

## Article

# Remote Sensing and GIS-Based Suitability Mapping of Termite Habitat in the African Savanna: A Case Study of the Lowveld in Kruger National Park

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**Abstract:** Termites (Isoptera) are among the most globally dominant macroinvertebrates in terrestrial environments and are an ecologically important group of soil biota in tropical and subtropical ecosystems. These insects function as essential ecosystem engineers that facilitate nutrient cycling, especially in the regulation of the physical and chemical properties of soil and the decomposition of organic matter that maintains heterogeneity in tropical and subtropical ecosystems. Termites, like all living organisms, require certain environmental parameters to support the distribution, abundance, and activities of the species. South Africa's Kruger National Park (KNP)—one of the most important protected areas in the world and a popular safari tourist destination—is an extraordinary savanna ecosystem in which termite mounds, or termitaria, are widely distributed. A range of biotic and abiotic factors found in the natural environment of KNP provide highly suitable ecological conditions for termite habitat range, and thus the development of termitaria. Previous research has shown that the most important factors affecting habitat suitability for termites and the geographic distribution of termitaria include climate factors, land cover, and other environmental characteristics such as soil composition and plant-litter biomass. However, the specific environmental mechanisms that regulate termite occurrence and the spatial distribution of termitaria in KNP are not fully understood, especially in the context of climate and land-cover changes. The present study examines the relationship between the spatial distribution of termitaria and selected climate and environmental factors in the Kruger Lowveld region, which contains one of the largest numbers of termitaria in KNP. Using high-resolution satellite imagery, 8200 training points of termitaria occurrence were collected throughout the study area to train classifiers and produce land-cover-classification maps for the Kruger Lowveld region of interest. We then applied a hybrid approach through the integration of remote sensing (RS) and a GIS-based analytical hierarchy process (AHP) and frequency-ratio (FR) methods to model the relationship between the spatial distribution of termitaria and selected environmental variables and to produce suitability maps. To our knowledge, this study is the first of its kind to examine the influence of combined sets of environmental attributes on the spatial distribution of termitaria in the Lowveld region of KNP. The results indicate that moderately and highly suitable conditions for termite range tolerance and termitaria development are correlated with undulating plains with clay soils, greater distance to drainage streams, high solar radiation, and low depth of groundwater. The findings of this study shed light on the need for future research that investigates the impact of climate and land-cover changes on termite habitat range and spatial distribution and that can inform park managers and policymakers about Kruger National Park and other protected areas with similar environmental conditions.

**Keywords:** termites; remote sensing; Kruger National Park; Lowveld; savanna ecosystem; suitability mapping; GIS; FR; AHP; hybrid methods



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## 1. Introduction

Termites (Isoptera) are a group of detritivore insects that are of enormous ecological importance in subtropical and tropical regions, distributed between latitudes 50° N and 45° S [1]. As major detritivores, termites play a crucial role in the decomposition processes of tropical ecosystems, providing ecosystem services via nutrient recycling [2]. Termites are often regarded as ‘soil engineers’ [3,4] or ‘major ecosystem engineers’ [5–7] because of the essential role they play in the energy flow and biochemical processes of ecosystems, and the indirect and direct effects they have on resource heterogeneity and availability to other organisms [8,9]. As eusocial insects, termites live in colonies and build nests of great architectural diversity ranging from arboreal and below-ground nests to the massive above-ground nests found in African savannas [4,10–14]. Above-ground termite mounds, or termitaria, are a striking aspect of the African savanna landscape that help maintain heterogeneous habitats that promote the success of other species in savanna ecosystems such as that of Kruger National Park (KNP) [8,9]. However, although KNP is rich in termitaria, the combination of environmental parameters that modulate termite habitat suitability and range extent is not fully understood. Likewise, the range of biotic and abiotic factors that regulate the distribution, diversity, density, and architectural shape of termitaria that promote ecosystem-level spatial heterogeneity in the savanna landscape of KNP have only rarely been studied [15].

Several recent studies have sought to understand the impact of environmental factors on ecosystem function and structure, and to examine the spatial distribution of such factors in relation to ecological communities across the landscape [16,17]. Depending on the qualitative or quantitative nature of the research, most of these studies employed hybrid approaches that rely on combining the strengths of different methods in spatial studies [18,19]. Some of the most frequently used methods including adaptive neuro-fuzzy inference system (ANFIS), frequency ratio (FR) [20], pressure-state response (PSR), ecological-niche modeling (ENM), species-distribution modeling (SDM) and analytical hierarchy process (AHP) have already been widely used to determine the habitat suitability of organisms. Each of these methods have both advantages and disadvantages in terms of species-distribution studies. For example, many ENM/SDM studies have used the presence-only data approach to successfully predict the potential geographic boundaries of organisms at spatial scales [21]. However, when more detailed distribution information of the species is not available, ENM/SDM can produce uncertain results that can lead to untestable decisions regarding impact assessment [22]. In most cases, it has been argued that ENM/SDM is not much better than using an expert opinion [23,24]. In the current study, we adopted a hybrid approach to examine the relationship between the spatial distributions of termitaria and environmental factors. The methods that we used here are spatial methods that are commonly conducted in the form of geographic information systems (GIS) and remote sensing (RS). Thus, the integrated analytical power of RS and GIS may quickly and more accurately detect the complex relationships between ecosystem composition and structural elements with specific environmental conditions [25].

With the recent developments in GIS and RS modeling techniques and data availability, the spatial distribution of ecosystem elements has garnered significant attention in the 21st century [26]. In this context, research aiming to map the spatial distribution of termitaria in savanna ecosystems and explain the influence of various environmental parameters on termite habitat range and distribution has also gained momentum [12,27–29]. Thus, termites, as ecosystem-regulating insects, have brought a new perspective to the mapping of environmental factors in the spatial distribution of ecological systems/communities related to the environmental factors [30,31].

Kruger National Park (KNP)—the largest game reserve in South Africa and one of the most iconic conservation areas in the world—is an important site of biological diversity and is very dense in terms of termite habitats [32]. The savanna biome of KNP provides a suitable natural environment for the foraging and habitat range of termites and contains an abundance of termitaria. Previous field research determined that 41 species of termites

belonging to 28 genera from 4 families inhabit KNP [33,34]. More recently, the current species checklist reported that species from all termite families found in South Africa were identified in KNP, with 75% belonging to the Termitidae family [35]. The mound-building macro termites are more common in the northern areas of KNP [12,26], with approximately 1.1 million active termite mounds estimated in this part of the park by Meyer et al. [36]. Therefore, examining the relationship between natural environmental characteristics and the geographic distribution of termite colonies is important to understand how the savanna ecosystem, climate, topography, and other factors affect the structure and function of the termite mounds. Such research will provide a better understanding of how termites interact with the environment and ecosystem elements, and how environmental conditions impact termite resource suitability and habitat range. Indeed, these motivations have been strongly emphasized in recent research on termites in KNP [31].

Various environmental factors that shape the natural ecosystem of KNP support habitat range and high resource suitability for termites as well as many other invertebrates and vertebrates alike. KNP is renowned for its abundance and diversity of African wildlife, including large ungulates and predators. In their role as soil engineers, termites help maintain the ecosystem heterogeneity that promotes the success of many other biodiverse species in the park. In the last three decades, KNP has become an attractive research area for the scientific study of termites and termitaria [26,33–53]. Although there have been numerous studies on termites and termitaria in KNP, research focusing on the relationship between specific environmental parameters and the spatial distribution of termitaria in KNP is limited.

The present study aimed to identify specific abiotic and biotic factors that influence the spatial distribution of termitaria in the Lowveld region of KNP. To achieve this goal, the relationship between the spatial distribution of termitaria and various environmental attributes was modeled to gain insight into factors that regulate termite habitat suitability and the occurrence of termitaria within the Kruger Lowveld ecosystem. The Kruger Lowveld was selected as the study area because it contains one of the largest termite populations and the density of termitaria in the park. The main objective of the study was to investigate the relationship between environmental parameters and termitaria to determine how the interactions of different ecosystem elements affect the structure and function of termite resource suitability and mound nests in the Lowveld region of KNP.

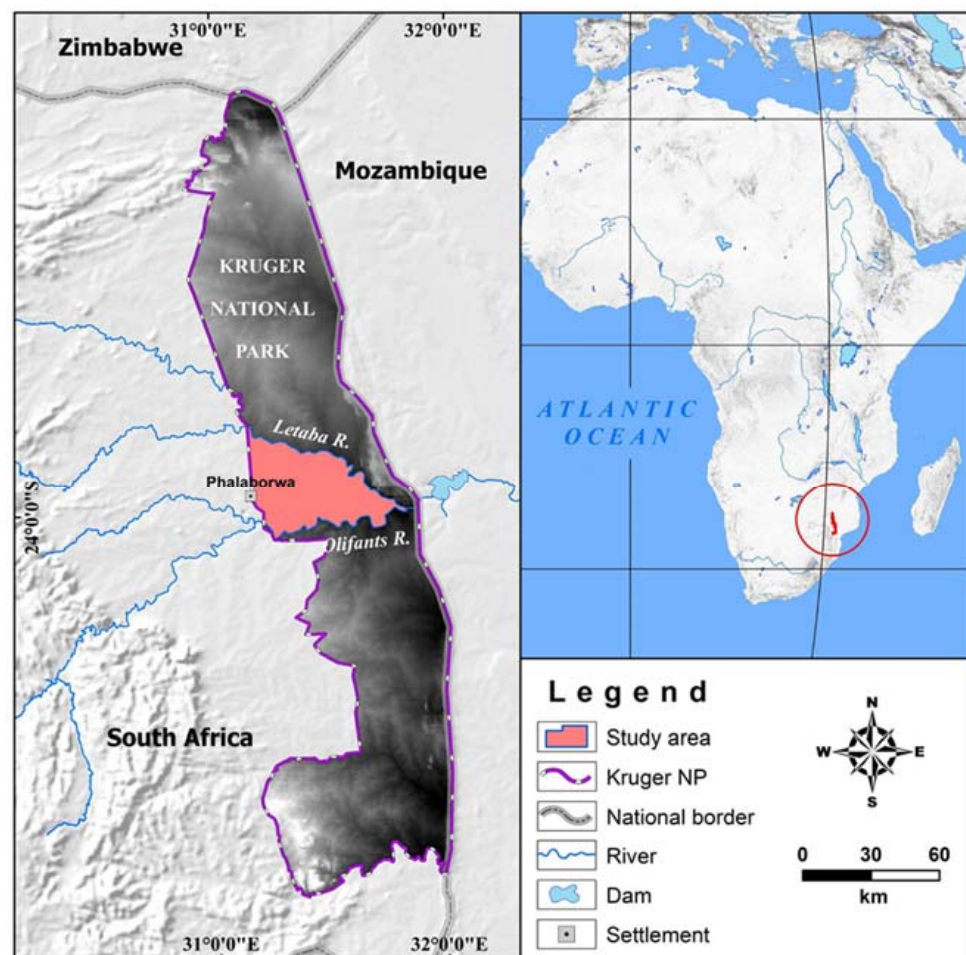
In the current study, a hybrid approach was adopted to investigate the relationship between the spatial distributions of termitaria and environmental factors. The hybrid model was built using GIS-based frequency-ratio (FR) and analytical-hierarchy-process (AHP) methods to map termite habitat suitability and hence the termite mounds, or termitaria. Thus, to achieve the research objectives of this study and gain a better understanding of the environmental parameters that influence the spatial distribution of termitaria, environmental and climate data that characterize the locations of termitaria occurrence across the Kruger Lowveld landscape were compiled. The present study was conducted as an extension of previous research that informed the variable selection and model-building approach, and with the intent of contributing to the existing body of literature. Notably, this study departs from previous research in several key aspects, including: (1) the integrated RS and GIS approach and the hybrid methodology used to identify suitable areas for termitaria, (2) the modeling and analysis of the maximum amount of relevant environmental factors, (3) the application of the applying variable importance elimination method to avoid the use of redundant variables and to select effective environmental factors, and finally (4) being the first study to use this methodology and modeling to examine the relationship between the spatial distribution of termitaria and environmental factors in KNP.

## 2. Material and Methods

### 2.1. Study Area

The research area of interest lies within the 'Lowveld' region of South Africa, between the eastern escarpment and the Lubombo mountains on the Mozambique border in the

northeast. The site of this study is the Kruger Lowveld, located in the central part of the KNP, and corresponding to the geomorphological region defined as the Lowveld plateau, which is drained by the Letaba and Olifants rivers (Figure 1). The Kruger Lowveld study area is characterized by a relatively flat relief with an average altitude of 333.8 m, and a topographic structure oriented toward the southeast. The study area has high biodiversity and is hence internationally recognized as an important wildlife habitat conservation area [54].



**Figure 1.** Location of the study area.

The study area is located on the granite bedrock, which is one of the two main lithological units that make up the KNP bedrock material [55]. However, it is possible to encounter locally different bedrocks in the study area. Geographically located in the region of sub-Saharan Africa, the climate of the study area generally tends to exhibit the characteristics of subtropical climatic zones. Most precipitation occurs from October to April, with an average of ~600 mm/year. The geological and climatic features of the area have led to the development of a wide variety of soil types and vegetation species. There are approximately 2000 plant species, including about 340 tree and 220 shrub species besides herbaceous plants [56]. Vegetation in KNP consists of about 75% broad-leaved and 25% thin-leaved savanna [55]. North of the Olifants River is predominantly mopane trees, while south of the Olifants the ecozones are thornveld [56].

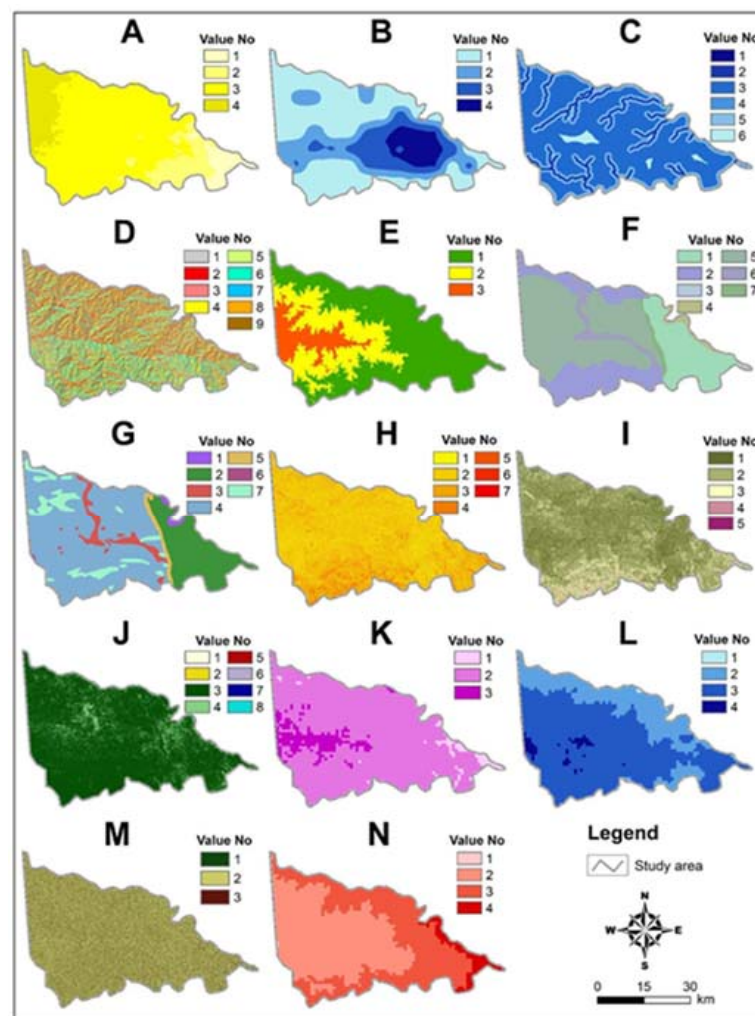
## 2.2. Material

In the present study, training-point data were obtained through the mound-survey sampling method [46] applied in accordance with remote-sensing techniques. Training-data collection was performed with the help of high-resolution images from Google Earth



between 2019 and 2021. Thus, spatial and spectral data of 8200 termite mounds were collected. The data were then subset into two groups: training and validation data for the model. Seventy percent of the data (5740 points) were used as training data and the remaining 30% (2460 points) were used as validation data to verify the predictive ability of the model. Spatial land-suitability analysis was performed for the termitaria by associating the training data with other spatial data obtained from multiple sources (Table 1). Suitability analysis was performed on 12.5 m-resolution DEM data. Topographic data such as aspect, slope, and altitude were produced from DEM data. Furthermore, the rest of the spatial data of the study area such as land-cover, soil, groundwater-depth, and climate data were obtained from various sources indicated in Table 1.

Termites are eusocial insects that are highly sensitive to environmental conditions and ecosystem processes [57]. Therefore, environmental factors affecting the distribution of termites differ between species and regions [12]. For this reason, the distribution of termites is determined using local environmental factors. The present study was conducted using the following environmental variables: solar radiation [58–60], groundwater depth [12,28,55], distance to streams [12,44,50], aspect [60,61], elevation [12], soil [11,62], lithology [12,50], slope [12,44,50], topographic relief [44,50], land use [8,11,12,44,48,57], wind speed [60], precipitation [11,44,50,58,63,64], slope position [12] and temperature [65] (Figure 2).



**Figure 2.** Subfactors that affect the distribution of termitaria: (A) solar radiation, (B) groundwater depth, (C) distance to the streams, (D) aspect, (E) elevation, (F) soil type, (G) lithology, (H) slope, (I) topographic relief, (J) land use, (K) wind speed, (L) precipitation, (M) slope position, and (N) temperature. See Table 2 for the details of legends (value numbers).

Although all environmental factors affect the distribution of termites to some degree, some are weighted more than others. Solar radiation is one of the most important abiotic factors controlling the spatial distribution of termites by influencing their geometric distribution and thermal performance [60]. The groundwater level has a mechanism that controls the height of termite nests as well as the species distribution of the insects. Therefore, the groundwater depth is one of the main environmental factors that play a decisive role in the spatial distribution of termitaria. In this regard, termitaria are found in abundance in shallow groundwater areas and well-drained areas. Furthermore, distance to the streams is another important factor that determines the geographical distribution of termites, as it causes floods that threatens the existence of the termite colony [12]. Indeed, it has been determined that the proximity to the drainage canals in the N'waswitshaka basin impacts the termite population [50]. Aspect is defined as the position of the topography against the sun; it is important in the spatial distribution of termitaria as it regulates the mound temperature more effectively for different geographical locations in relation to solar radiation [60]. In terms of elevation, moderate elevation levels show suitable conditions for the construction of termitaria. Termites not only affect the physical, chemical, and biological properties of the soil and the water dynamics in the soil but also facilitate the decomposition of organic matter and microbial activity. Previous studies have revealed that termitaria, which are controlled by soil properties, are abundant in soils with increased clay content, while they are more limited in well-drained sandy soils [44].

### 2.3. Methods

A hybrid approach based on GIS, FR, and AHP methods was used to determine the factors that affect the spatial distribution of termite mounds and hence termite habitat suitability in the Lowveld study area within KNP. The relationship between the training data and environmental factors was analyzed using the FR method, and the reciprocal relationship between the spatial factors was analyzed using the AHP method. This hybrid method was employed because FR is more effective in determining the in-class weights of environmental factors, and AHP is more effective in determining the relative importance of individual classes [66]. Thus, the factors that were determined directly based on the sample data were compared within the framework of a statistical consistency ratio. Therefore, a more objective and applicable evaluation is plausible with such a hybrid method. In addition, various GIS techniques were used in the analysis and imaging phase of the study (Figure 3).

#### 2.3.1. Variable Importance

Not all factors are important in GIS-based spatial modeling and analysis, and it is not certain that using multiple criteria will yield better results. Therefore, to obtain reliable results, the effects of the selected factors should be tested with various methods [12]. Variable importance, a stage of the random-forest method, was used to determine the effect levels of the environmental factors used in this study and to eliminate the ineffective variables. The variables used in the model included 15 different environmental factors known to affect the spatial distribution of the termitaria, as derived from the literature and field studies. Data types of these factors were fixed to a standard level in DEM resolution and converted to Esri Grid format prior to analysis (Table 1). As a result of the analysis, all factors were taken into consideration, except for those whose significance value was close to zero. Thus, it was determined that 14 environmental factors were appropriate for use in spatial suitability modeling.

#### 2.3.2. Frequency Ratio (FR)

The impact ratio of environmental factors on the land suitability of termitaria was determined by the FR method (Table 2). FR is a bivariate statistical method that has been reported to be effective in determining the correlation between the spatial distributions of termites and environmental factors.

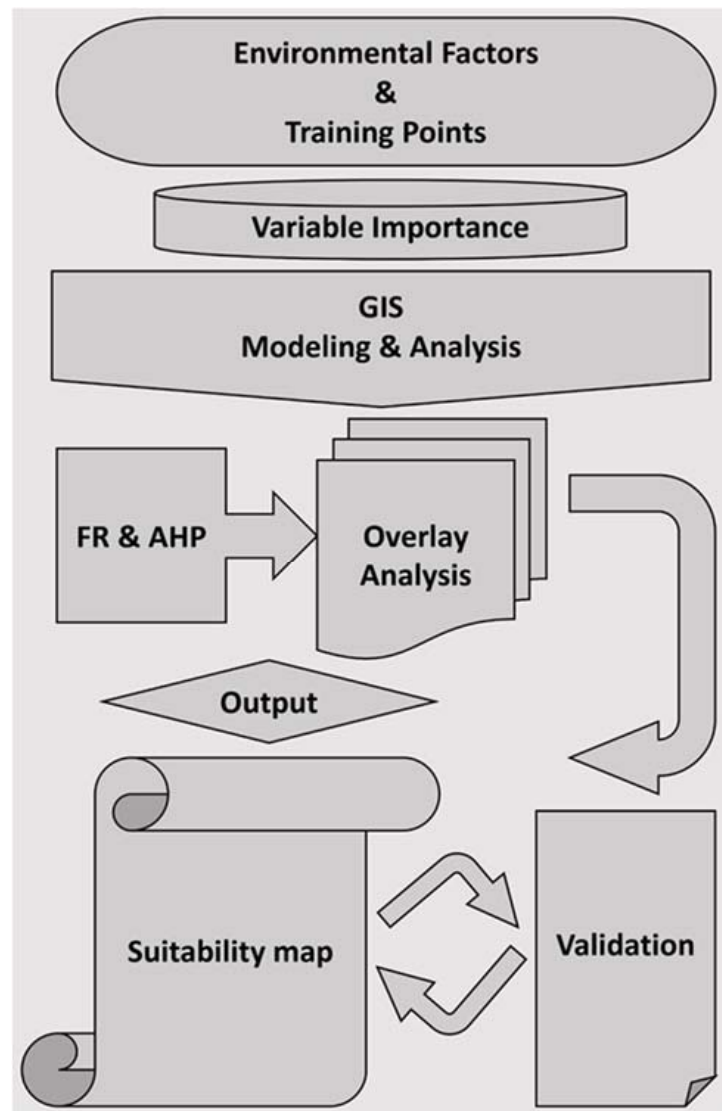


Figure 3. Flowchart of the model.

Table 1. Data and the Variable Importance of the data used in the present study.

No.	Factors	Data Type	Sources	Var. Importance (%)
1	Solar radiation	DEM/Grid	Fick and Hijmans, 2017 [67]	15
2	Groundwater depth	Raster	MacDonald et al., 2012 [68]	14
3	Distance to the Drainage	Polyline	Andreadis et al., 2013 [69]	13
4	Aspect	DEM/Grid	ASF DAAC, 2015 [70]	12
5	Elevation	DEM/Grid	ASF DAAC, 2015 [70]	9
6	Soil	Polygon	Viljoen, 2015 [54]	8
7	Lithology	Polygon	Viljoen, 2015 [54]	6
8	Slope	DEM/Grid	ASF DAAC, 2015 [70]	5
9	Topographic relief	DEM/Grid	ASF DAAC, 2015 [70]	4
10	Land cover	Raster	SAPAD, 2020 [71]	4
11	Wind speed	DEM/Grid	Fick and Hijmans, 2017 [67]	3
12	Precipitation	DEM/Grid	Fick and Hijmans, 2017 [67]	3
13	Slope Position	DEM/Grid	ASF DAAC, 2015 [70]	2
14	Temperature	DEM/Grid	ASF DAAC, 2015 [70]	2

**Table 2.** Frequency-ratio (FR) values of the subfactors.

Factor No	Factor	Value No	Variables/Subfactors	FR Value
1	Solar radiation (MJ m <sup>-2</sup> day <sup>-1</sup> )	1	<17.500	0.00
		2	17.500–17.750	0.00
		3	17.750–18.000	1.27
		4	18.000->	0.96
2	Groundwater depth (m)	1	Very shallow (0–25 m)	0.57
		2	Shallow (25–50 m)	2.00
		3	Mid (50–100 m)	0.95
		4	Deep (100-> m)	0.00
3	Distance to drainage network (m)	1	<100	0.37
		2	100–250	0.60
		3	250–500	0.80
		4	500–1000	0.80
		5	1000–5000	1.10
		6	5000>	2.36
4	Aspect	1	Flat	0.98
		2	North	0.82
		3	Northeast	0.78
		4	East	0.93
		5	Southeast	1.09
		6	South	1.03
		7	Southwest	1.21
		8	West	1.17
		9	Northwest	1.06
5	Elevation (m)	1	Very low (<350 m)	0.14
		2	Low (350–400 m)	1.85
		3	Moderate (400>)	3.37
6	Soil type	1	Weakly developed shallow soil	0.00
		2	Weakly developed shallow & Lithosol	0.30
		3	Lithosol	0.00
		4	Alluvial	0.00
		5	Fersiallitic	1.85
		6	Smectitic clay & weakly developed shallow	0.88
		7	Fersiallitic & Lithosols	0.00
7	Lithology	1	Alluvium	0.00
		2	Basalt	0.00
		3	Gabbro	0.91
		4	Granite/Gneiss	1.49
		5	Sandstone	0.00
		6	Pyroxenite/Carbonite	0.00
		7	Greenstone belt	0.21
8	Slope (%)	1	0–2	1.01
		2	2–6	1.05
		3	6–12	1.01
		4	12–20	0.27
		5	20–30	0.00
		6	30–45	0.00
		7	45+	0.00
9	Topographic relief (m)	1	0–2	0.97
		2	2–5	1.12
		3	5–9	0.64
		4	9–16	0.15
		5	16–47	0.00



Table 2. Cont.

Factor No	Factor	Value No	Variables/Subfactors	FR Value
10	Land-cover type	1	Barren land	0.00
		2	Settlements	0.00
		3	Forested land	1.02
		4	Grassland	0.90
		5	Mines & Quarries	0.00
		6	Scrublands	0.00
		7	Water bodies	0.00
		8	Wetlands	0.00
11	Wind speed (m/s)	1	1.0–1.6	0.00
		2	1.6–2.3	0.74
		3	2.3–3.0	3.68
12	Precipitation (mm)	1	438–470.7	0.00
		2	470.7–503.5	0.09
		3	503.5–536.2	0.60
		4	536.2–569	3.52
13	Slope Position	1	Concave (<−0.1)	0.90
		2	Flat (−0.1+0.1)	1.01
		3	Convex (>+0.1)	1.06
14	Temperature (°C)	1	21.9–22.3	2.65
		2	22.3–22.6	0.58
		3	22.6–23.0	0.00
		4	23.0–23.3	0.00

For the application of the method, the percentage values of environmental factors representing the sample (b) and the population (a) were proportioned to each other and hence the frequency ratio was determined. The frequency ratio was calculated according to the following equation:

$$W = (1000(b/a)) - (1000(\Sigma b/\Sigma a)) \quad (1)$$

where W represents the weight values of the subfactors, b is the number of samples in the subfactor class, and a is the total number of pixels in the subfactor class. The subfactor weight value tends to be positive as the spatial suitability increases, and negative as the spatial suitability decreases. The subfactors whose weight values were determined were then classified according to their weight values and converted to raster format.

### 2.3.3. The Analytic Hierarchy Process (AHP)

The spatial suitability model was run using the weight values of the subfactor clusters. AHP is a widely used method in multi-criteria and complex decision-making studies because the method is an effective approach that evaluates both qualitative and quantitative variables [72] and produces a hierarchic importance ranking of the subfactors included in a given model. After running the model, the hierarchic importance results of the subfactors that were effective in the application of the model were graded according to the AHP importance scale (Figure 4).

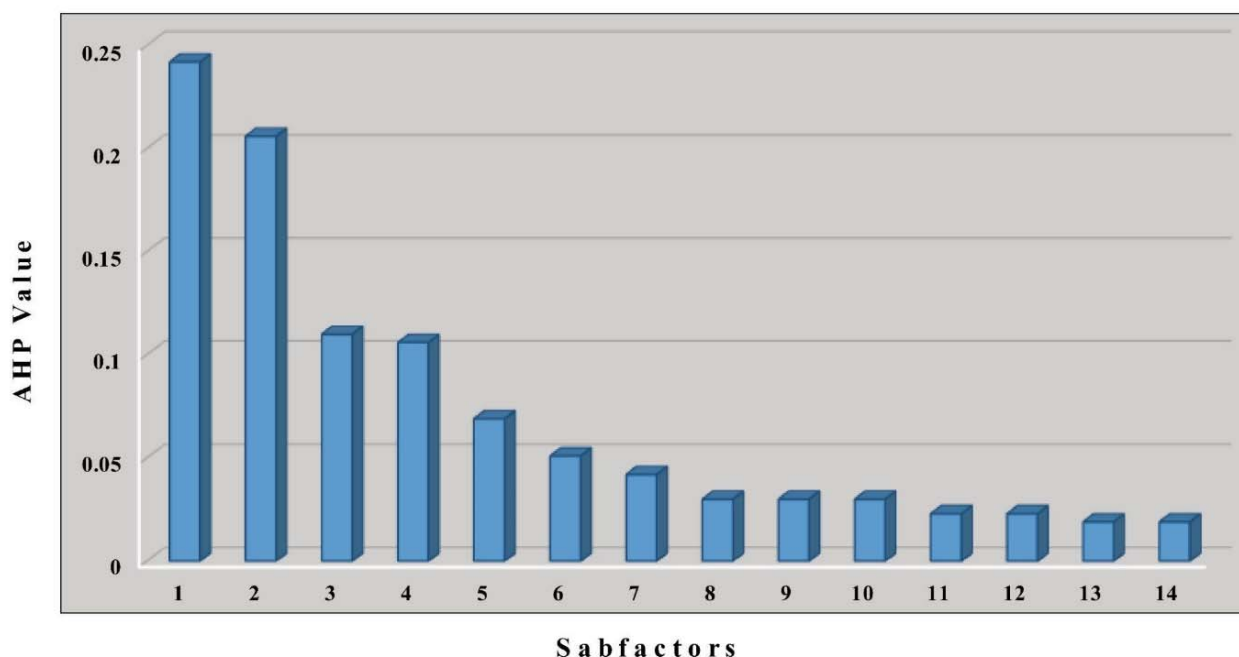
Thus, the scale coefficients were assigned in such a way that the consistency of the importance weights of the determining factors could be validated. The validity of the consistency was checked by calculating the consistency index and ratio. The consistency ratio was calculated using the following equation:

$$CI = ((\lambda_{\max} - n))/n(n - 1) \quad (2)$$

and,

$$CR = CI/RI \quad (3)$$

where: CR is consistency ratio, CI is consistency index, and RI randomness index. The matrix is considered to be consistent if the CR is 10% or less [72].



**Figure 4.** The Analytic Hierarchy Process (AHP) values of the factors.

### 3. Results

#### 3.1. The Most Effective Factors in the Distribution of Termitaria

Although most of the variables included in the model influence the presence of termites to some degree, some environmental factors proved more influential in regulating termite habitat range and the distribution of termitaria. Among these factors, the present analysis found solar radiation, groundwater depth, distance to the streams, aspect, elevation, and soil type to be the most important environmental attributes affecting the geographic range of termites and the spatial distribution of termitaria.

**Solar radiation:** In the study area, the density of termitaria is higher in areas where solar radiation is between  $17.750\text{--}18.000\text{ MJ m}^{-2}\text{ day}^{-1}$ . Hence, in the study area, these sites are more preferred for the construction of termitaria.

**Groundwater depth:** It was determined that termites in the study area are more common in areas where the groundwater level is between 25–50 m. Hence these sites are more suitable for the construction of termitaria.

**Distance from the streams:** Similarly, it was determined that the number of termites increased as the distance to the drainage channels increased in the study area. Therefore, as the distance from the drainage channels in the study area increases, the spatial suitability for the construction of termitaria increases.

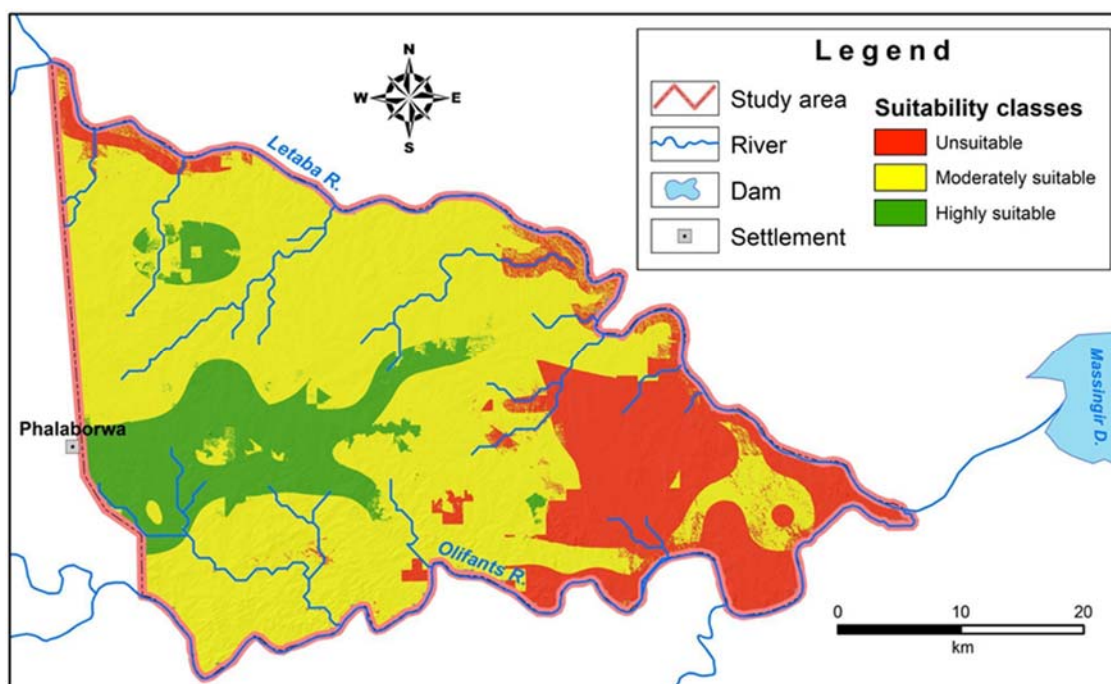
**Aspect:** As the study area is located in the southern hemisphere, the southwest appears to be the most suitable aspect for the termitaria construction.

**Elevation:** It was observed that the elevation above 400 m in the study area appears to be the most suitable area for the termitaria. On the other hand, unsuitable conditions prevail in the low elevations, which are well below the average elevation in the study area.

**Soil type:** In the study area, fersiallitic and smectitic clay, as well as weakly developed shallow soils where the clay content is high, are the areas where termitaria were intensely observed. These areas, therefore, appear to be more suitable for the construction of termitaria.

### 3.2. The Distribution of Land Suitability for Termitaria

With a new application of the hybrid approach, we combined the GIS-based environmental factors with the weighted sum, which is a spatial-analysis-overlay method. Thus, a suitability map for the optimal locations of termitaria was produced (Figure 5) using the 'Equal Interval' classification, which equally divides the value range and creates an easy-to-understand indicator. Spatial suitability was classified into three categories as highly suitable, moderately suitable, and unsuitable, following Ahmed et al [12].



**Figure 5.** The spatial distribution of the suitability classes for termitaria.

The results of the suitability map indicate that a large part of the study area (79.19%) was suitable for the construction of termitaria where the highly suitable class covers 14.26% and moderately suitable covers 64.93% of the study area. On the other hand, only 20.81% of the study area was found to be unsuitable for termitaria construction (Table 3). The unsuitable areas were mostly located at the conjunction of the two rivers, Letaba and Olifants.

**Table 3.** The distribution of the suitability areas for termitaria.

Suitability Class	Index Value	Area (ha)	Ratio (%)
Highly suitable	1.27–1.78	25,078.11	14.26
Moderately suitable	0.76–1.27	114,205.06	64.93
Unsuitable	0.25–0.76	36,609.22	20.81
TOTAL		175,892.00	100

### 3.3. Validation

The validation of the data that were used for the model was calculated using the coefficient of determination ( $R^2$ ), which is a normalized statistic that determines the relative magnitude of the residual variance compared to the observed data variance [73].  $R^2$  indicates how well the plot of observed versus predicted data fits the 1:1 ratio.  $R^2 = 1$  indicates the highest match of the model to the observed data whereas  $R^2 = 0$  indicates the lowest. The validation outcomes indicated that the  $R^2$  value of the measured and predicted results of the validation data set was found to be 0.95 (Figure 6).

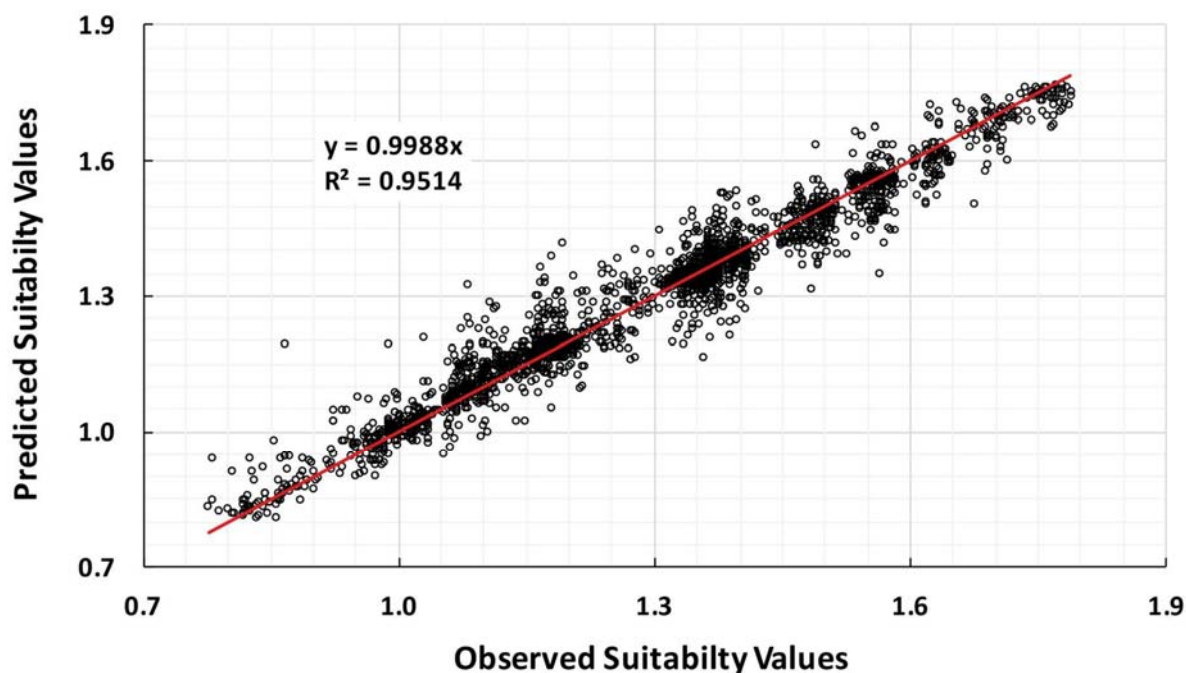


Figure 6. Scatter plot of  $R^2$ .

#### 4. Discussion

Termite mounds that show spatial distribution depending on various environmental factors [74] are quite robust and long-lasting structures [50]. The density and structural material of the termitaria depend on environmental conditions rather than the variety of the species [75]. These conditions are decisive in the spatial distribution of termitaria at different rates. It has been described in the literature that the spatial distributions of termitaria are strongly associated with the combined effect of multiple environmental factors [60]. Indeed, in natural environments, the relation between foraging and habitat range and resource suitability has a significant influence on the distribution of animals [9]. Nonetheless, it is often difficult to determine the relative importance of various elements of an ecosystem that contribute to the occurrence and distribution of a given species, including termites. This study emphasized that environmental factors affecting the spatial distribution of termitaria can be utilized to the extent of their impact ratios in determining suitable areas for termitaria construction.

The literature shows that termite mounds are built with an architecture that suits climate and groundwater conditions [44]. In this study, environmental factors affecting the spatial distribution of termitaria such as solar radiation and groundwater depth were found to be the main determining factors for the construction of termitaria in the study area, as they were highly correlated with the spatial distribution of termite mounds. Ocko et al. [76], Vesala et al. [77] and Fagundes et al. [60] suggested that termites need solar radiation to maintain the climate of the mounds at an optimum level. Ahmed and Pradhan [28] and Ahmed et al. [12,29] stated that termitaria have higher groundwater potential compared to their surroundings. The integration of our findings with those of the aforementioned studies provides a new perspective on the structure and function of termitaria within the savanna ecosystem of KNP.

Previous research has indicated that the relationship between the spatial distribution of termitaria and environmental factors has important effects on ecosystem structure and function [78]. Termitaria, which protect termites from strong environmental influences, also serve as climate-controlled microhabitats that allow them to exchange energy, information, and matter with the outside world [79]. Therefore, it is important to determine the spatial distribution of termitaria and identify suitable areas for termitaria construction. In this respect, the present study, which was carried out in a small subsection of KNP, provides

a critical first step for identifying specific environmental factors that regulate the spatial distribution of termitaria occurrence in African savanna ecosystems. However, since this study does not address termitaria distribution for the total geographic area of KNP, it is not a complementary study but provides a scientific basis for further research.

Several previous studies have investigated certain elements of the spatial distribution of termitaria in KNP. Van der Schijff investigated the relationship between termite development and plant ecosystems [80]. Meyer et al. [36] investigated the distribution and population density of termitaria in the northern region of KNP. Davies et al. determined how termites modify the geographical distribution of specific tree species in KNP [47]. Davies et al. examined the association between the distribution and density of termitaria and the change in land cover in the Lowveld section of the KNP [48]. In the present work, a new application of a hybrid approach was employed to identify favorable sites for termitaria, which were subsequently mapped by examining environmental parameters that significantly influence the geographical distribution of termitaria. Thus, by utilizing suitability mapping, not only can the existing distribution and density of termitaria be geographically located, but future distribution patterns of termitaria may also be predicted. This is significant because future temperature and land-cover changes will likely affect the habitat appropriateness for termites and the many other species they help support in KNP and in other subtropical and tropical ecosystems throughout the globe.

The complexity and difficulty of understanding the relationship between termites and climate and land-cover changes are pronounced in the existing body of literature [48,81]. The recent literature on savanna ecosystems emphasized that if climate or land-cover changes adversely affect termitaria, savanna ecosystems can become more homogeneous and vulnerable to ecosystem resilience of the ecosystem collapses with gradual effects on all ecosystem components [82,83]. Therefore, further research on the relationship between termitaria and future climate- and land-cover-change scenarios for savanna ecosystems is critically needed.

The termitaria suitability map, produced within the scope of the Kruger Lowveld study area, indicated that optimal termite habitat suitability corresponds to areas that receive high solar irradiance, are located farther from streamlines, where groundwater depth is shallow and clay soils are widespread, and areas dominated by clay soils and characterized by moderately high undulating plains. Jouquet et al. [6] explained that termites are densely distributed in subtropical habitats developed mostly on low or moderately elevated plains. Davies et al. [47] found that termites, which mediate the spatial distribution of tree species in the savanna landscape, are found in dry areas away from drainage lines and in slightly elevated hilly areas that are relatively less vegetated. Levick et al. [26] explained that the distribution of termitaria in African savannas is largely determined by topographically related hydrological and edaphic features controlled by climatic conditions. Therefore, the present study supported these findings and concluded that the spatial distribution of termitaria in the study area is mostly controlled by climatological, hydrological, and edaphic factors.

## 5. Conclusions

In the current study, a spatial land-suitability model for the construction of termitaria was conducted to predict the spatial distribution of termitaria. The model was developed by conducting a hybrid approach based on GIS-based FR and AHP methods. As a result, it was determined that a large portion of the study area (79.19%) is highly suitable for the construction of termitaria. It was determined that termitaria were distributed with the interaction of all environmental factors at different levels, with climatic, hydrographic, and edaphic factors being the most important. The findings of this study show that the environmental parameters most influential for termitaria construction are characterized by moderately high undulating plains with clay soils, shallow groundwater depth, greater distance from streams, and high solar radiation. The results of the study highlight the importance of groundwater as a determinant of termitaria location, and the impact of climate



or land-cover changes on the savanna ecosystem structure and function. In addition, this research demonstrates how a GIS-based hybrid approach for spatial suitability-classification studies can provide more advantageous and robust results compared to similar approaches. The hybrid model used in this study can be applied to other subtropical and tropical regions of the world that contain ecosystems inhabited by termitaria. Further, the spatial distribution of termitaria can be associated with the effects of climate and land-cover changes, and accordingly, there is a need for more spatial suitability-classification studies that can provide more accurate predictions about future changes in the savanna-like ecosystems.

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