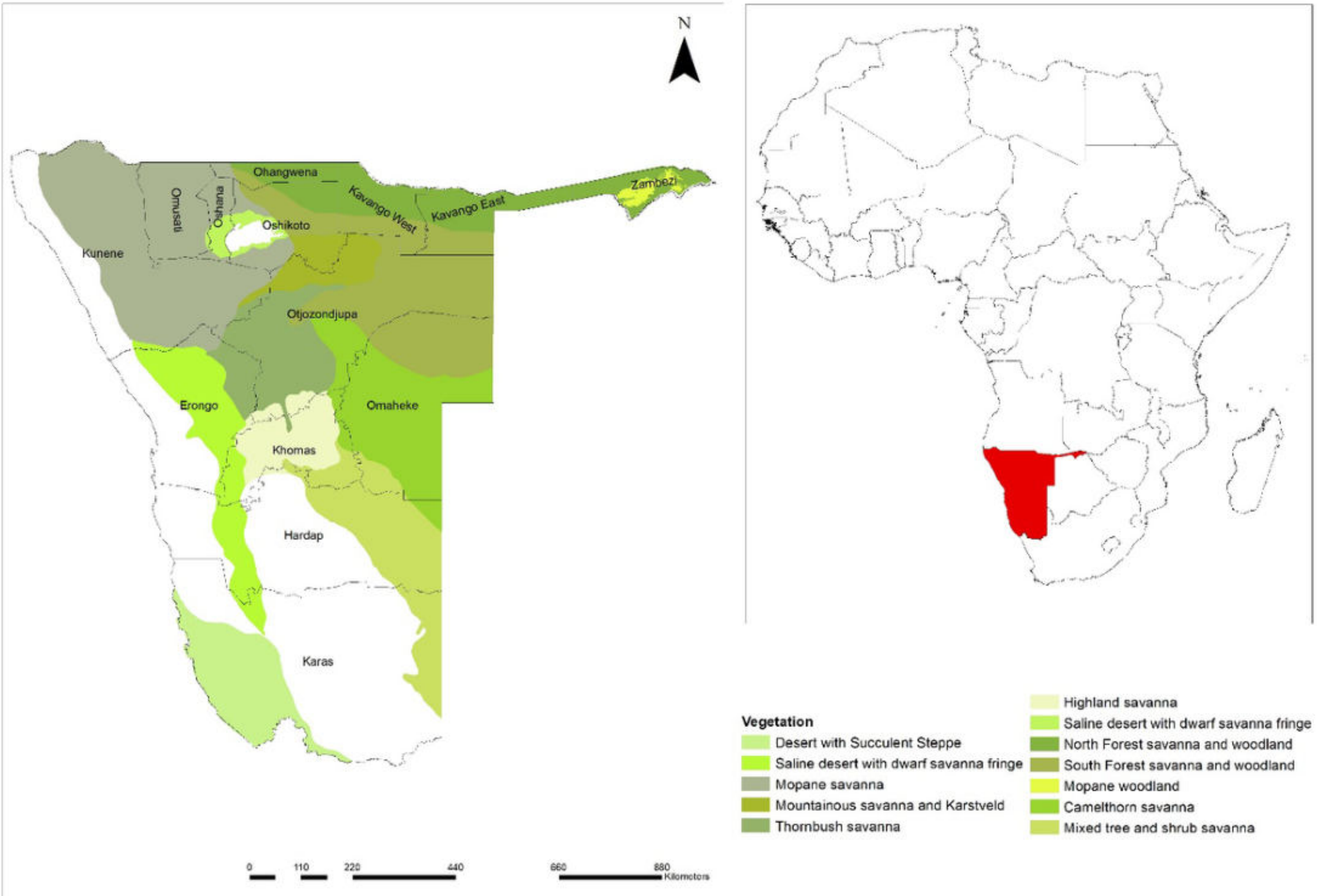

Figure 1

Map of the study area (Namibia) and forest covers.

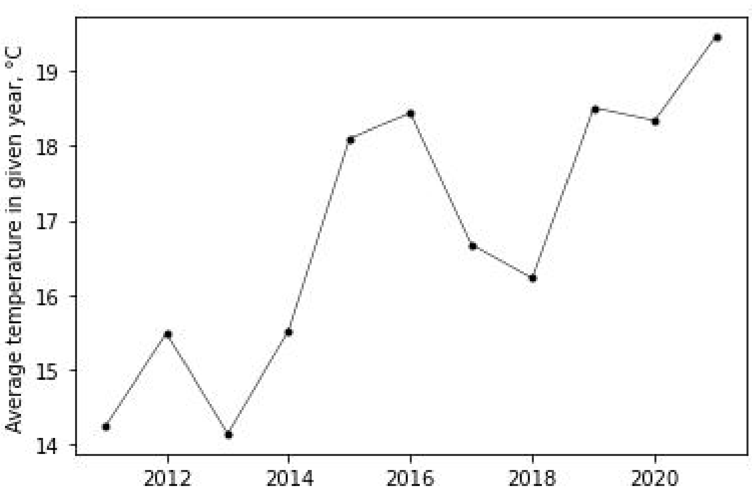

Figure 2

Time series of average annual temperature in the study area

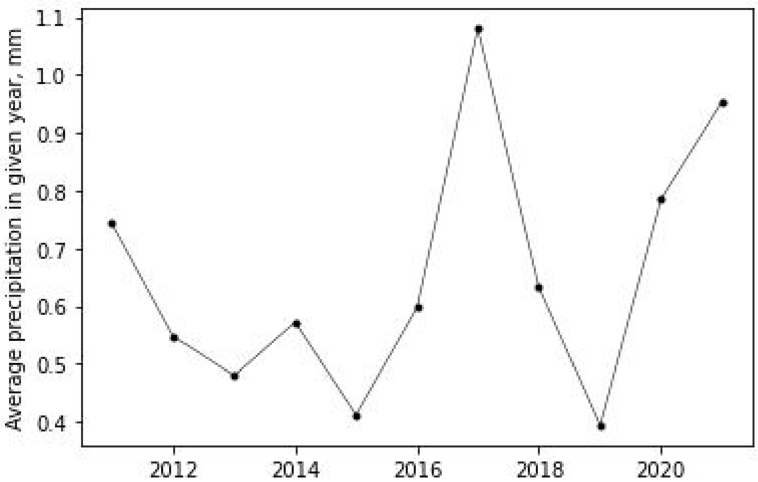

Figure 3

Time series of average annual precipitation in the study area

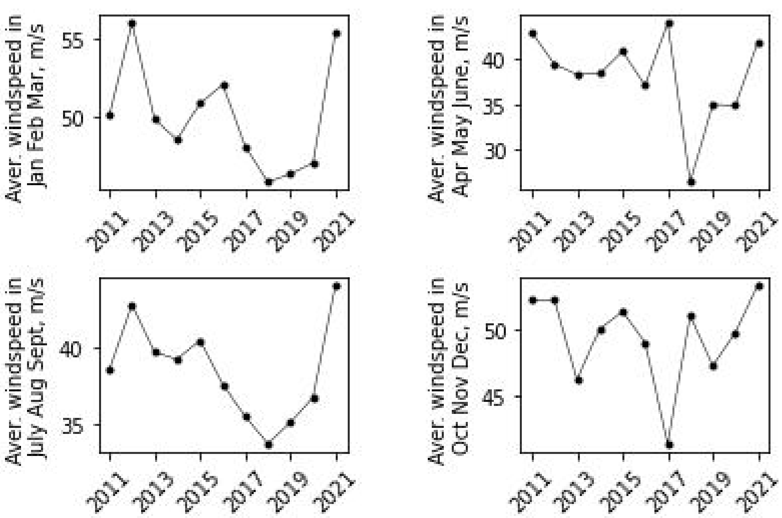

Figure 4

Time series of average wind speed in three-month periods in the study area.

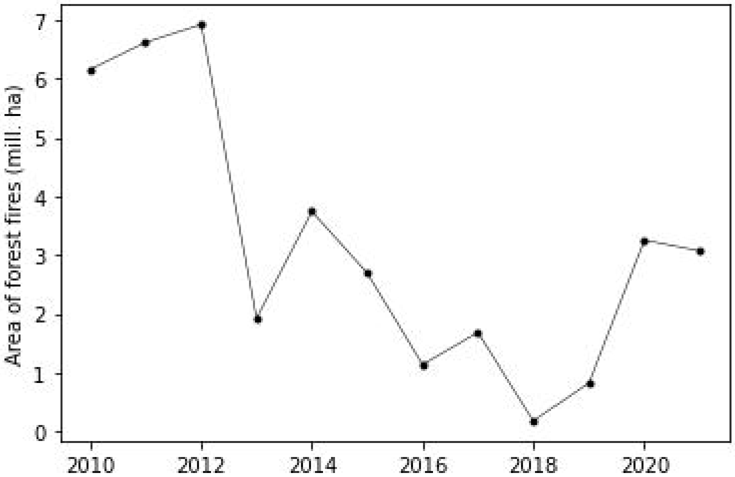

Figure 5

Annual burned area (Mha)

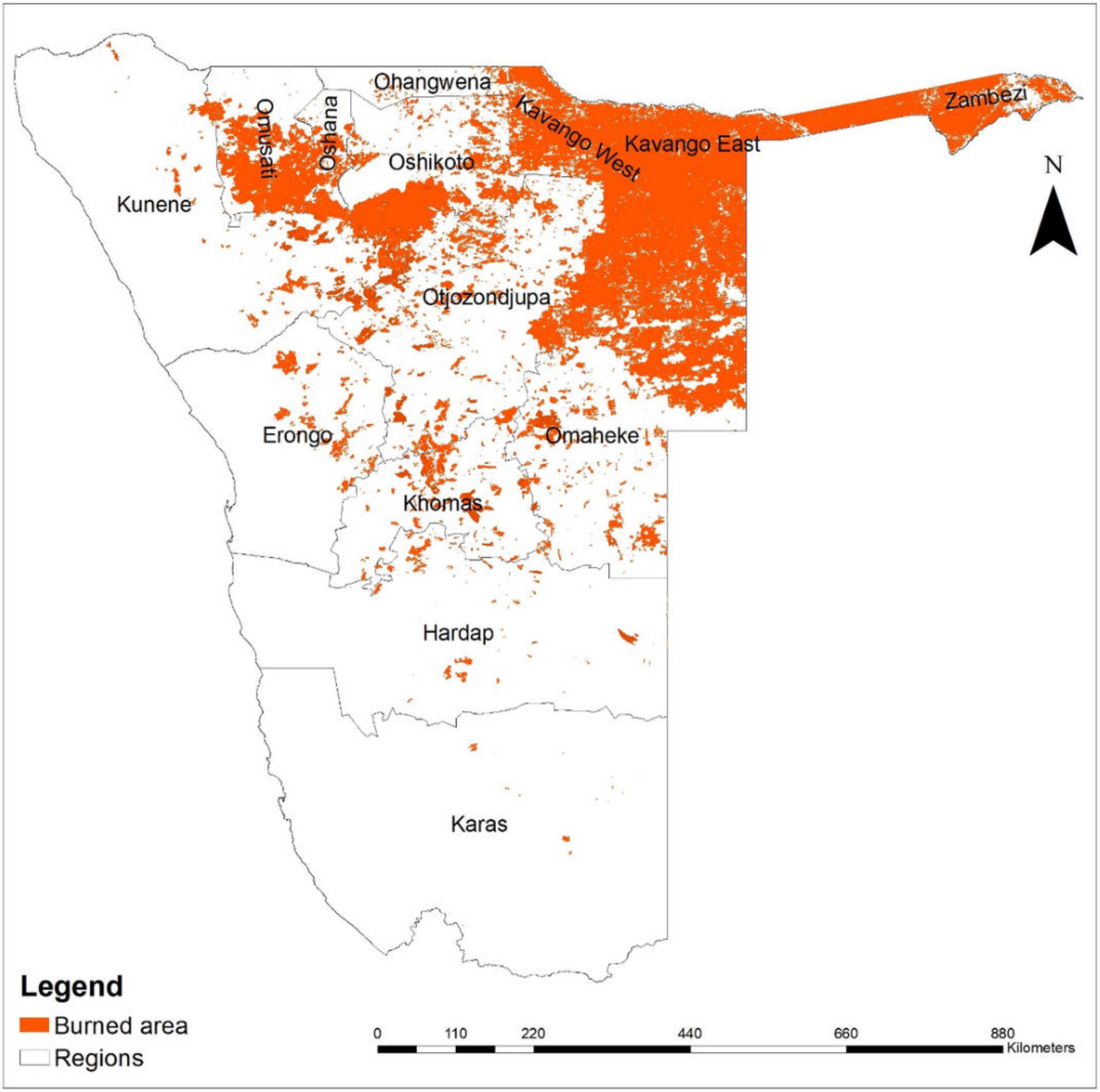

Figure 6

Fire forest occurrence distribution across Namibia in the period of 2010-2021.

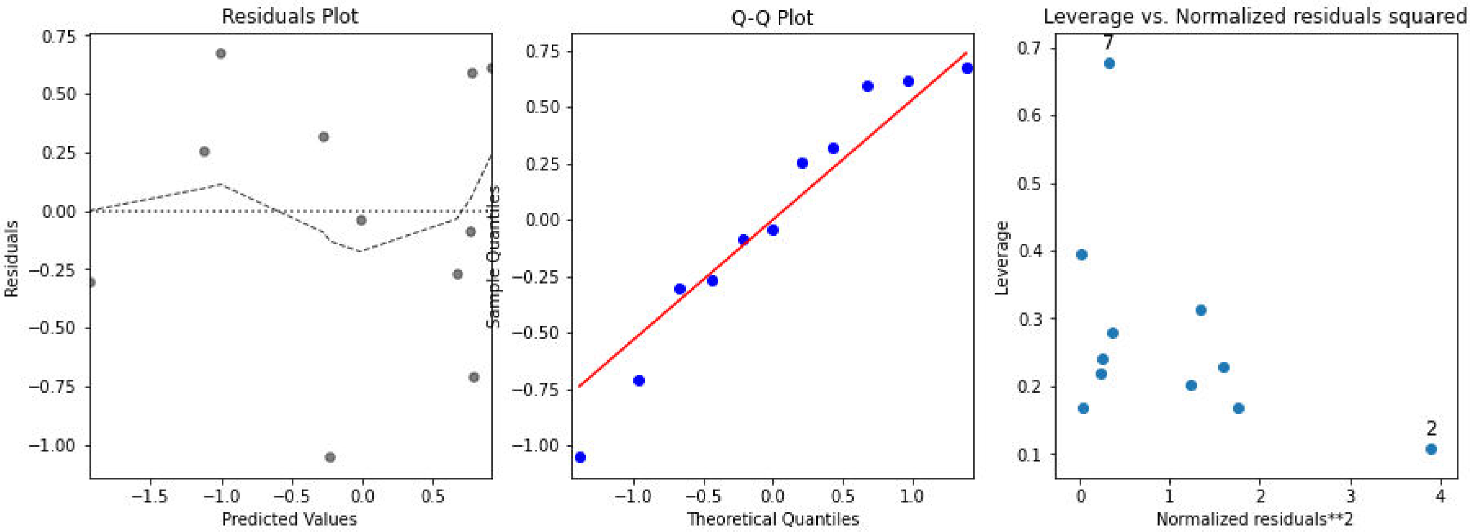

Figure 7

The result of fitting a two-predictor best model visualisation of LM function for the relation between the annual burned area of the August average wind speed in a given year (AugW), and average wind speed in the period of July, August, and September in a given year (JAS_W) in a 12-year study in Namibia.