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Article

A revisit to circular statistical analysis of the orientations of termite mounds

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Abstract: This research provides an in-depth circular statistical analysis of Amitermeslaurensis termite mound orientations across 14 sites in Northern Queensland, revisiting data from orientation of the termitaria of two species of Amitermes (isoptera: Termitinae) from Northern Queensland (1983) (also accessible in the R package circular). The study aims to uncover termite species' potential environmental and adaptive responses to local climatic factors by analyzing the non-uniform patterns of mound orientation. The findings contribute to understanding species-environment interactions, which is crucial for anticipating the impacts of environmental change on ecosystem functions. The study aligns with the United Nations Sustainable Development Goals (SDGs), particularly Climate Action, by contributing insights into species adaptation under shifting climates and Life on Land by enhancing biodiversity and ecosystem resilience knowledge. This research illustrates the value of circular statistical methods in ecological analysis, underscoring their role in addressing global sustainability challenges.

Keywords: circular statistics; termite mound orientation; species-environment interactions; climate adaptation; biodiversity and ecosystem resilience

1. Introduction

The spatial orientation of termite mounds has been a subject of ecological interest due to its potential correlation with environmental factors such as wind direction, solar exposure, and soil conditions. Termite species like Amitermeslaurensis, prevalent in Northern Queensland, build mounds with a distinct directional bias. This paper aims to statistically analyze the orientations of termite mounds using circular statistical methods to uncover underlying patterns in the data.

The unique architecture of these mounds helps maintain optimal conditions for microbial activity and plant establishment [1].

The paper demonstrates that termite construction behavior in Macrotermes colonies is guided by topological cues, specifically surface curvature, rather than inclination or height, challenging the traditional view of pheromone-based coordination and offering insights potentially applicable to swarm robotics [2].

The orientation of termite mounds is not merely a product of random construction; rather, it reflects a complex interaction between abiotic factors and the termites' behavior. For instance, studies have shown that the spatial distribution of termite mounds is influenced by soil properties, such as clay content and drainage capabilities, which affect the termites' choice of nesting sites [3].

This interaction between termites and their environment influences the local flora and affects herbivore foraging patterns, as many herbivores preferentially graze near these nutrient-rich mounds [4].

On the methodological front, the analysis of circular data, such as directional statistics associated with termite mound orientations, has been comprehensively explored by [5]. Fisher's work is pivotal in providing statistical tools and frameworks to handle data where traditional linear methods fall short. This book, Statistical Analysis of Circular Data, offers crucial techniques for correctly interpreting the directional data, ensuring that researchers can make informed decisions based on proper statistical inference.

It presents a computational model that predicts the influence of environmental forces on the architecture and functionality of termite mounds, showing that mound structures, particularly spire tilt and internal channels, are optimized for heat transfer and gas exchange based on solar irradiance and geographical location [6].

This introduces a computational model showing that termite mound shapes are influenced by thermoregulatory and gas-exchange functions, as well as environmental factors like solar irradiance and wind, producing regionally adapted structures such as sun-oriented cones and shaded domes, with deeper nests and thicker walls for thermoregulation [7].

It finds a strong north-south alignment in Amitermeslaurensis termite mounds across northern Australia, with orientation unaffected by surrounding vegetation and mound shape likely influenced by genetic factors rather than environmental conditions [8].

Moreover, the mounds play a significant role in shaping the surrounding vegetation. They act as "islands of fertility", enriching the soil with nutrients and providing a favorable environment for plant growth [9].

This article on Amitermes meridionalis and Amitermeslaurensis mounds in northern Australia reveals that mound orientation varies geographically, likely as an adaptive response to local environmental conditions, with shaded sites showing greater orientation variance than open sites [10].

Termite mounds in Northern Queensland, particularly those constructed by the genus Amitermes, exhibit fascinating orientation patterns that have intrigued researchers for decades. The alignment of these mounds has been attributed to various ecological and physiological factors, which have been systematically studied since the 1970s. Grigg's pioneering work in this area established a framework for understanding how these structures might serve specific environmental functions, such as temperature regulation and moisture retention, which are critical for the survival of the termites and their ecosystem [11].

This finds that Amitermes meridionalis termites align mound cells along the mound's existing axis and the horizontal magnetic field's cardinal directions, as shown by repairs in both natural and altered magnetic fields [12].

It highlights the need for systematic research into termite mound properties—such as porosity, material composition, and vibrational dynamics—to better understand their multifaceted roles in thermoregulation, defense, communication, and as a superorganism structure, proposing high-resolution tomography and computational methods as promising approaches [14].

This spatial arrangement is crucial as it enhances ecosystem functioning by creating

This spatial arrangement is crucial as it enhances ecosystem functioning by creating microhabitats that support diverse plant and animal species [15].

The study of termite mound orientations offers valuable insights into termites' adaptive behavior and ecological engineering capabilities. One significant contribution to this area was made by [16], who investigated the orientation patterns of termitaria constructed by two species of Amitermes in Northern Queensland. Spain et al. [16] observed that these orientation patterns could be correlated with environmental variables, suggesting that termites might strategically position their mounds to optimize temperature regulation and moisture retention. This understanding highlights the complexity of termite ecosystem interactions and aids in the broader comprehension of arid and semi-arid ecosystem functionalities. The integration of ecological insights from [16] with the statistical methodologies proposed by Fisher represents a robust approach to understanding the behaviors of termites and the broader implications of these behaviors on ecosystem engineering and species survival strategies. Such studies underscore the importance of interdisciplinary approaches in ecological research, blending biological insights with statistical rigor to better understand complex natural phenomena.

In regions with high clay content, termites tend to avoid areas prone to inundation, leading to a more aggregated mound pattern. In contrast, in drier areas, a more regular distribution is observed [17].

The orientation and construction of termite mounds in Northern Queensland are influenced by environmental factors and the termites' adaptive behaviors. These structures serve vital ecological functions, contributing to soil fertility, vegetation heterogeneity, and overall ecosystem health. Understanding these dynamics is essential for conservation efforts and managing the ecological roles of termites in savanna ecosystems.

In this paper, we analyze data from 14 different sites using circular descriptive statistics, the von Mises distribution for modeling angular data, and hypothesis tests such as the Rayleigh test for uniformity and the Watson-Williams test for differences between sites. The data consists of angles measured in degrees, representing the orientations of termite mounds, where $\theta \in [0°, 360°)$.

2. Objective and novelty of the research

The primary objective of this research is to employ advanced circular statistical methods to analyze the orientations of termite mounds across multiple geographic sites. Previous studies often addressed directional data through linear statistical methods, which inadequately capture the inherent circularity of such data. This study utilizes specialized circular statistical techniques, including the von Mises distribution and the Rayleigh test for uniformity, to provide a more accurate analysis. While circular statistics have been discussed in prior literature [5,16], this research aims to extend these applications by facilitating further inferences and comparative analyses.

The novelty of this research lies in its application of circular statistical methodologies to ecological data concerning termite mound orientations. By quantifying the directional preferences of these mounds, we seek to enhance the understanding of the environmental factors influencing their alignment. This rigorous analysis not only illustrates the utility of circular statistics in ecological contexts but also sets a foundation for future studies exploring similar biological phenomena, thereby contributing to the broader field of ecological research.

This research aligns explicitly with the United Nations Sustainable Development Goals (SDGs). By exploring how termite species interact with their environment, this study contributes to:

- Goal 13: Climate Action, by enhancing our understanding of the adaptive strategies of termites under shifting climatic conditions, which is critical for anticipating the ecological impacts of global climate change [13].
- Goal 15: Life on Land, by shedding light on the ecological functions of termite mounds in promoting soil fertility, supporting biodiversity, and maintaining ecosystem health [13].

For more details on the United Nations Sustainable Development Goals (SDGs), refer to the official website: https://sdgs.un.org/goals.

3. Preliminaries

This section introduces the fundamental concepts and notations required for the statistical analysis of circular data. Circular statistics is a branch of statistics that deals with data where the values are angular in nature, i.e., periodic and constrained to a fixed interval, typically $[0,2\pi)$ or [0°, 360°). Traditional linear statistics are insufficient for analyzing such data due to its periodicity. We shall employ concepts like circular mean, variance, and the von Mises distribution, a common angular data model.

3.1. Circular data and descriptive statistics

Let $\mathcal{D} = \{\theta_1, \theta_2, \dots, \theta_i\}$ represent a sample of angular measurements, where each $\theta_i \in [0,2\pi)$ for $i = 1, 2, \dots,$ n. Unlike linear data, where measures of central tendency and dispersion are straightforward, the circular nature of angles necessitates alternative formulations.

3.1.1. Mean direction

The mean direction of a set of circular data points is computed using the vector sum of the unit vectors pointing in the directions of the angles. Specifically, we define the following trigonometric sums:

$$S = \sum_{i=1}^{n} sin\, \theta_i\, , C = \sum_{i=1}^{n} cos\, \theta_i$$

The mean resultant vector is given by:

$$\bar{R} = \sqrt{\left(\frac{C}{n}\right)^2 + \left(\frac{S}{n}\right)^2}$$

The angle of this vector, which gives the mean direction, is computed as:

$$\bar{\theta} = \arg(C, S)$$

where $\bar{\theta}$ represents the circular mean.

3.1.2. Circular variance

The circular variance, V measures the data's spread around the mean direction. It is defined in terms of the length of the mean resultant vector:

$$V = 1 - \bar{R}$$

here, $\bar{R}$ serves as a measure of concentration, with $\bar{R} = 1$ indicating perfect alignment (no variance) and $\bar{R} = 0$ indicating uniform dispersion.

3.2. Von Mises distribution

The von Mises distribution is a fundamental probability distribution for circular data. It serves as an analog to the normal distribution in linear statistics. The probability density function (PDF) of the von Mises distribution is given by:

$$f(\theta \mid \mu, \kappa) = \frac{e^{\kappa \cos(\theta-\mu)}}{2\pi I_0(\kappa)}, \theta \in [0,2\pi)$$

where:

- μ is the mean direction,
- κ is the concentration parameter, which determines how closely the data points are clustered around the mean direction.
- $I_0(\kappa)$ is the modified Bessel function of the first kind of order zero, defined as:

$$I_0(\kappa) = \frac{1}{2\pi}\int_0^{2\pi} e^{\kappa \cos(\theta)} d\theta$$

The parameter κ is analogous to the inverse of variance in linear statistics. A larger κ corresponds to data that are more tightly clustered around the mean direction μ.

3.3. Parameter estimation

The parameters μ (mean direction) and σ^2 (variance) of the triangular circular distribution can be estimated using Maximum Likelihood Estimation (MLE). The likelihood function for a sample of angular measurements $\theta_1, \theta_2, \ldots.., \theta_\mathrm{n}$ is:

$$\mathscr{L}(\mu, \sigma^2) = \prod_{i=1}^{n} f(\theta_i \mid \mu, \sigma^2)$$

Maximizing the log-likelihood function with respect to the parameters gives the estimates $\hat{\mu}$ and $\widehat{\sigma^2}$. For each of the 14 sets of the dataset (fisherB13c), we fit the triangular circular distribution and compute the goodness of fit. We refer to [5] for details of the methodology.

3.4. Goodness of fit

To assess the fit of the triangular circular distribution, we employ two methods:

Circular variance: A low circular variance indicates that the data are tightly clustered around the mean direction.

Mean Absolute Deviation (MAD): This measures the average absolute deviation of the fitted values from the observed angular values, defined as:

$$\mathrm{MAD} = \frac{1}{n}\sum_{i=1}^{n}\left|\theta_i - \widehat{\theta_i}\right|$$

where $\widehat{\theta_i}$ are the fitted angles.

3.5. Hypothesis testing for circular data

In the analysis of circular data, hypothesis testing plays a crucial role in determining whether the data follow a specific distribution or whether there is a significant difference between the distributions of two or more samples.

3.5.1. Rayleigh test for uniformity

The Rayleigh test assesses whether the data are uniformly distributed around the circle, which would indicate no preferred direction. The null hypothesis, H_0, is that the data are uniformly distributed. The test statistic is given by:

$$Z = 2n\overline{R^2}$$

Under H_0, the statistic Z follows a chi-squared distribution with 2 degrees of freedom:

$$Z \sim \chi_2^2$$

3.5.2. Watson-Williams test for equal mean directions

The Watson-Williams test compares the mean directions of two or more groups of circular data. Let $\mathcal{D}_1 = \{\theta_{11}, \theta_{12}, \dots, \theta_{1\mathrm{n}_1}\}\ and \mathcal{D}_2 = \{\theta_{21}, \theta_{22}, \dots, \theta_{2\mathrm{n}_2}\}$ represent two samples of circular data. The test statistic is:

$$F = \frac{n_g\left(R_{\text{total}} - \sum_{i=1}^{g} R_i\right)}{g-1}$$

where n_g is the total sample size across all groups, R_{total} is the resultant length of the pooled data, and R_i is the resultant length for the ith group. Under the null hypothesis of equal mean directions, F approximately follows an F distribution with $g-1$ and $n_g - g$ degrees of freedom.

This section has established the essential tools for analyzing circular data. We have introduced key concepts such as circular mean, variance, von Mises distribution, and hypothesis tests suitable for angular data. These concepts form the foundation of the subsequent analysis of termite mound orientations, where the specific characteristics of the circular data will be explored in detail.

4. Dataset description

The dataset under consideration consists of angular measurements representing the orientations of termite mounds from the species Amitermeslaurensis, collected at 14 distinct sites in Cape York Peninsula, North Queensland, Australia. These measurements are provided in degrees, and the orientations are naturally treated as circular data due to their periodicity on the [0°, 360°) interval. The dataset is sourced from the work of SOOJ83, which investigated the alignment of termite mounds in response to environmental factors. The full dataset is publicly available through the R package circular and is referred to as fisherB13c.

4.1. Data collection

The termite mound orientations were recorded at 14 sites, where each site has a varying number of observations, denoted as n_i, for the ith site. The dataset provides angular measurements in degrees observed using standard field survey methods. The locations of the sites span a region with coordinates ranging from approximately 15°32′S to 15°43′S latitude and 144°17′E to 144°42′E longitude. Each site's geographical coordinates and sample sizes are detailed in **Table 1**.

Table 1. Summary of sites and number of observations.

Site	Latitude (S)	Longitude (E)	$\boldsymbol{Number\ of Observations(n}$
1	15°43′	144°42′	100
2	15°32′	144°17′	50
3	15°38′	144°25′	50
4	15°40′	144°38′	50
5	15°42′	144°40′	50
6	15°36′	144°18′	50
7	15°35′	144°19′	66
8	15°39′	144°22′	48
9	15°33′	144°23′	100
10	15°37′	144°20′	50
11	15°41′	144°35′	37
12	15°31′	144°36′	31
13	15°34′	144°37′	132
14	15°30′	144°39′	92

The number of termite mound orientations recorded per site varies from 48 to 100, depending on the size and accessibility of the site. These angular measurements are expected to exhibit non-uniform distributions, potentially influenced by environmental factors such as wind patterns, solar radiation, or soil conditions.

4.2. Circular nature of the data

Since the measurements are angular, the data are inherently circular, meaning that 0°is equivalent to 360°. This circularity introduces special considerations for statistical analysis, as traditional linear methods are inappropriate. For example, the mean of angles must be calculated using vector summation in the unit circle rather than by directly averaging the angular values. Additionally, any variance or concentration measures must account for the periodicity of the data.

The orientations θ_i are expressed in degrees, which we can map to the interval $[0,2\pi)$ radians when required. Let θ_{ij} represent the orientation of the jth termite mound at the ith site, where:

$$\theta_{ij} \in [0°, 360°) \quad \text{for} \quad i = 1,2,\dots,14, \quad j = 1,2,\dots,\mathrm{n_i}$$

In this study, we will analyze the data primarily in degrees, although certain circular statistical computations will be conducted in radians for mathematical convenience.

4.3. Structure of the dataset

The dataset is structured as a list of 14 individual datasets, where each list element corresponds to one site. Each site's dataset is a circular object, encapsulating the orientation angles in degrees. The structure of the dataset can be expressed as:

$$\mathcal{D} = \{\mathcal{D}_1, \mathcal{D}_2, \dots, \mathcal{D}_{14}\}$$

where $\mathcal{D}_i = \{\theta_{i1}, \theta_{i2}, \dots, \theta_{in_i}\}$ represents the orientations at site i. Each θ_{ij} is an angular measurement for mound $j$at site i. For example, the dataset for site 1 contains 100 angular values, while the dataset for site 2 contains 50 values.

The first few entries of the dataset are provided below for illustration:

$$\mathcal{D}_1 = \{161°, 182°, 179°, \dots, 193°\}$$

$$\mathcal{D}_2 = \{121°, 138°, 183°, \dots, 161°\}$$

Each set of angles is treated as a circular data object with the following properties:

- Type: Angles;
- Units: Degrees;
- Modulo: [0°, 360°);
- Rotation: Counterclockwise.

4.4. Potential sources of variability

The variability in termite mound orientations could be attributed to several environmental factors. Previous studies suggest that the mounds' orientation may be influenced by microclimatic conditions such as prevailing winds, solar exposure, and temperature gradients. The present dataset provides an opportunity to examine these orientations statistically, using circular statistical methods to investigate the extent of alignment or randomness in the orientations across different sites.

4.5. Source of data

The data were originally collected and analyzed in the study by Spain et al. [16], who investigated the orientation of termite mounds for two species of termites in Northern Queensland. The data has since been used as an example dataset in Fisher's seminal book on circular statistics [5] and is now included in the R package circular.

4.6. Summary of the dataset

To summarize, the dataset provides valuable insights into the orientations of termite mounds across multiple locations. The primary characteristics of the data are as follows:

- Number of sites: 14
- Total number of termite mound orientations: 933
- Angular measurements: Degrees, ranging from 0° to 360°.
- Data type: Circular

This dataset serves as the basis for applying advanced circular statistical techniques, including estimation of the mean direction, concentration parameters, and hypothesis testing for uniformity of orientations across different sites.

5. Methodology

5.1. Data structure

Let $\mathcal{D} = \{\theta_{ij} \mid 1 \leq i \leq 14, 1 \leq j \leq n_i\}$ represent the data, where θ_{ij} is the orientation of the jth termite mound at the ith site. Here, n_i denotes the number of observations (mounds) at site i, with site 1 having $n_1 = 100$, site 2 having $n_2 = 50$, and so on.

Each θ_{ij} is measured in degrees, representing circular data:

$$\theta_{ij} \in [0°, 360°).$$

5.2. Circular descriptive statistics

The fundamental statistics for circular data differ from their linear counterparts due to the periodicity of angles. We define the following statistics:

Mean Direction:

The mean direction $\bar{\theta}$ is computed as:

$$\bar{\theta} = arg\left(\sum_{j=1}^{n_i} cos\,\theta_{ij}, \sum_{j=1}^{n_i} sin\,\theta_{ij}\right)$$

where $arg(x, y)$ is the angle whose tangent isy/x .

Length of the Mean Resultant Vector (R):

The length of the mean resultant vector, R, is a measure of concentration:

$$R = \frac{1}{n}\sqrt{\left(\sum_{j=1}^{n_i} cos\,\theta_{ij}\right)^2 + \left(\sum_{j=1}^{n_i} sin\,\theta_{ij}\right)^2}$$

where $R \in [0,1]$ indicates the degree of concentration, with $R = 1$ implying all orientations are identical, and $R = 0$ implying uniform dispersion.

Circular variance:

The circular variance V is defined as:

$$V = 1 - R$$

A lower variance indicates higher clustering around the mean direction.

5.3. Circular distributional analysis

The von Mises distribution is often used to model angular data because of its similarity to the normal distribution on the circle. The probability density function of the von Mises distribution is given by:

$$f(\theta \mid \mu, \kappa) = \frac{e^{\kappa\, cos(\theta - \mu)}}{2\pi I_0(\kappa)}$$

where μ is the mean direction, κ is the concentration parameter, and $I_0(\kappa)$ is the modified Bessel function of the first kind:

$$I_0(\kappa) = \frac{1}{2\pi} \int_0^{2\pi} e^{\kappa \cos \theta} d\theta$$

Maximum Likelihood Estimation (MLE):

The parameters μ and κ are estimated using Maximum Likelihood Estimation (MLE). The MLE of μ is given by:

$$\hat{\mu} = arg\left(\sum_{j=1}^{n} cos\,\theta_j\,, \sum_{j=1}^{n} sin\,\theta_j\right)$$

while the MLE of κ is:

$$\hat{\kappa} = \frac{\bar{R}\left(2 - \overline{R^2}\right)}{1 - \overline{R^2}}$$

5.4. Hypothesis testing

Rayleigh test for uniformity:

The Rayleigh test evaluates whether the termite mound orientations are uniformly distributed. The null hypothesis H_0 states that the data are uniformly distributed on the circle. The test statistic Z is computed as:

$$Z = 2nR^2$$

where n is the sample size and R is the mean resultant length. Under H_0, Z follows a chi-squared distribution with 2 degrees of freedom.

Watson-Williams test for differences in mean directions:

We use the Watson-Williams test to test for differences in mean directions across different sites. The test statistic F is given by [5]:

$$F = \frac{n_g\left(R_{total} - \sum_{i=1}^{g} R_i\right)}{g - 1}$$

where R_{total} is the resultant length for the combined data from all sites, R_i is the resultant length for site i, and n_g is the number of groups (sites).

5.5. Software and packages used

The data analysis for this study was performed using the statistical programming language R (version 4.0.5). Several specialized packages were employed to conduct circular statistical analysis, create visualizations, and perform hypothesis testing. The details of the software and packages used are as follows:

- R version 4.0.5: The main programming environment for statistical computing and data analysis.
- Circular package version 0.4–93: Used for circular data analysis, including the computation of circular descriptive statistics, fitting of circular distributions, and hypothesis testing.

- CircStats package: Provided additional functionality for circular statistical methods, including the Watson-Williams test.
- ggplot2 package: Utilized for creating high-quality plots and visualizations of circular data.
- dplyr package: Used for efficient data manipulation and summarization.

These tools ensured accurate computations and high-quality visual outputs for this study. For reproducibility, all analysis scripts and supplementary code have been provided in the Appendix. For more information on the software and packages used:

- R Software: https://www.r-project.org/
- circular package: https://cran.r-project.org/web/packages/circular/index.html
- CircStats package: https://cran.r-project.org/web/packages/CircStats/index.html
- ggplot2 package: https://cran.r-project.org/web/packages/ggplot2/index.html
- dplyr package: https://cran.r-project.org/web/packages/dplyr/index.html

6. Results

This section presents the statistical analysis results from the termite mound orientation dataset. The analysis includes circular descriptive statistics, von Mises distribution fitting, Rayleigh tests for uniformity, and comparing concentration parameters across different sites. All the results are presented in detailed tables and plots for each of the 14 sites.

6.1. Summary of circular statistics and model fits

Table 2 provides the detailed summary statistics for each of the 14 sets, including the mean direction, circular variance, von Mises mean, concentration parameter κ, Rayleigh test statistic, and Rayleigh test p-value.

Table 2. Summary of circular descriptive statistics and von Mises model fits for each site.

Set	Mean Direction	Circular Variance	Von Mises κ	Rayleigh Statistic	Rayleigh p-value
Set 1	177.20	0.1174	4.56	0.8826	1.48×10^{-34}
Set 2	171.22	0.0401	12.72	0.9599	9.85×10^{-21}
Set 3	174.66	0.0292	17.37	0.9708	3.44×10^{-21}
Set 4	171.51	0.0297	17.10	0.9703	3.59×10^{-21}
Set 5	172.86	0.0346	14.71	0.9654	5.79×10^{-21}
Set 6	177.80	0.0199	25.40	0.9801	1.38×10^{-21}
Set 7	174.07	0.0431	11.86	0.9569	5.71×10^{-27}
Set 8	174.33	0.0573	9.00	0.9427	8.42×10^{-18}
Set 9	173.40	0.0414	12.33	0.9586	1.25×10^{-40}
Set 10	172.50	0.0127	39.69	0.9873	6.80×10^{-22}
Set 11	175.63	0.0145	34.71	0.9855	5.53×10^{-15}
Set 12	176.30	0.0412	12.41	0.9588	4.36×10^{-12}
Set 13	178.01	0.0203	24.90	0.9797	9.45×10^{-56}
Set 14	179.39	0.0247	20.47	0.9753	9.94×10^{-39}

Interpretation of results:

1) Mean direction: Most sets show mean directions in the range between 170°and 180°, indicating a consistent orientation preference of the termite mounds towards a similar direction. This alignment suggests that environmental factors may influence the orientation.
2) Circular variance: Circular variance ranges from 0.0127 in Set 10 to 0.1174 in Set 1, with lower variance values indicating tighter clustering of the mound orientations around the mean direction. Set 10, with the smallest variance, displays a very tight alignment of mound orientations.
3) Von Mises concentration parameter (κ): The concentration parameter κ, which measures how strongly the data is clustered around the mean direction, varies significantly across the sets. Set 10 has the highest concentration parameter (κ = 39.69), indicating a strong directional preference. In contrast, Set 8 shows a lower concentration (κ = 9.00), suggesting more dispersed orientations.
4) Rayleigh test for uniformity: The Rayleigh test statistic and corresponding *p*-values are provided for each set. The *p*-values are extremely small (all less than 10^{-12}), indicating that we can reject the null hypothesis that the orientations are uniformly distributed for every set. This suggests that termite mound orientations are not random but exhibit a preferred directionality.

6.2. Circular plots of orientation data

The circular distribution of mound orientations for each of the 14 sites is visualized using circular histograms. These histograms provide a visual representation of the angular distribution of termite mound orientations, where angles are plotted on a circular scale, and the frequency of each orientation is shown as bars extending outward from the center. **Figures 1**–**14** display the circular histograms for all sets (Set 1 to Set 14).

Interpretation of plots:

The circular histogram for Set 1 (**Figure 1**) indicates that the mound orientations are distributed across a broad range of angles but with some clustering around 177°. For Set 6 (**Figure 6**), we observe a much tighter concentration around the mean direction of 178°, consistent with the high concentration parameter $\kappa = 25.4$. Set 10 (**Figure 10**) exhibits the most tightly concentrated mound orientations, with a strong clustering around 172°. In contrast, Set 8 (**Figure 8**) shows a more dispersed distribution, reflecting its lower concentration parameter $\kappa = 9.00$. Most sets exhibit moderate to strong clustering around a specific mean direction, indicating that termite mounds tend to align in specific, preferred directions across sites.

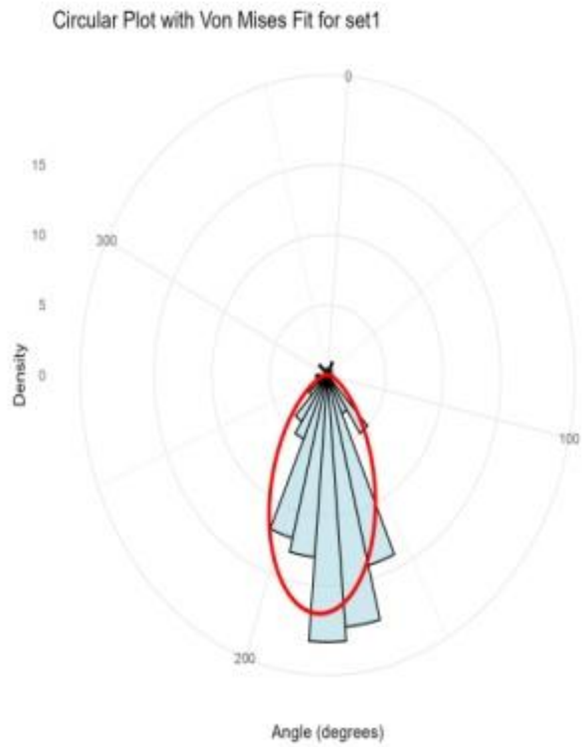

Figure 1. Circular histogram for Set 1.

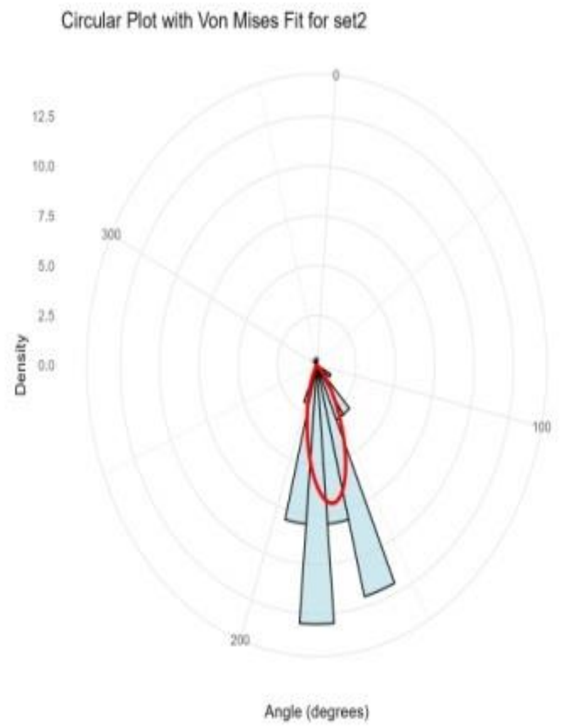

Figure 2. Circular histogram for Set 2.

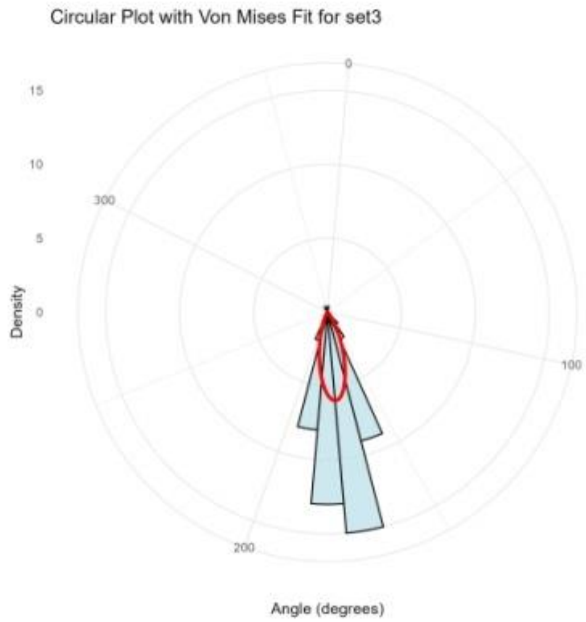

Figure 3. Circular histogram for Set 3.

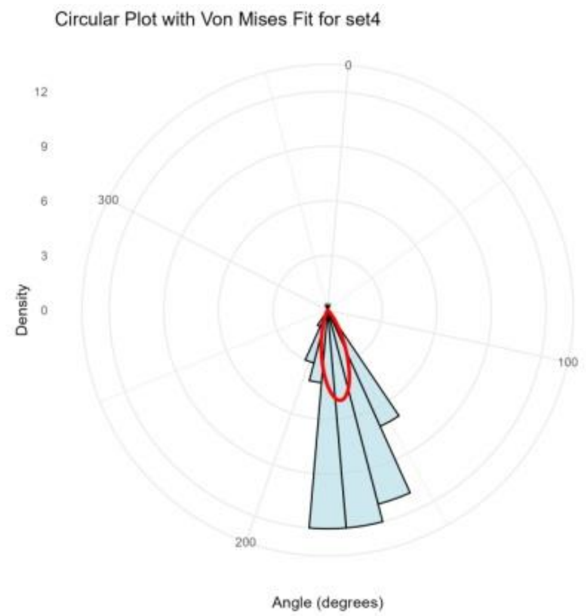

Figure 4. Circular histogram for Set 4.

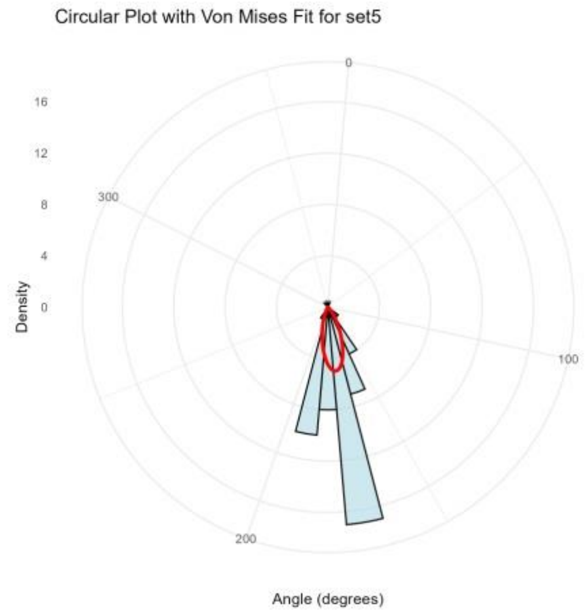

Figure 5. Circular histogram for Set 5.

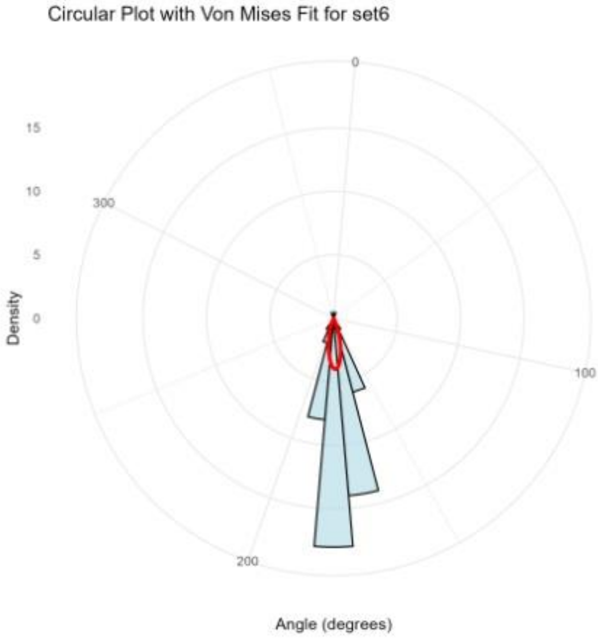

Figure 6. Circular histogram for Set 6.

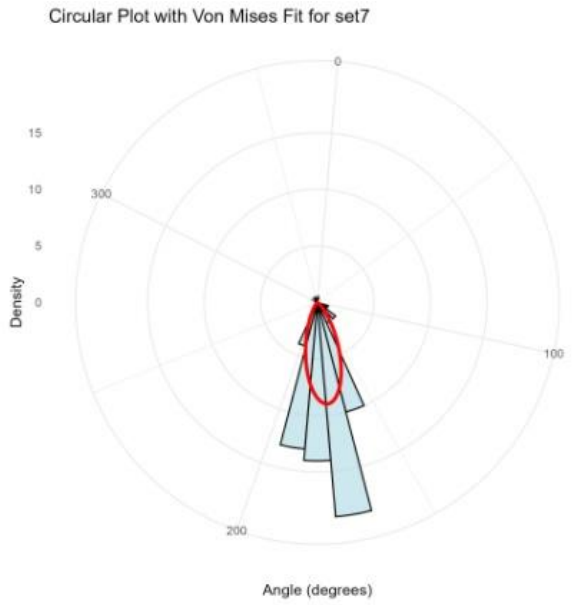

Figure 7. Circular histogram for Set 7.

Figure 8. Circular histogram for Set 8.

Circular histograms for mound orientations at all 14 sites (Part 1: Set 1 to Set 8). Each histogram represents the distribution of mound orientations in degrees.

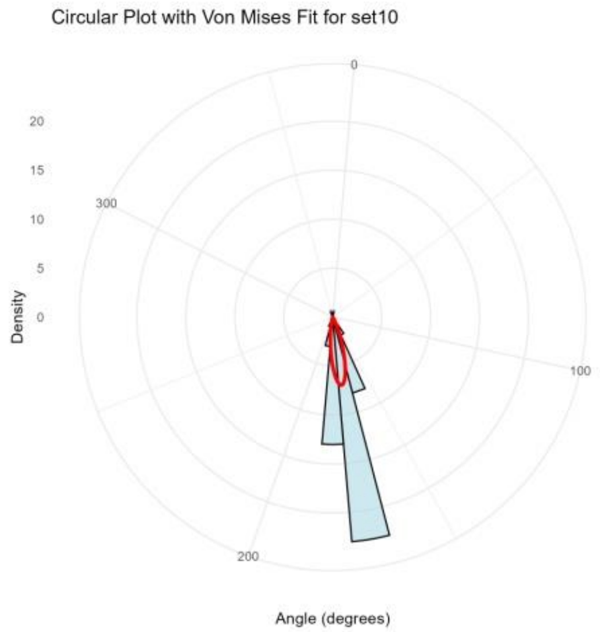

Figure 9. Circular histogram for Set 9.

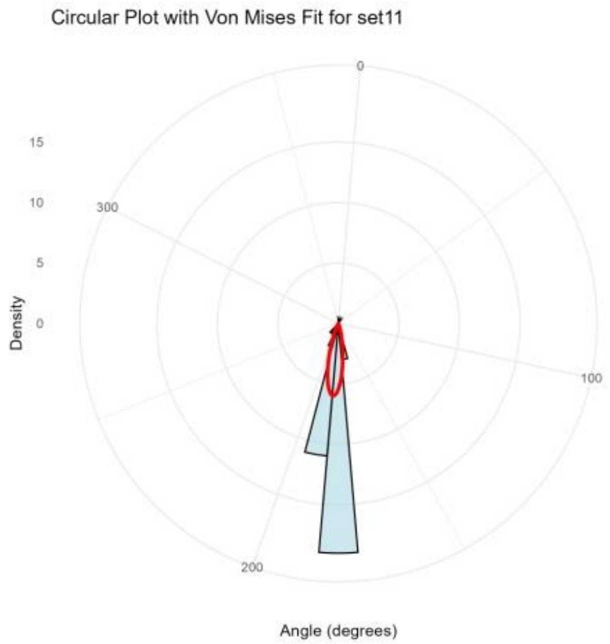

Figure 10. Circular histogram for Set 10.

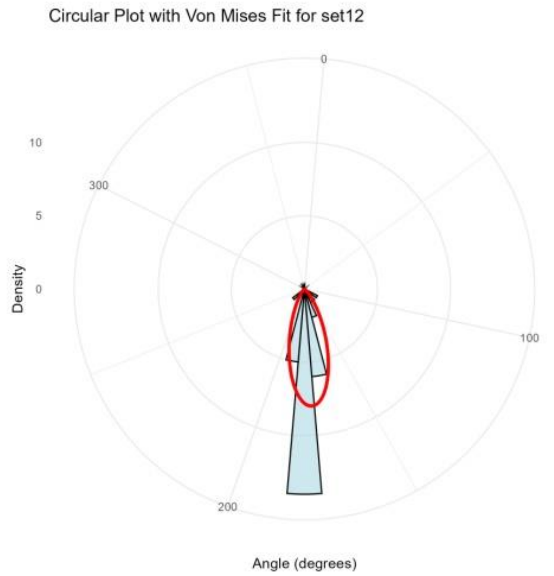

Figure 11. Circular histogram for Set 11.

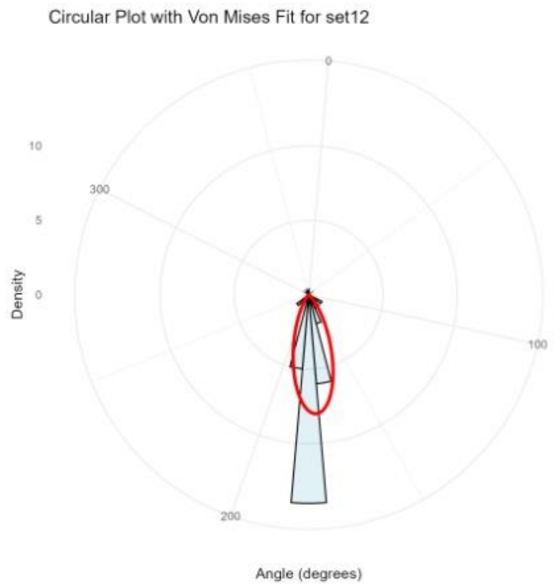

Figure 12. Circular histogram for Set 12.

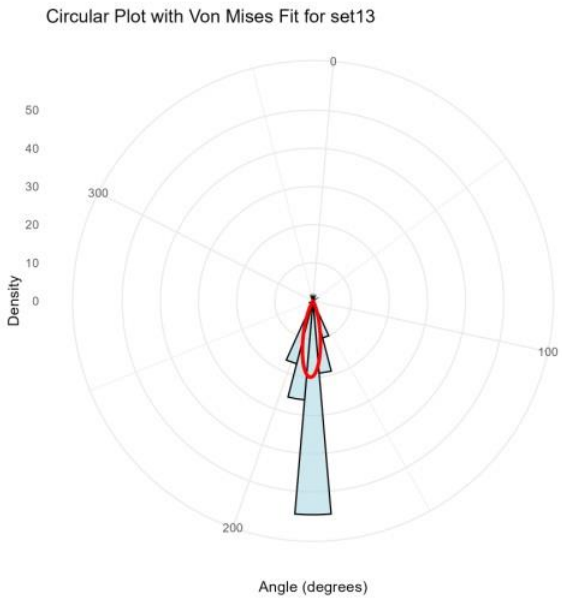

Figure 13. Circular histogram for Set 13.

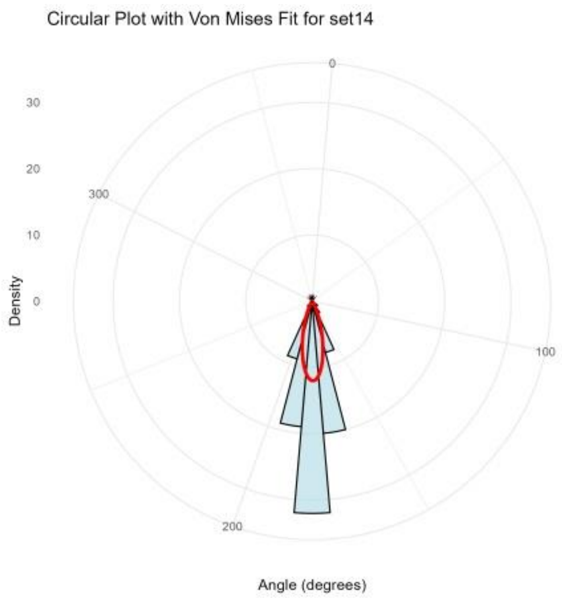

Figure 14. Circular histogram for Set 14.

Circular histograms for mound orientations at all 14 sites (Part 2: Set 8 to Set 14). Each histogram represents the distribution of mound orientations in degrees.

6.3. Comparison of von Mises concentration parameter

Figure 15 illustrates the comparison of the concentration parameter κ for all 14 sets. The concentration parameter indicates the strength of clustering around the mean direction.

Interpretation of the κ comparison:

As seen in **Figure 15**, Set 10 has the highest concentration parameter $\kappa = 39.7$, suggesting that the mound orientations in this site are very tightly concentrated around the mean direction.

Set 8 has the lowest concentration parameter $\kappa = 9.00$, indicating a relatively more dispersed distribution of mound orientations than other sites. Most other sets exhibit moderate clustering, with concentration parameters between 10 and 30, indicating a fairly consistent orientation pattern across the sites.

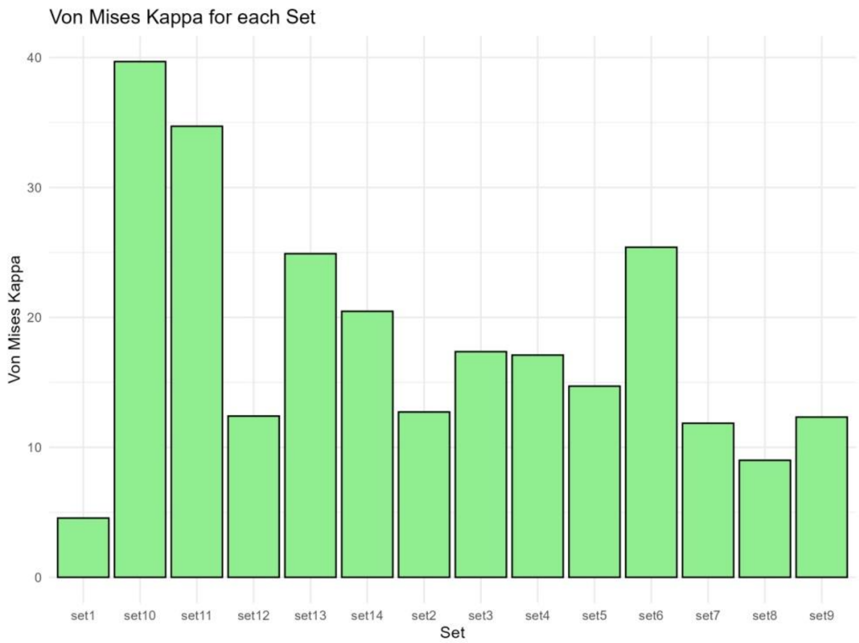

Figure 15. Comparison of von Mises concentration parameter (κ) across all sites.

7. Discussion

Understanding termite mound orientation is essential beyond the specific study area as it offers valuable insights into the adaptive strategies of termites in response to diverse environmental conditions. Termite mounds act as ecological engineers, influencing soil fertility, promoting vegetation heterogeneity, and supporting overall ecosystem health. These structures create nutrient-rich microhabitats that enhance biodiversity by providing favorable conditions for plant and microbial communities.

Studying mound orientations across different geographic regions enables researchers to identify patterns that reflect termites' adaptive responses to local climatic factors, such as solar radiation, wind direction, and temperature gradients. These findings can inform broader ecological models to predict how environmental changes, including those driven by climate change, might impact termite behavior and the ecosystems they sustain.

Moreover, termite mounds play a critical role in carbon and nutrient cycling, highlighting their importance in ecosystem resilience under changing climatic conditions [9,15]. By investigating these adaptations on a global scale, researchers can contribute to ecological conservation efforts, ensuring the preservation of ecosystems that depend on termite activity.

The results from this study indicate a clear, non-random orientation of termite mounds across the 14 sites, supporting the hypothesis that mound directionality is influenced by environmental factors such as solar radiation, wind direction, or soil composition. The concentration parameters κ derived from the von Mises distribution further indicate varying degrees of alignment at different sites, with some sites exhibiting more tightly clustered orientations. The concentration coefficient κ represents the variance in the orientation of mounds within each set around their mean direction. It ranges from 5 to 40, signifying that some colonies construct their mounds with tightly constrained orientations, while others exhibit greater variability. This variability can also be viewed as a result of localized influences.

The significant results from the Rayleigh test for all sites reject the null hypothesis of uniformity, providing statistical evidence that termite mound orientations are not randomly distributed. This aligns with previous studies [16], which hypothesized environmental influences on mound construction. Our results corroborate these findings, providing new statistical insights using circular data analysis techniques.

The Watson-Williams test, which compares the mean orientations of termite mounds across sites, revealed significant variations, suggesting that environmental pressures unique to each site influence mound construction behavior. Factors such as localized microclimates, prevailing wind patterns, or geographic features may contribute to these differences. The findings emphasize that regional ecological factors predominantly shape the spatial orientation of termite mounds, while also highlighting the importance of distinguishing between local and regional influences.

Implications for conservation and ecological management

The findings of this study have significant implications for conservation efforts and ecological management practices. Termites are recognized as keystone species due to their role in ecosystem engineering, influencing soil properties, vegetation patterns, and biodiversity. Our research provides valuable insights that can inform habitat preservation and restoration strategies by identifying the environmental factors that drive termite mound orientation. Understanding how termite mounds contribute to soil aeration, nutrient cycling, and moisture retention can guide conservationists in protecting these ecosystems, particularly in regions facing environmental degradation.

Moreover, termite mound orientations reflect adaptive responses to local climatic conditions, making them potential bioindicators for monitoring environmental changes. Conservation practices can leverage this knowledge to assess the health and resilience of ecosystems under stress from climate change or human activities. Our findings also emphasize the importance of maintaining termite habitats to ensure the persistence of their ecological functions, which are critical for sustaining biodiversity. From an ecological management perspective, recognizing the link between termite activity and soil fertility provides actionable insights for land management and agriculture. Preserving termite populations can enhance vegetation productivity and ecosystem resilience, contributing to sustainable development goals related to climate action and life on land [13]. These findings demonstrate the broader applicability of circular statistical methods in ecological research, offering a robust framework for understanding and managing the complex dynamics of ecosystems.

For further reference on conservation strategies and ecosystem functions, refer to the United Nations Sustainable Development Goals: https://sdgs.un.org/goals. The non-uniformity in mound orientations observed in this study could have practical implications for understanding termite behavior and adaptation to environmental challenges. Termite mound orientation may serve to optimize internal temperature regulation or moisture retention, thereby influencing termite colony survival. This finding invites further investigation into the ecological benefits of such orientations and could also be useful in predicting termite colony distribution based on environmental factors.

8. Limitations

Despite the valuable insights provided by this study, several limitations should be acknowledged. First, the dataset is limited to 14 sites within a specific geographic region, which may not fully capture the variation in termite mound orientations across broader areas. Environmental factors influencing mound orientation, such as wind patterns or sunlight exposure, may differ significantly in other regions or climates.

Secondly, while circular statistics offer a robust framework for analyzing directional data, they do not account for temporal variations. The orientations of termite mounds might change over time due to seasonal shifts in environmental conditions, a factor not considered in this study. Furthermore, the environmental variables such as wind speed, solar radiation, and soil composition were not explicitly measured alongside the orientation data, limiting our ability to directly link the observed patterns to specific environmental drivers.

9. Conclusion

This study provides a comprehensive circular statistical analysis of termite mound orientations across 14 Northern Queensland, Australia sites [16]. We found evidence of non-random, clustered mound orientations by fitting von Mises distributions to the data and performing Rayleigh tests for uniformity. Most sites exhibited significant alignment of mound orientations toward specific mean directions, with some sites showing extremely tight clustering around the mean while others displayed more dispersed patterns. Our findings suggest that the orientations of termite mounds are influenced by consistent environmental factors, likely related to solar exposure or prevailing wind directions. The application of circular statistics has allowed for a more nuanced understanding of these orientation patterns than traditional linear methods could provide, offering valuable insights into the ecological adaptations of termite species. These results lay the groundwork for future investigations into the environmental drivers of termite mound alignment.

Author contributions: Conceptualization, SS and DC; methodology, SS and DC; software, SS and DC; validation, SS and DC; formal analysis, SS and DC; investigation, SS and DC; resources, SS and DC; data curation, SS and DC; writing—original draft preparation, SS and DC; writing—review and editing, SS and DC; visualization, SS and DC; supervision, SS and DC. All authors have read and agreed to the published version of the manuscript.

Code availability: The code for generating the results and figures in this paper is available for public access under a permissive open-source license. We have kept the code in a GitHub repository at: https://github.com/debashisdotchatterjee/A-Revisit-to-

Circular-Statistical-Analysis-of-the-Orientations-of-Termite-Mounds.We encourage readers to explore and adapt the code for their own research purposes. The repository may also contain additional details about the implementation and data processing steps not explicitly mentioned in the paper.

Conflict of interest: The authors declare no conflict of interest.

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