Multi-criteria Evaluation of Suitable Sites for Termite Mounds Construction in a Tropical Lowland

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Abstract

Termite mounds influence ecosystem heterogeneity and contribute to the stabilization of the system under global change. A number of environmental factors influence the distribution, height, diameter and designs of termite mounds but these factors are not only poorly understood, they cannot be extrapolated for everywhere. In this study, we employed a ground based survey and Geographical Information System (GIS) technique to map 156km^2 study area in Keffi, Nigeria. The aims were to (1) estimate the density and area covered by termite mounds, (2) sample and identify species types and how they are distributed, and (3) use five environmental factors (elevation, geology, surface water drainage, land use/land cover and static water level) to model suitable sites for mounds construction. A total of 361 mounds were mapped representing a density of about 0.8 mounds ha^{-1} and covering only about 0.31% of the studied area. . Next, the effect of the five chosen environmental factors on the geographic distribution, life status, height and diameter of mounds and species diversity were analysed and their relationships plotted in pairwise comparison matrices using the Saaty's Analytical Hierarchy Process. Normalized rates for classes in each factor and corresponding weights were computed and aggregated using the Weighted Linear Combination method. The result depicted that moderate to low elevation (270 – 330m amsl), rock cover types that are more susceptible to weathering (schist), cultivated areas and shallow water table zones are most favourable for termites to build mounds. The result obtained in this study shows a promising correlation between the environmental factors and termite mounds distribution. The proposed model can easily be replicated in a different but similar multi-land use and rock cover types.

Keywords: Termite mounds, Multi-criteria evaluation, GIS, geology, water table

1. Introduction

Termite mounds or termitaries are familiar landscape features in many tropical and subtropical environments (Levick et al., 2010). Built from surrounding soils and organic matter by different species of termites, they do not only serve as nests for the termites and other inquilines, but also function as heterogeneity drivers of the ecosystem and foraging hotspots for many browsing and grazing animals (Bonachela et al., 2015; Davies et al., 2015; Marins et al., 2016). Mapping the distribution of termite mounds in any environment can deliver both ecological and economic benefits. For instance, termites through ecosystem engineering are well-known to modify the physical, chemical and biological characteristics of in-situ soils (Jouquet et al., 2016). The above phenomenon results in increment of nutrient level and moisture content on mounds and annular zones surrounding the mounds (Davies et al., 2014b) thereby supporting the growth of nutrient rich vegetation, all year round. With less grazing land available due to drought and increase in land cultivation and food production in many parts of the tropics, localities with such high density of termite mounds can be reserved to support animal (livestock) grazing.

Termite mounds are also excellent sites for metallic mineral prospecting (Arhin et al., 2015; West 1970). Through burrowing, termites vertically transport residual soils rich in metallic mineralization from deeper soil horizons to deposit on mounds surface during construction. Similarly, mound soils are consumed by humans and animals alike for the regulation of stomach pH, absorption of toxins among other benefits (Sako et al., 2009). Studies have suggested that termite mounds are likely to boost the resilience of dry ecosystems against water shortages (Bonachela et al., 2015) and in other circumstances indicate the presence of groundwater (Mège and Rango, 2010).

Although termite mounds are common in many tropical landscapes, they are not constructed just anywhere. A number of environmental factors are at play to influence mounds distribution, density and architecture (Korb and Linsenmair, 2000). These environmental factors which include topography, geology, rainfall distribution, vegetation type, land cover type, disturbance level, food and moisture availability furnish the criteria used by termites to select suitable sites for mound construction and colony settlement (Sands, 1967; Jones et al., 2003; Attignon et al., 2005; Pribadi et al., 2011; Davies et al., 2014a). Criteria for site selection are likely to vary between species and regions. For example, *Macrotermes natalensis* and *Macrotermes falciger* are found to prefer granitic sandy soils over basaltic clayey soils in an undulating landscape of South Africa (Meyer et al., 1999; Levick et al., 2010), whereas, *Macrotermes Michaelseni* is observed to have preference for loamy soils and aeolian sands over granitic sands in nearby Zimbabwe (Mitchell, 1980). Mound distribution and density over lithological cover have so far been compared only between volcanic and plutonic cover rocks (granite vs basalt; Davies et al., (2014a), dolerite dyke vs basaltic lava flow; Mege and Rango, (2010)), but no attention to areas covered by poly-cylic rocks. Notwithstanding, the overall conditions for continued termite colony existence are availability of permanent water supply and avoidance of places with risk of inundation in addition to other species specific requirements (Grasse and Noirot, 1960; Bouillon 1970; Davies et al., 2014b).

Few studies have attempted to conduct full-scale mapping of termite mounds using aerial remote sensing approaches (e.g. Jones, 1990; Levick et al., 2010), but many others focused on ground surveys, drawing few measurement transects across relatively small areas (e.g. Attignon et al., 2005; Grohmann et al., 2010; Meyer et al., 1999; Ackerman et al., 2007; Adhikary et al., 2016). Even though the use of aerial remote sensing provides a rapid means of mapping large areas in a short time, the logistics cost as well as ground-truth measurements such as checking life status of mounds and species sampling remains a serious limitation.

Previous studies focused mainly on natural and semi-natural habitats with less attention to other land use types such as cultivated lands and built-up areas. Another shortcoming is measurement along small transects which tend to overestimate mound densities. In this study therefore, we employed systematic ground surveys and GIS technique to cover a relatively large area. The main aim of this study is to establish the spatial distribution and nesting patterns of termites in a multi-land use and heterogeneous geological setting since previous studies only focused on natural to semi-natural environments. Other specific objectives are to (1) estimate the density and area covered by termite mounds, (2) sample termites to determine species types and distribution since it is currently unstudied in the study area, (3) use five environmental factors of elevation, geology, surface water drainage, land use/land cover and static water level to model suitable sites for mounds construction.

2. Materials and Methods

2.1 Study Area

The area under study covers Keffi and a part of Karshi in Nasarawa State, Nigeria (figure 1). Geographically, the area is located within latitude N8^0 46’ 40” - N8^0 53’ 30” and longitude E7^0 46’03” – E7^0 55’ 30”. The once forested and vegetated area has been reduced to open grass land as a result of urbanization, logging for fuel wood and farming activities (Opara et al., 2016). The climatic condition is tropical following Köppen and Geiger classification and characterized by distinct wet and dry seasons (Peel et al., 2007). The wet season lasts from May to October with average annual rainfall of about 1403mm while the dry season is experienced between November and April (Ahmed II et al., 2013). The relief is mostly undulating with elevation ranging from 271m to 388m above mean sea level. The area consists predominantly of biotite-gneiss rock (>50%) and is outcropped in many parts of the study area with other occurrences of schist and granodiorite and sporadic occurrences of pegmatites and quartz veins.

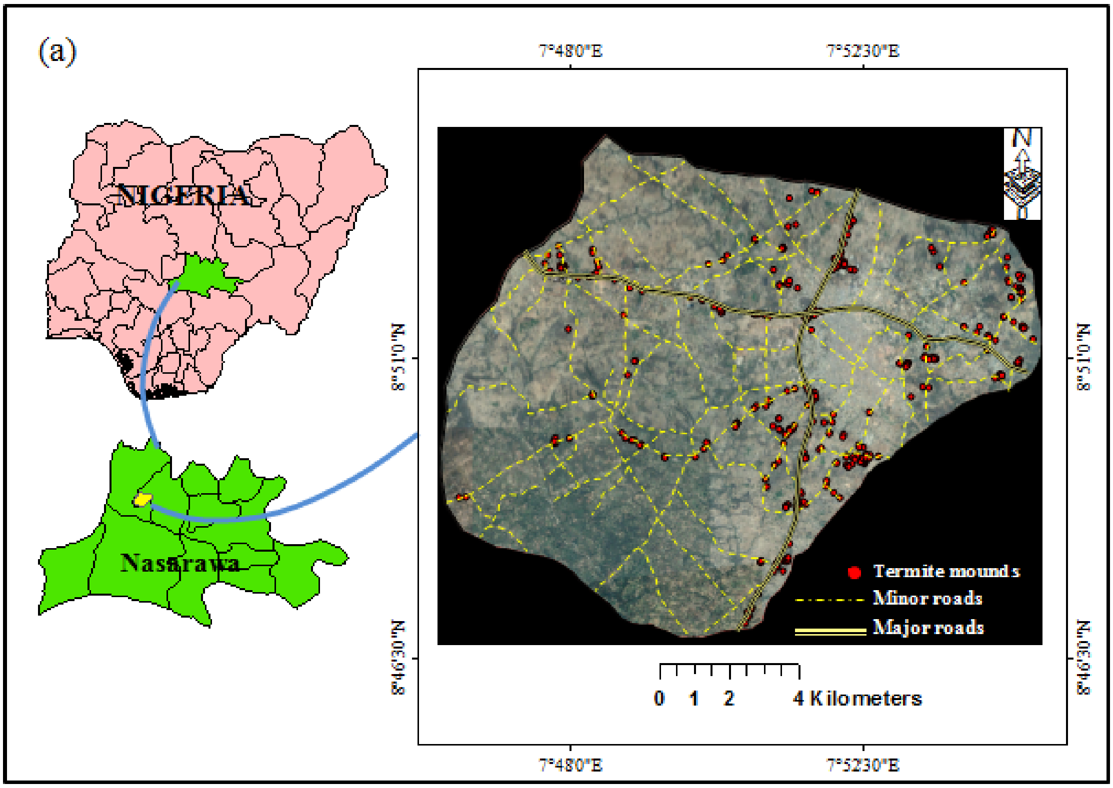

(a)
NIGERIA
Nasarawa
7°48'0"E
7°52'30"E
8°51'0"N
8°46'30"N
N
Termite mounds
Minor roads
Major roads
0 1 2 4 Kilometers

Fig. 1. (a) Map of study area showing roads along which survey was conducted and the spatial distribution of mapped termite mounds; and (b) A cathedral shaped mound with field assistant in the process of height measurement.

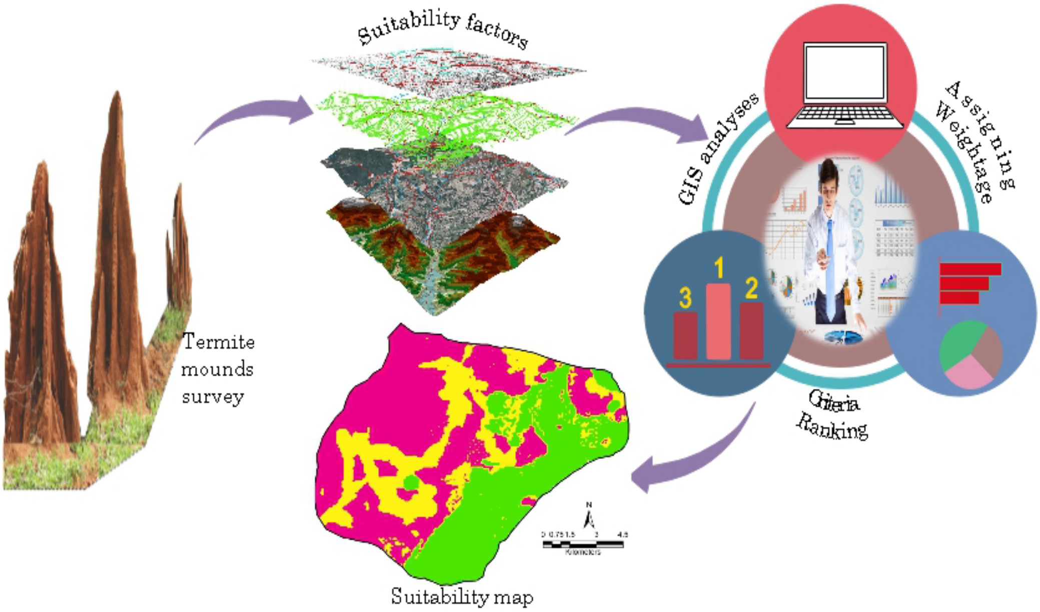


Fig. 2. Graphical abstract of the study methodology

2.2 Field data collection

The field work comprises of termite mounds mapping, termite species collection and static water level measurements. The fieldwork started with a preliminary survey to understand the study area and gather information relevant to planning data collection. The fieldwork lasted for 60 days during the dry season (between February to April 2017). We traversed on foot along 2 major highways and 66 minor roads and footpaths of variable lengths (total length of 226.35 km and roadside bank of 10 m on each side of the road) to cover about 156km^2 study area. This is in consonance with the survey protocol employed by Pomeroy (1977) who observed roadside banks to sometimes be preferred sites for mounds.

Using a base map, compass and mobile phone, the survey was carried-out along each of the roads and footpaths and data recorded using Survey 123 for ArcGIS mobile interface. The Survey 123 GIS application makes use of XLSForm which allows designing customized surveys including the use of validation rules, skips logic, enables audio and images, use multiple languages and have the option of selecting how the survey questions would be answered while on the field. The application also uses the Ground Positioning System (GPS) of the mobile device (accuracy of ~ ±3m) to locate the position of features on map. The application functions both when online and offline and at the end of the survey, the result is immediately available for visualization and analyses on ArcGIS desktop. ArcGIS 10.5 version was used for this study.

During the field survey, features of each termite mound including height, basal diameter, architecture, life status and land use/land cover around the mounds were recorded. These important features of termite mounds (height, diameter and architecture) are thought to be responsible for homeostasis, food storage and maintenance of humidity and efficient exchange of respiratory gasses and are species specific (Turner 2000; Nauer et al., 2015). Measuring tape was used in measuring height and basal diameter of the mounds. Levelling instruments, which could provide more accurate height measurements were not available. For diameter, two measurements along the longest axis and the axis perpendicular to it were obtained.

For termite species sampling, active mounds were partly destroyed at strategic parts for species sampling. Sampling was carried out in the early hours of the morning or late evenings because as the day gets hotter, termites return to subterranean parts of the mounds making it difficult to locate them. When present in a mound, a metallic forceps was used to pick as many samples as possible (workers and soldiers) and carefully placed in a properly labelled sample collection bottle filled with 70% alcohol (Ackerman et al., 2007; Choosai et al., 2009; Sarcinelli et al., 2009). The samples were then transported to Zoology Department of Nasarawa State University Keffi for species identification.

Apart from mounds mapping and species sampling, static water levels of fifty one (51) hand dug wells were measured during the wet season of 2017 (August – September). A 50m dip meter was carefully lowered into the wells (before the commencement of pumping/fetching episode of the day). On contact with water, the sensor of the dip meter makes a beam sound from where the depth to water level is read off from its calibrated meter tape. Where available, the steel cup above the ground surface is also measured (height) and subtracted from the measured static water level to obtain the actual water level. Also the coordinates of each well together with the mean sea level was obtained using a GPS.

2.3 Ancillary data

Other data obtained for this study comprised; geology map of Keffi Sheet 208NE (Arikawe, 2016) from where the study area was clipped and digitized in ArcMap 10.5.

ASTER Digital Elevation Model was used for extraction of elevation and drainage lines. Landsat OLI/TIRS with path 188 and row 54 acquired on 30/03/2018 was used for analysis and supervised classification of Land use/land cover in ENVI 5.3. The March 2018 Landsat image provided better quality with low cloud cover compared with the image of the same month in 2017, and thus was used because land use change within the time interval will not be significant.

2.4 Preparation of thematic layers and analysis

The preparation of thematic layers involve digitizing existing maps, digital processing of remote sensing data and integration with field data. Elevation layer was prepared from ASTER DEM and categorized into 5 classes according to Jenk's classification to obtain natural elevation groupings that best group similar values and maximize the differences between classes. Geology layer was digitized from existing source (Arikawe, 2016), while stream orders were prepared from ASTER DEM using the Strahler algorithm in ArcGIS 10.5. From Landsat 8 OLI/TIRS image, a land use/cover map layer was derived using supervised classification and maximum likelihood algorithm. The classification accuracy was assessed using field data obtained from 361 points and the overall classification accuracy is 79.2% (Table A.1). Static water table layer was prepared using the inverse distance weight (IDW) interpolation using data from 51 hand dug wells. The IDW is based on weighted distance average and so the average cannot be greater than the highest nor less than the lowest input.

2.5 Statistical Analysis

The distribution of mounds (i.e. density, height, diameter, life status and species types) was assessed across elevation range, broad geology, hydrology (stream order), land use/land cover and groundwater level using Kruskal-Wallis H Test with post-hoc Pairwise Wilcoxon rank sum test. For surface water drainage, the drainage lines were calculated to stream orders from where distance of mounds to each segment of the drainage lines was computed and differences between such distances were then compared using Kruskal-Wallis H Test and post-hoc Pairwise Wilcoxon rank sum tests.

2.6 Multi-criteria Decision Analysis

Having analysed how the above environmental factors affect the distribution of termite mounds (including density, height, diameter, life status and species diversity), a multi-criteria decision support tool was employed to combine the set of factors (criteria) to model a suitability map. The Analytical Hierarchy Process (AHP) developed by Saaty (1980) is widely used in the natural resources and environmental management fields (Rahmati et al., 2014; Chezgi et al., 2015; Sangchini et al., 2016). This method allows the determination of rates/weights of factors that indicate strength of one factor over others in pairwise comparison matrices. Comparisons are made on Saaty's scale 1 to 9 (Table A.2) from where a matrix M = (a_{ij}) is produced. Where $a_{ij} = 1$, it indicates that criterion *i* and *j* are of equal importance, while $a_{ij} = 9$ implies that criterion *i* is much more important than criterion *j*. The matrix produced is a reciprocal one, i.e.

$$a_{ij} = \frac{1}{a_{ji}} \qquad \text{(Eq. 1)}$$

All comparisons in a reciprocal matrix satisfy the equality a*ij* = P*i*/P*j*, where P*i* = priority of alternative *i* and P*j* = priority of alternative *j*.

$$M = \begin{pmatrix} \frac{P1}{P1} & \dots & \frac{Pi}{Pj} & \dots & \frac{Pi}{Pn} \\ \dots & 1 & \dots & \dots & \frac{Pi}{Pn} \\ \frac{Pi}{P1} & \dots & 1 & \dots & \frac{Pi}{Pn} \\ \dots & \dots & \dots & 1 & \dots \\ \frac{Pn}{P1} & \dots & \frac{Pn}{Pj} & \dots & \frac{Pn}{Pn} \end{pmatrix} \qquad \text{(Eq. 2)}$$

In this study, five (5) comparison matrices were produced, four (4) for classes in each of the environmental factors and one (1) produced to compute weights of each factor. Three steps were followed to compute the pairwise comparison reciprocal matrix viz;

1. Summation of all elements of column *j* of the matrix.

$$\frac{P1}{Pj} + \cdots + \frac{Pi}{Pj} + \cdots + \frac{Pn}{Pn} = \frac{\sum_{i=1}^{n} \mathrm{Pi}}{\mathrm{Pj}} \qquad \text{(Eq. 3)}$$

2. Normalisation of the *j* column which is achieved by dividing the comparison a*ij* = P*i*/*Pj*.

$$\frac{\frac{Pi}{Pj}}{\frac{\sum_{i=1}^{n} \mathrm{Pi}}{\mathrm{Pj}}} = \frac{Pi}{Pj} \times \frac{Pj}{\sum_{i=1}^{n} \mathrm{Pi}} = \frac{\mathrm{Pi}}{\sum_{i=1}^{n} \mathrm{Pi}} \qquad \text{(Eq. 4)}$$

3. The weight of each factor is the averages of the elements of row *i*.

$$Wi = \left(\frac{\mathrm{Pi}}{\sum_{i=1}^{n} \mathrm{Pi}} + \dots + \frac{\mathrm{Pi}}{\sum_{i=1}^{n} \mathrm{Pi}} \right) \times \frac{1}{\mathrm{n}} \qquad \text{(Eq. 5)}$$

It is necessary to guarantee consistency in judgements; as such a measure of consistency among the pairwise comparisons called Consistency Ratio (CR) is calculated. Saaty (1980) recommended a CR of ≤ 0.1 for consistent judgements, otherwise (CR > 0.1) the pairwise values are not consistent and the comparison matrix must be reconstructed. Three steps are implemented in the calculation of CR viz;

1. Calculate the Eigenvalue (λ_{max}) – Multiply the normalized values (Eq. 4) by the corresponding weights (Eq. 5) and add together, the values of the products.

$$\Lambda_{max} = \sum_{i=1}^{n}\left(Wi \times \frac{Pi}{\sum_{i=1}^{n} Pi}\right) \tag{Eq. 6}$$

2. Calculate the Consistency Index (CI). This is given as;

$$CI = (\lambda_{max}{}^{-n})/(n-1) \tag{Eq. 7}$$

3. Finally, the Consistency Ratio (CR) is calculated using;

$$CR = \frac{CI}{RI} \tag{Eq. 8}$$

where RI is Saaty's random index (constant)

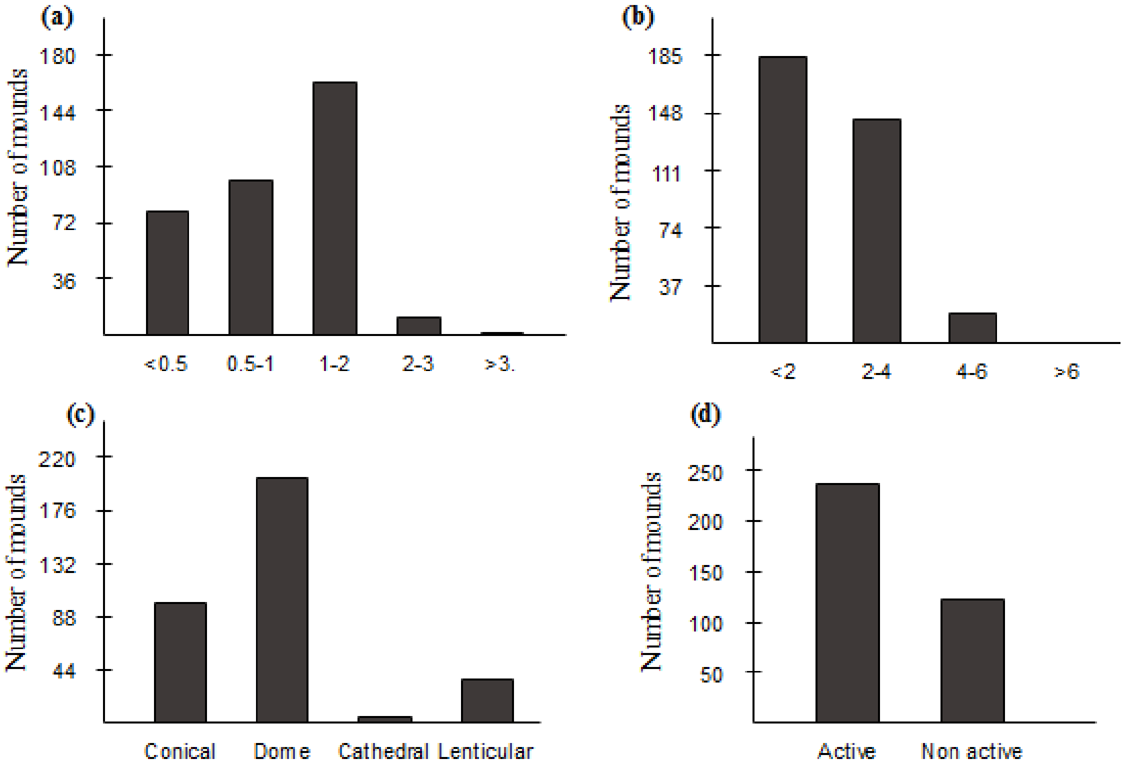
3 Results and Discussion

3.1 Mounds density and pattern

From the 68 roads and footpaths cutting across the study area, a total of 361 termite mounds were mapped (Fig. 1). This is equivalent to a density of about 79.7 mounds per square kilometre (0.8 mounds per hectare). This is perhaps a low mound density compared to other studies. Ekundayo and Aghatise (1997) recorded a density of 2–5 mounds ha^{-1} in Midwestern Nigeria while Wood et al. (1982) recorded 2-4 mounds ha^{-1} in Rabba forest, central Nigeria. In other parts of the globe, 760 ha^{-1} have been reported in Amazonia, Brazil (Ackerman et al., 2007), 2.9 ha^{-1} in D.R. Congo (Mujinya et al., 2014) and 1.96 – 3.40 ha^{-1} in India (Jouquet et al., 2015). The low density recorded in this study is due to the scale of mapping employed as all the aforementioned studies either selected a small study site with pervasive termite activity or surveyed few patches and inference made from them as density for the area. However, a more realistic and similar density figures were obtained using an airborne Light Detection and Ranging (LIDAR) survey in Kruger National Park, where densities of 0.73, 0.6 and 0.46ha^{-1} were respectively recorded by Meyer et al. (1999), Levick et al. (2010) and Davies et al. (2014a).

Another cause for the low density in this study site can be attributed to the level of environmental disturbance (Pribadi et al., 2011). The area has several land use types (not just a park), some of which are not favourable for termite colony establishment while others are prone to disruption by human activities.

Further, termite mounds heights range between 0.23m to 3.1m with overall mean of 0.99m (SD = ±0.5m), while mound basal diameter range between 0.3m to 6.15m with a mean of 2.0m (SD = ±1.14). The computed basal area of all mounds is 0.484km^2, covering only about 0.31% of the study area. Life status of mounds (whether inhabited or abandoned) was investigated through evidence of mound reconstruction and species sampling. It showed that 66% of mounds were active and the remaining were either abandoned or destroyed by grazers and human activities. As for mound architecture, four basic designs were mapped which include dome, conical, lenticular and cathedral designs in order of distribution (Fig. 3).



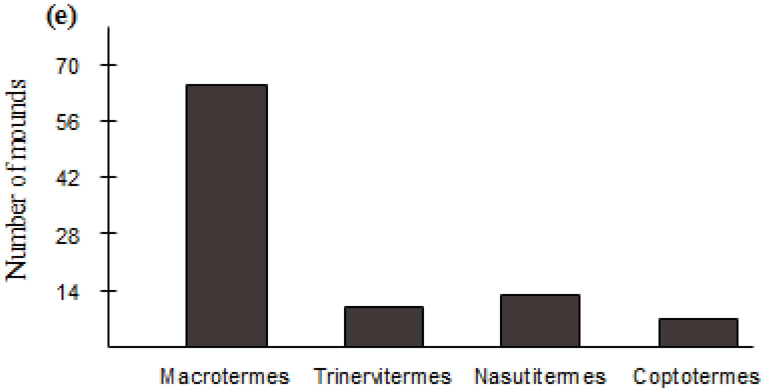


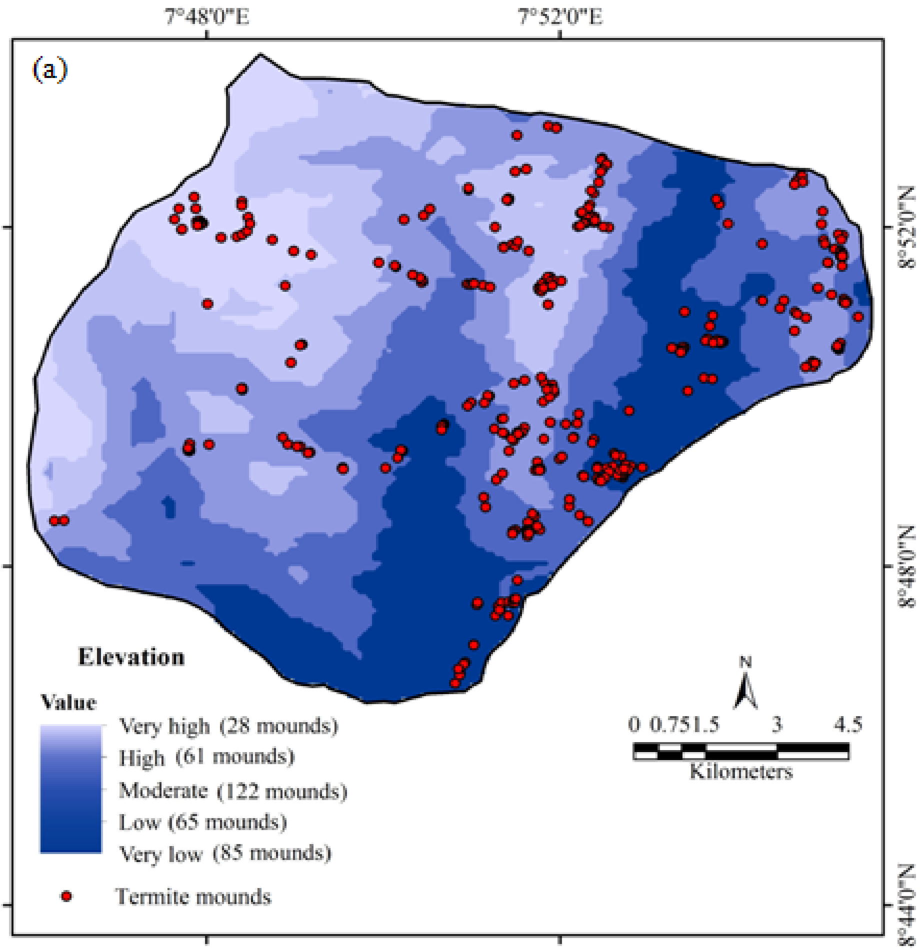
Fig. 3. Termite mounds distribution across the study area in terms of (a) height in meter (b) diameter in meter (c) mounds architecture (d) mounds life status (e) termite genera distribution. **Note:** we could not determine the height of 7 mounds, the diameter of 13 mounds and architecture of 15 mounds due to destruction on the field.

3.2 Termite species

Termites were found in 95 mounds out of which four (4) termite species were identified down to genera taxonomic classification level. The most frequently encountered genus is *Macrotermes* found in 65 mounds. Others are *Coptotermes*, *Nasutitermes,* and *Trinervitermes*. No mound was found to host more than one termite genus, however, many accomodate other non-termite species such as ants, earthworms, spiders and scorpions.

3.3 Elevation effect on Mounds distribution

ASTER DEM was utilized to prepare elevation map and further classified into five (5) classes according to Jenks natural breaks classification (Fig. 4a). The superimposition of termite mounds layer on the elevation map revealed that mounds were constructed across all the five (5) classes of elevation but there are more mounds (33.8%) located on moderately elevated areas while fewer mounds are present in very high elevated areas, indicating a case of unsuitability for mounds construction. Also, mounds mortality rate is higher on the very high elevated areas recording about 46.4% mortality rate (Fig. 4b). A Kruskal-Wallis H Test showed that both mounds height ($X^2 = 18.144, p = 0.001$) and diameter ($X^2 = 13.136, p = 0.011$) vary significantly across the elevation classes. Pairwise comparisons demonstrated that the height differences was recorded between very low elevation and high elevation classes ($p = 0.027$) and between very low elevation and very high elevation classes ($p = 0.001$). This means that tall mounds (≥ 2m) are located in very high elevated areas while short mounds (≤ 1m) predominate low to very low elevated areas and increases with decreasing elevation (Fig. 4c). As for the diameter, pairwise comparisons revealed significant difference between very low and very high elevation classes ($p = 0.014$). The very high elevated areas host more of small diameter mounds whereas larger diameter mounds are found in the moderate to low elevated areas (Fig. 4d). Though the genus *Macrotermes* can adapt to all elevation ranges, they mostly prefer higher elevation than low lands but the reverse is the case for *Cobtotermes* and *Nasutitermes*. *Trinervitermes* on the other hand show total dislike for low grounds and preference for moderate elevations (Fig. 4e).


(a)
7°48'0"E
7°52'0"E
8°52'0"N
8°48'0"N
8°44'0"N
Elevation
Value
Very high (28 mounds)
High (61 mounds)
Moderate (122 mounds)
Low (65 mounds)
Very low (85 mounds)
Termite mounds
N
0 0.751.5 3 4.5
Kilometers

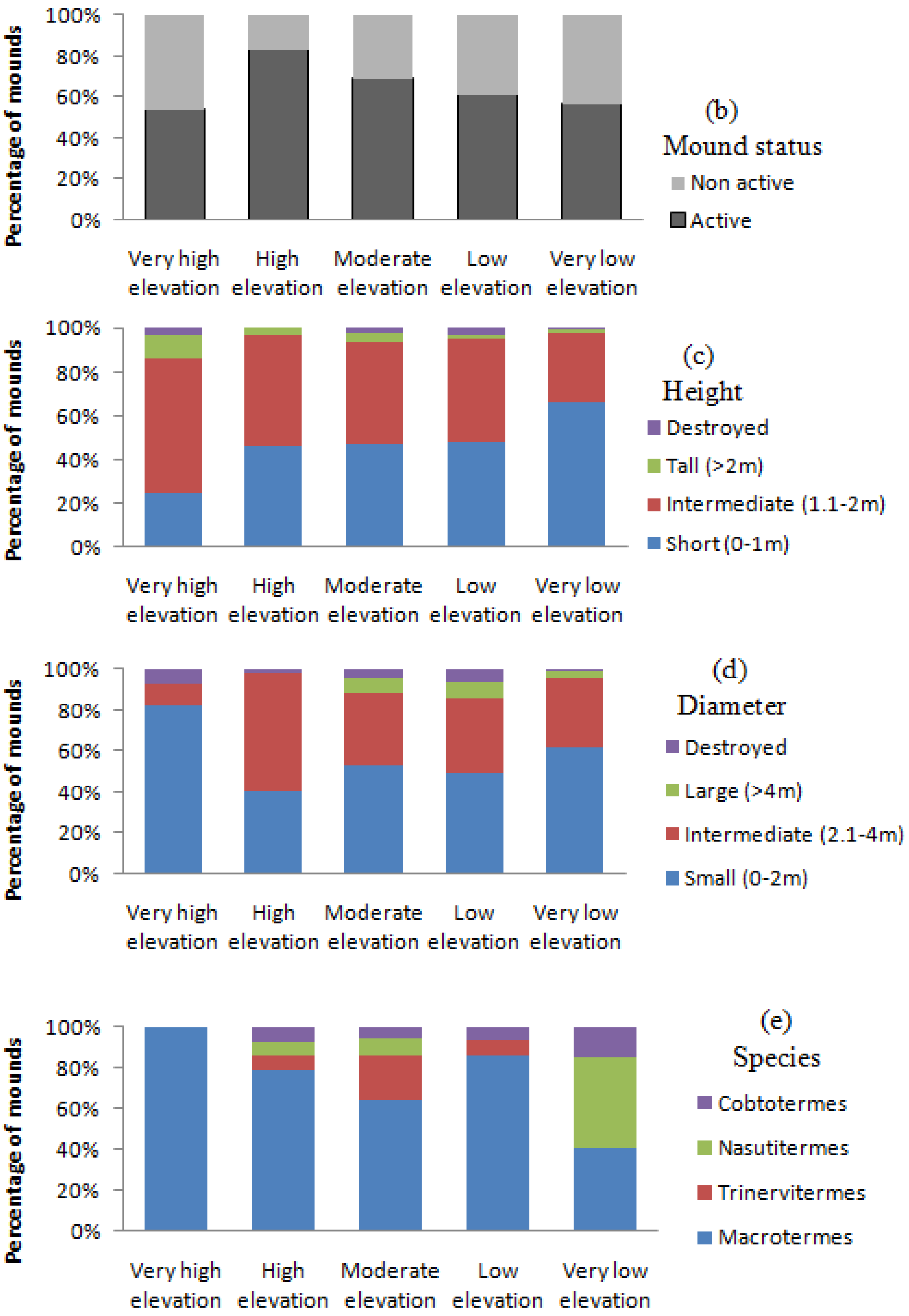
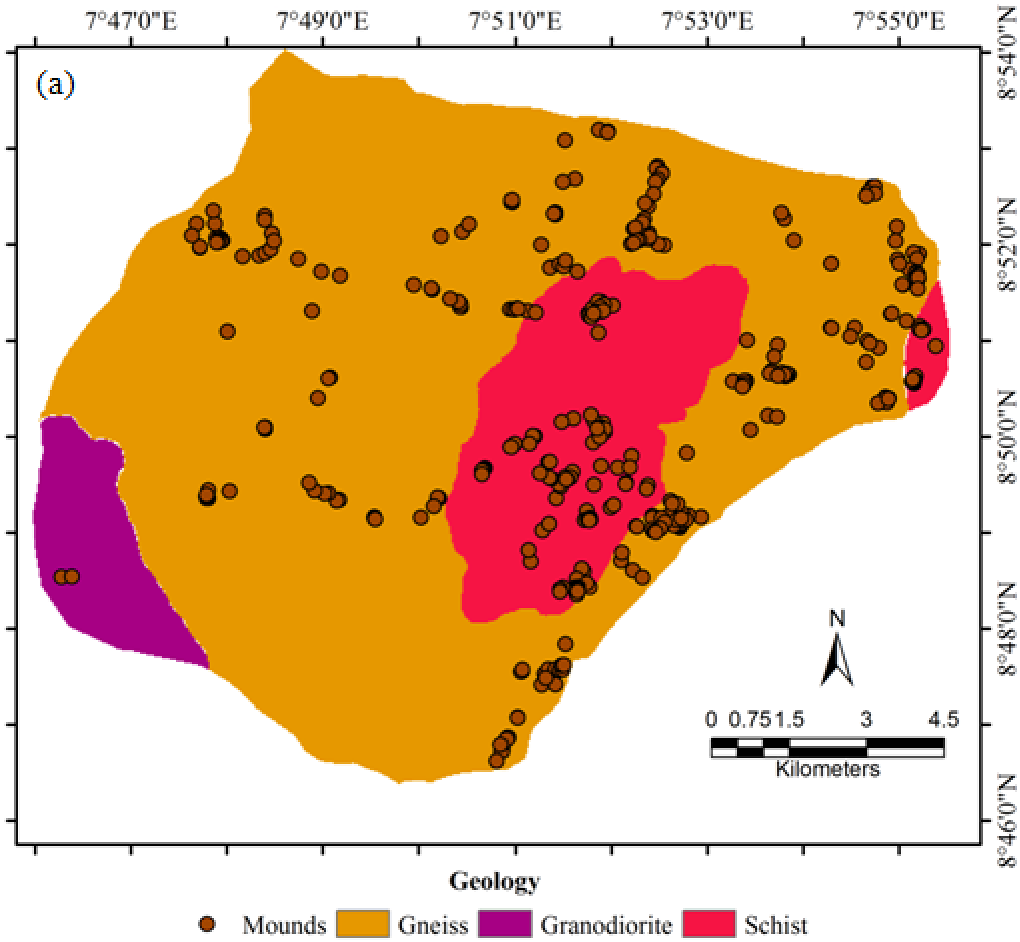


Fig. 4. (a) Mounds distribution across five elevation classes (b) mortality rate (c) mounds height (d) basal diameter and (e) Termite species

3.4 Effect of geology on mounds distribution

The study area is characterized by poly-cyclic metamorphic rocks and igneous rocks of the central Nigeria Basement Complex with three (3) major rock units viz; biotite-gneiss, schist and granodiorite (Arikawe, 2016). The major rock units are intruded by minor occurrences of pegmatites and quartz veins well known for their pervasive jointing and hosting of precious and industrial minerals such as tourmaline, tantalite and mica sheets often in commercial quantities but not mapable due to small area coverage. In the field, termites' affinity to jointed pegmatites and quartz veins was observed. Some mounds are strategically built upon some of these structures probably due to high humidity derivable from them (Mege and Rango, 2010). It was also observed that the longer axis of the mounds diameter tends to be aligned with the strike direction of these structures indicating horizontal nest growth parallel to the regional fracture trend.

Mound density is significantly different across the rock types ($X^2 = 77.33, p < 0.001$) and this difference exists between granodiorite and biotite-gneiss ($p = 0.014$) as well as between schist and biotite-gneiss ($p < 0.001$). The density distribution of mounds is in the order of schist (1.14/ha), gneiss (0.73/ha) and granodiorite (0.13/ha) (Fig. 5a). . Mounds height ($X^2 = 1.823, p = 0.402$) and diameter ($X^2 = 1.513, p = 0.469$) distribution across the rock types do not vary significantly. Areas covered by gneissic rock recorded the highest mound mortality rate of about 40% but supports termite diversity better than the other rock cover types (Fig. 5b and f).


(a)
7°47'0"E
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8°54'0"N
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8°48'0"N
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N
0 0.75 1.5 3 4.5
Kilometers
Geology
● Mounds
Gneiss
Granodiorite
Schist

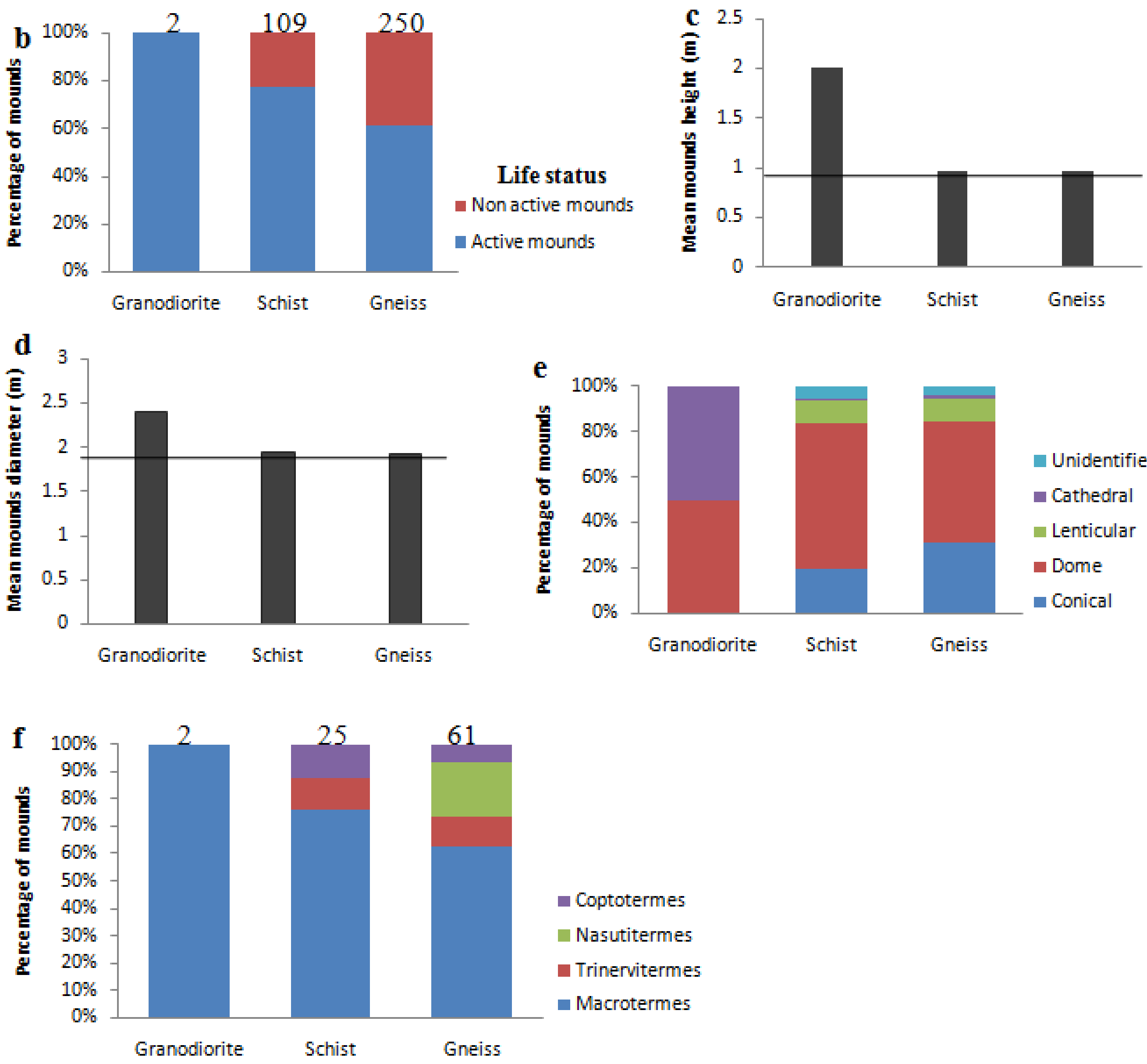


Fig. 5. (a) Geology map of Keffi (Adopted from Arikawe 2016) showing distribution of termite mounds across broad geology (b) Life status of mounds across geology. The number on each bar indicates the number of termite population in that class (c and d) shows respective mean height and diameter of mounds across lithology. The straight

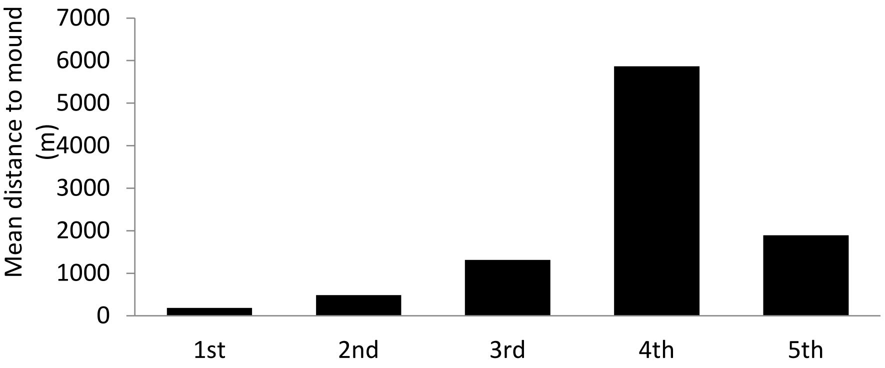
line indicates the entire study area mean height and diameter respectively (e) Mounds architecture (design), revealed schist and gneiss to host all the 4 mound designs while granodorite hosts only 2 (f) Termite species distribution across the lithology showing more diversity in areas covered by gneiss.

3.5 Effect of surface water channels on mounds distribution

Studies have reported that mound building termites avoid near surface water environments for fear of inundation which threatens colony existence (Pomeroy, 1977; Choosai et al., 2009; Freymann et al., 2010; Davies et al., 2016). For this reason, we investigated the effect of surface water channels on the distribution of termite mounds, and specifically modelled the distance away from drainage lines most suitable for termite colonies to flourish. The result revealed that the distance from drainage lines to the nearest mound increases with increasing drainage order (Fig. 6). Kruskal-Wallis test indicates that the distances vary significantly ($X^2 = 1{,}333.3$, $p < 0.001$). Also, pairwise comparison revealed that the distance is significant between all the stream orders ($p < 0.001$). This means that there is increase in the mean distance to nearest mound when moving from a first order stream to a second order stream and also to a third order stream. The mean distance when moving from a third order to a fourth order stream increased more than 4-folds, but however, reduced drastically when moving to the fifth order stream.

Further, we investigated the effect of stream orders on the life status of the mounds. The result revealed that mounds inactiveness is slightly a function of its proximity to stream channels (Table 1). For example, within 0-20m buffer of the first order stream, 4.2% active and 7.3% non-active mounds were mapped. Likewise, within the same distance buffer of the second order stream, about 2% of non-active mounds were recorded and non for the active mounds. The pattern is similar across the higher order streams corroborating earlier findings that termites avoid near surface water environments. For this reason, water channels layer was not included in the final suitability map.

(a)



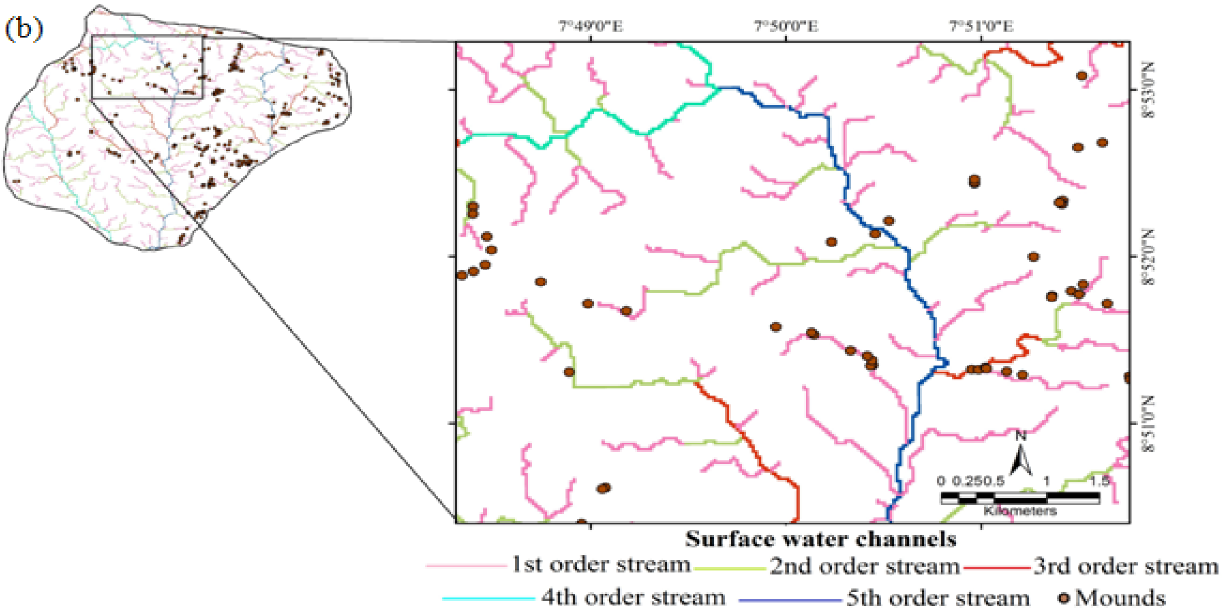


Fig. 6. (a) Mean distance of surface water channels divided into stream orders to nearest termite mounds (b) Termite mounds distribution across drainage channels (stream orders) in the study area

Table 1

Summary of distance ranges from stream orders to nearest mounds

	Mean distance (m)		**Minimum distance**		**Maximum distance**		**% mounds within Buffer**	
Stream order	Active	Non-active	Active	Non-active	Active	Non-active	Active	Non-active
1st order	188.8	187.4	5.0	5.72	692.8	440.7	4.2%	7.3%

2nd order	498.7	462.7	22.5	2.5	1212.0	1219.2	0	2%
3rd order	1306	1330	7.36	4.06	4190.1	4395.4	2.1%	4.1%
4th order	5963.7	5677.1	656.8	660.6	11155.7	10737.8	0	0
5th order	1905	1866	4.8	8.84	7565.7	4728	1.3%	1.6%

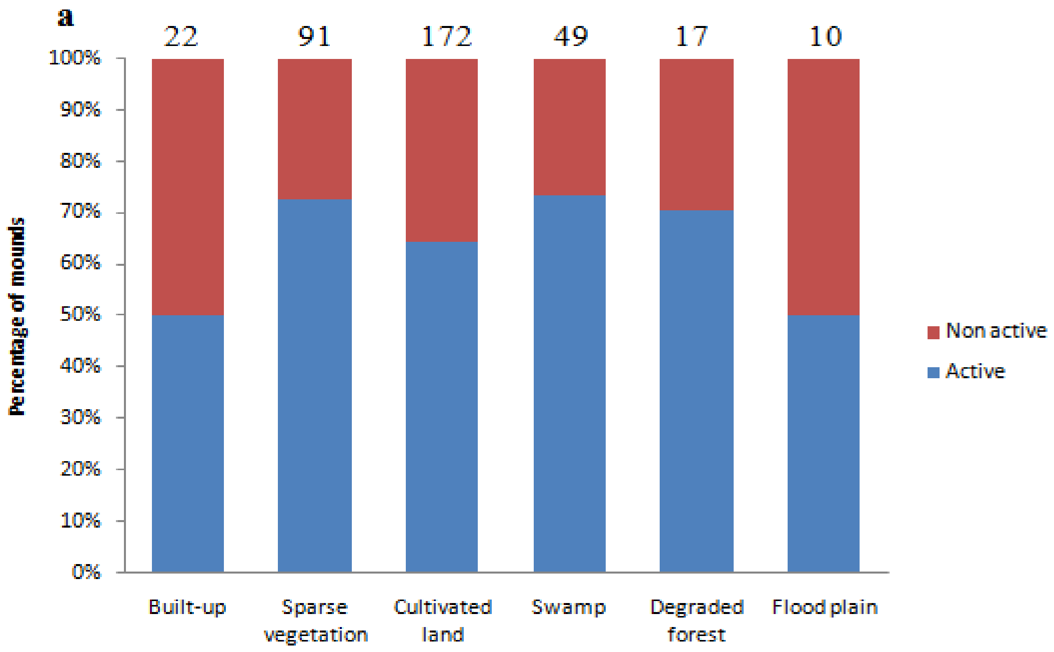
3.6 Effect of land use on mounds distribution

Land use type is directly related to surface disturbance level and have profound effect on the ecological behaviour of termites (Pribadi et al., 2011). Land use dictates the type of habitat specific species of termites are confined to, for example, which species occupy open grassland and forested areas (Bouillon, 1970). From our result, we identified six (6) land use types namely; built-up, cultivated land, sparse vegetation, degraded forests, floodplains and swamps. Mounds distribution across these land use types vary significantly ($X^2 = 155.360$, $p < 0.001$). The highest relative abundance of mounds is recorded in cultivated areas and lowest in flood plain areas. Flood plains and built-up areas are the most unsuitable land use types for termites because termite colony has only 50% chance of survival (Fig. 7). Moreover, there is indication that each species has specific land use preferences and are summarized in Table 2.

Table 2

Termite species distribution/abundance in six (6) land use types

Species	Land use type					
	Built-up	Sparse Vegetation	Cultivated land	Swamps	Forest	Flood Plain
Macrotermes	5	5	18	1	0	4
Trinervitermes	0	5	4	1	2	0
Nasutitermes	0	1	5	5	2	0
Coptotermes	0	0	2	3	2	0
TOTAL	**5**	**11**	**29**	**11**	**6**	**4**


a
22
91
172
49
17
10
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percentage of mounds
Built-up
Sparse vegetation
Cultivated land
Swamp
Degraded forest
Flood plain
🟥 Non active
🟦 Active

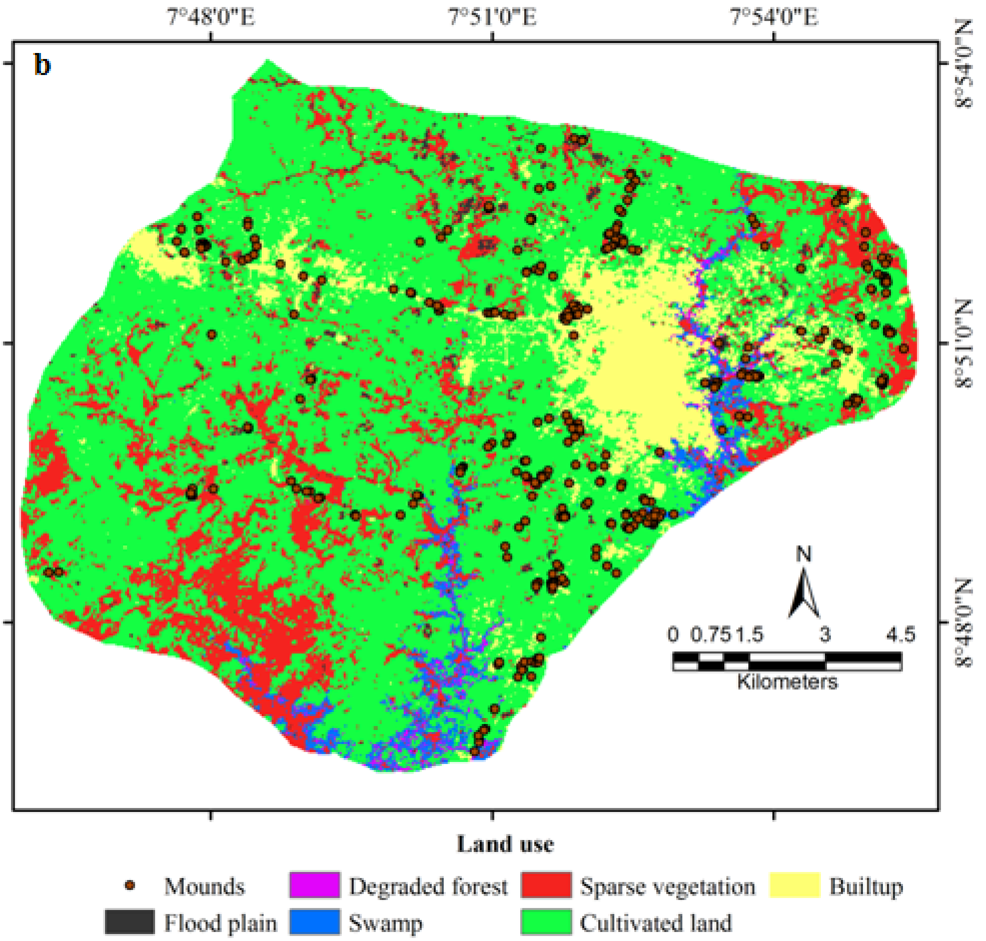


Fig. 7. (a) Mound distribution and life status across land use types. Number on each indicate number of termite population in that class (b) Land use map of the study area with termite mounds (brown dots) distribution.

3.7 Effect of groundwater level on mounds distribution

Termites depend so much on water for their body metabolism (Dangerfield et al., 1998), yet our result and that of other studies (e.g. Freymann et al., 2010; Davies et al., 2014a; Davies et al., 2016) illustrated that they avoid near surface water environments. Consequently, we examined their interaction with the next likely source of water which is water from the groundwater table (Grasse and Noirot, 1960). Our findings established that mound density across three (3) categories of water table depth analysed vary significantly ($X^2 = 88.274$, $p < 0.001$) and that the difference exist between all the categories ($p < 0.001$). Mound densities are 4.02, 1.42 and 1.63 mounds/km^2, in places with low (0m – 3.0m below ground level), intermediate (3m – 6m below ground) and deep (6 – 11m below ground) groundwater table zones respectively (Fig. 8). It is quite revealing that groundwater level tends to control the mechanism behind termite mounds height and species distribution. The percentage of short mounds (≤ 1m) decreases when moving from shallow to deep groundwater table areas, while the percentage of tall mounds (> 2m) increases from shallow to deep groundwater table zones. This implies that in the deep groundwater table zone, termites need to excavate deeper to reach water table and the excavated soil material is used to increase mound heights. Mound height is said to be directly proportional to the depth of soil excavation (Arhin et al., 2015). It is observed also that *Coptotermes* and *Nasutitermes* reside in shallow water table zone, while on the other hand, *Trinervitermes* thrives in both shallow and intermediate zones leaving only *Macrotermes* in the deep water table zone. The genus *Macrotermes* are about three (3) times larger in body size than the other genera and also have larger colony populations (Turner, 2006), hence, their ability to excavate into deeper grounds.

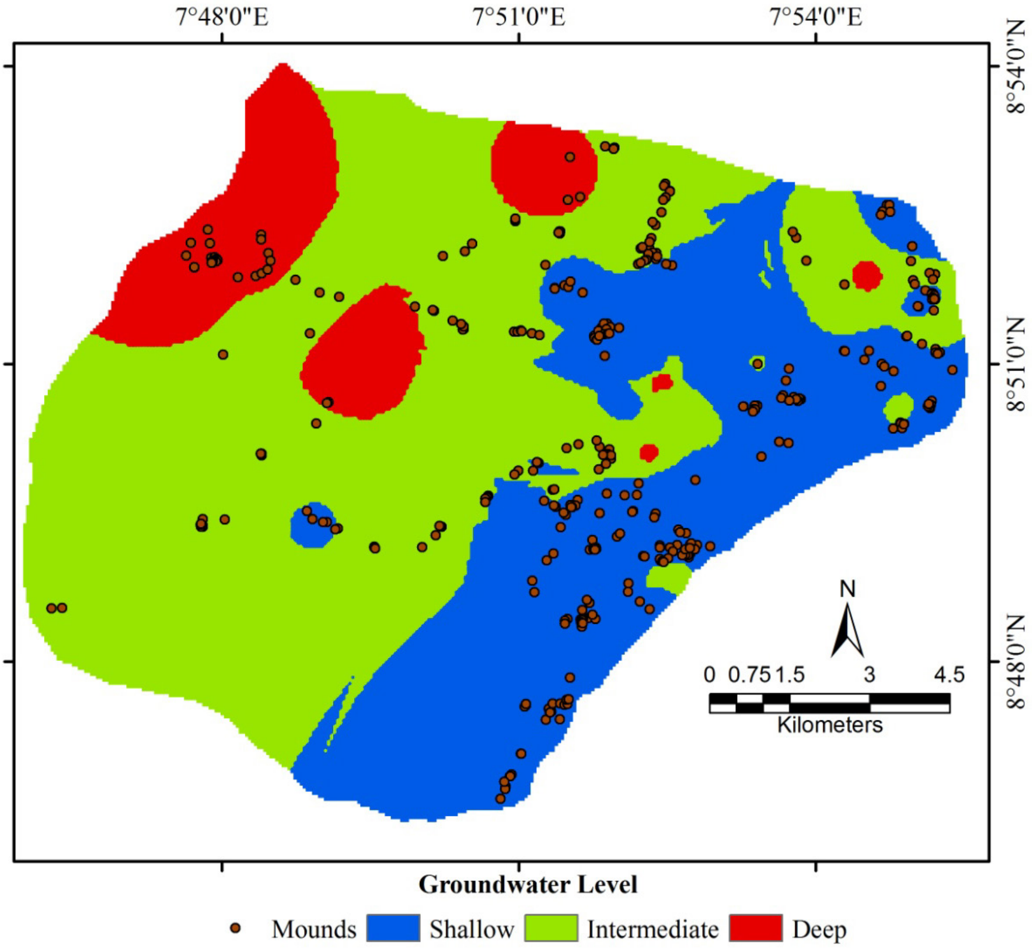


Fig. 8. Groundwater table (below ground level) of the study area divided into shallow (≤3m depth), mid (3 – 6m depth) and deep (>6m depth).

3.8 Multi-criteria Evaluation

Pairwise comparisons between the environmental factors affecting termite mounds distribution based on Saaty's scale 1-9 led to scaling of weights of factors and rates for classes in each factor. The results are presented in tables 3-4).

Table 3

Pairwise comparison matrix for the environmental factors affecting termite mounds distribution (CR = 0.084)

	Elevation	**Geology**	**Landuse**	**Water table**
Elevation	1	7	3	1/3
Geology	1/7	1	1/5	1/7
Landuse	1/3	5	1	1/3
Water table	3	7	3	1
Summation	**4.48**	**20**	**7.2**	**1.81**

Table 4

Relative weights and ranks of the environmental factors (Normalisation)

	Elevation	**Geology**	**Land use**	**W-table**	**Weight**	**Rank**
Elevation	0.223	0.350	0.417	0.184	0.294	2
Geology	0.032	0.050	0.027	0.079	0.047	4
Landuse	0.075	0.250	0.139	0.184	0.162	3
W-table	0.670	0.350	0.417	0.553	0.498	1

Table 5

Relative weights of classes in the environmental factors

Environmental factors	Classes	Suitability	Rates	Factor weight
Elevation	Very high	Very low	0.0418	0.294
	High	Low	0.0806	
	Moderate	Very high	0.4382	
	Low	Medium	0.1468	
	Very low	High	0.2926	
Geology	Biotite-Gneiss	Medium	0.260	0.047
	Schist	High	0.634	
	Granodiorite	Low	0.106	
Landuse	Cultivated land	Very high	0.435	0.162
	Sparse vegetation	High	0.260	
	Swamp	medium	0.125	
	Forest	medium	0.087	
	Built-up	low	0.057	
	Flooded	Very low	0.036	

Water table	Shallow	Very high	0.634	0.497
	Mid	Moderate	0.260	
	Deep	Low	0.106	

3.9 Termite mounds suitability map

The final map was obtained by aggregating the four factors and their classes using Weighted Linear Combination. The process involves multiplying the class rates in each factor by the factor weight and summing the products of all the four factors in raster calculator using eq. 9.

$$S = \sum_{i=1}^{n} WiXi \qquad \text{(Eq. 9)}$$

where S is suitability, Wi is the weight for each factor and Xi is the rate for classes in a factor.

The suitability map was then grouped into three (3) classes of highly suitable, moderately suitable and unsuitable (Fig. 9).

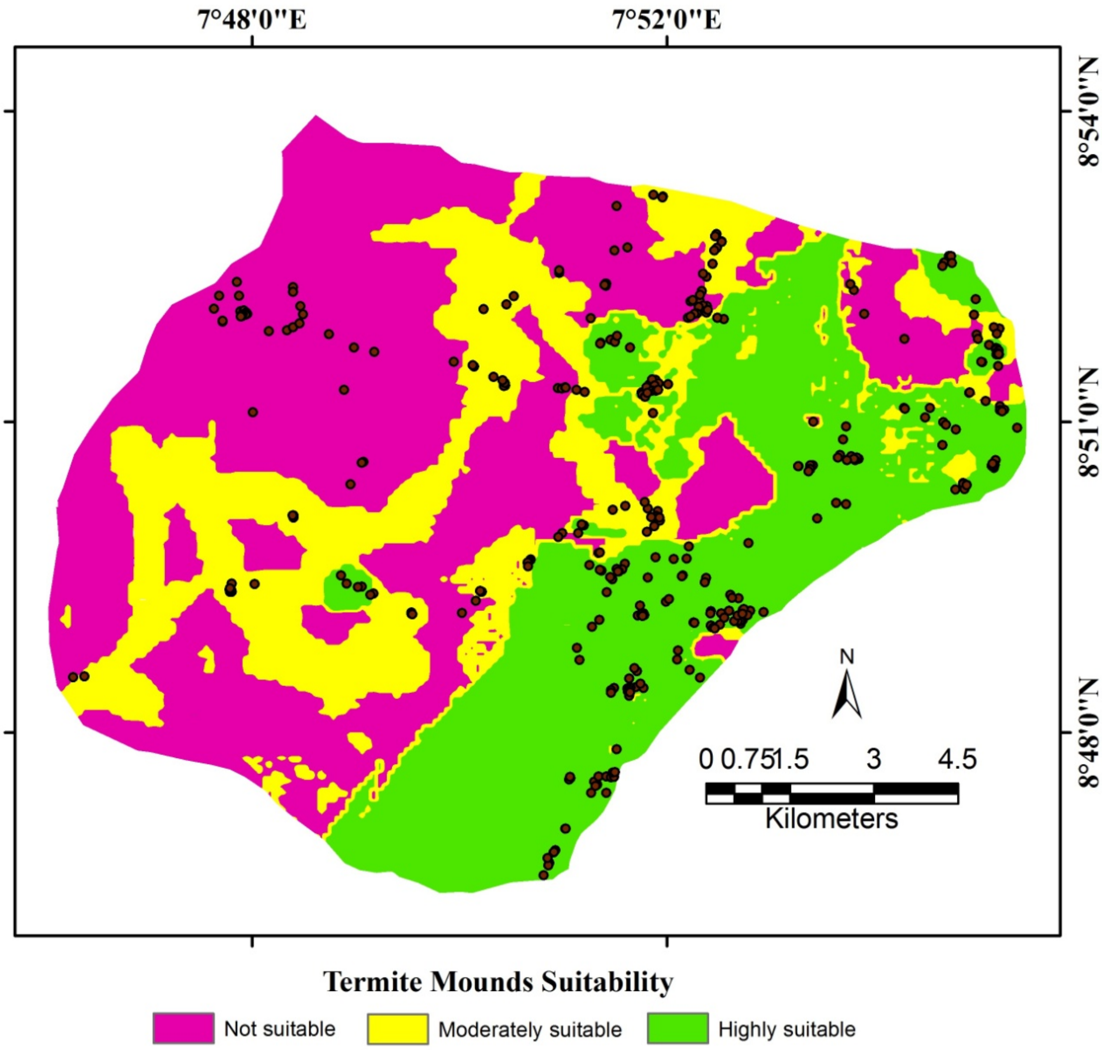


Fig. 9. Termite mounds suitability map

4. Conclusion

This paper is the first to present a suitability model for termite mounds in a multi land use and rock cover landscape. Analytical Hierarchy Process (AHP) was used to compute the rates and weights of four factors considered to have control over the distribution of termite mounds. These four factors which include elevation, geology, land use and static water level were aggregated using Weighted Linear Combination (WLC) method and divided into highly suitable, moderately suitable and non suitable areas. The highly suitable areas are characterized by moderate to very low elevation, cover rocks that are more susceptible to weathering (Schist), areas that are cultivated (which serves as source of food for the termites) and areas with shallow water table. Water table was seen to exert the greatest influence on mounds distribution as over 57% of mounds reside in the shallow water table zone. Even though we presented a general model, slight modifications are likely when specific species are to be taken into account. *Macrotermes* for instance, which is the largest in terms of colony and body size have a broader geographical distribution than the other genera but are completely absent in forested areas, prefer higher grounds and can withstand some level of perturbation in built-up and flood prone areas. All the other genera are sensitive to such disturbances and this has limited their distribution to places with minimal disturbance and availability of food and moisture conditions only.

Further studies to test our model in other areas are recommended. The use of other statistical and data mining models such as Evidential Belief Function (EBF), Weight of Evidence (WoE), Boosted Regression Trees (BRT) and Random Forest (RF) can also be attempted once there is good understanding of the environmental factors influencing the distribution and structure of termite mounds in a certain locality. Also, understanding the connection between mound building termites and groundwater dynamics may be important in predicting promising areas for groundwater abstraction as many localities in the study area lack potable water supply. The limited number of mounds in places with deep water table suggests that a longer dry barrier exist between the foot of mounds and water table and this is likely to have adverse low humidity effect on termite colonization, especially during long periods of drought. On the other hand, termites within the shallow water table zone endure limited seasonal desiccation and might not need to migrate to far depths to collect water and maintain nest humidity.

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