Termite Mounds: Bioinspired Examination of the Role of Material and Environment in Multifunctional Structural Forms

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Introduction: Nature as a Model of Sustainable Design

It can be argued that the advent of the modern curtain-wall building system created opportunities in advancing structural design by isolating the response of the structure from the building envelope. The other side of this argument is that the impact of the structural system on sustainability is limited by the lack of integration of the structure with other building systems, because integration in design is considered by proponents of green design such as Leadership in Energy and Environmental Design (LEED) to be a core principle of sustainable building design (USGBC 2017). By necessity, nature takes a fundamentally different approach. Many builders in nature are what historically would be considered master builders; through structural form alone, the builders create habitats that provide shelter, protection from predators, regulation of temperature and moisture, and gas exchange. Often argued to be the animal kingdom's champion master builders are termites; termite mounds have provided an example for decades of biologically built structures with integrated function using natural materials.

This paper provides an overview of how termites create, based on the scale of the builders, massive skyscrapers that provide both structural stability and environmental regulation. It looks fundamentally at how these biologically created habitats can be examined as structural forms and can potentially inform new paradigms in the future for integrated structural and mechanical design. A meta-analysis of published studies on mound-building termites establishes correlations between the primary form of the termite mound and traditional drivers of resulting structural form, namely loads and materials. Additonally, and analgous to culture affecting forms of human construction, termite species is tied to structural form. The paper shows that, similar to human-designed structures, selection and availability of materials are strong factors in the resulting structural shape. Termite species also plays a role. However, despite the mechanical regulation provided by the mounds, environmental loads have less to do with the primary topology and more to do with the scale of the resulting mound shape. Because published data reporting internal topology of mounds is quite limited, this meta-analysis considers the categorization of external mound shape only. The study is based on analysis of over 70 termite mounds for which there were published data. The database of mounds is available online (Claggett et al. 2017).

Biomimicry in Structural Design

Obtaining inspiration from biological and natural systems, or biomimicry, has been successfully used in engineering and science to develop both new technology and new paradigms in design. Lessons from nature have been used in multiple engineering disciplines to develop solutions to problems, but application to structural engineering has been somewhat slower to take hold. Chen et al. (2014) and Waggoner and Kestner (2010) provided background on and insight into how biomimicry is applicable to structural engineering by examining coral reefs and cell growth patterns, respectively. Biomimicry is also applicable to analysis and material development; for example, Mattheck and Burkhardt (1990) used tree growth as a model for topology optimization (Mattheck and Burkhardt 1990), and Wegst et al. (2015) provided an overview of structural materials inspired by nature.

The complex topology of termite mounds has been studied with respect to their applicability to multiple domains. For example, Perna et al. (2008b) considered the topological efficiency of organically determined termite mound galleries as transportation networks compared with random and planned networks. Guo et al. (2011) used a termite mound analogy in mapping complex fracture systems. However, the most-studied aspect of the mounds with potential application to human habitation is the manner in which the mound construction creates natural ventilation (e.g., Turner 2001; Korb 2003; Abou-Houly 2010; King et al. 2015). The construction and resulting natural ventilation of termite mounds directly ties to biomimetic principles described by Tsui (1999), including the use of local materials, the enhancement of air circulation, and energy efficiency without an external supply of power.

Termites are one of nature's most accomplished structural engineers. Mounds built by termites rank among some of the largest

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Fig. 1. Approximately 6-m-high mound constructed by approximately 1-cm-long builders of *Macrotermes michaelseni* in Otjiwarango, Namibia. (Image by Andrea Surovek.)

and most complex structures built by any creature in the animal kingdom. Relative to the size of their builders, the construction of these mounds has been likened to humans creating mountains (Harris 1956). These mounds can be incredibly diverse, ranging from small, simple domes to the tall conical mounds of *Macrotermes michaelseni* in Namibia (Fig. 1) and ornate cathedral-shaped mounds, such as those produced by the termite *Odotermes obsesus* in India.

The motivation to create mounds is very similar to our own species' tendency to create buildings: survival from elements and physical threats. Like humans, termites are not particularly well-adapted to survival without some form of shelter. Termites lack the thick layer of chitin that protects most other insects from desiccation and extreme temperature fluctuations just as humans lack the thick fur and biological adaptations of animals that survive harsh environments (Bignell et al. 2011). Despite these limitations, both humans and termites have become ubiquitous creatures on the planet.

Termites live on every continent except Antarctica. Globally they can be found in a range approximately between the 45° N and 45° S parallels, roughly coinciding with the 10°C mean annual temperature isotherm (Emerson 1955), commonly referred to as the tree line. Mound-building termite species are particularly abundant in the tropical regions of Africa, South Asia, Indonesia, Australia, and South America. Although most mound builders are found in warm environments, some species, such as *Macrotermes natalensis*, can be tolerant of cold as well (Gay and Wetherly 1970), and mound-building termites are abundant in both arid and wet climates, despite their vulnerability to dry conditions (Bignell et al. 2011).

Termites' abilities to thrive in regions of the world that would otherwise be inhospitable arises from their ability to manipulate their environment to form habitats, primarily in the form of mounds. These mounds have been shown to promote the survival of the colony by efficiently managing environmental characteristics, including temperature and humidity, while providing mechanisms for gas exchange (Korb and Linsenmair 1999; Turner 2001, 2006). To provide context on the need for gas exchange, Turner (2005) reported that a typical *Macrotermes* colony with approximately one million workers requires oxygen at the rate of a large mammal such as a goat or a cow.

Along with shelter from the environment, human habitats require structural stability, thermal and moisture regulation, and ventilation; however, unlike natural habitats, human-built structures primarily rely on separately designed load-bearing and mechanical systems to provide these functions. They also rely on external energy sources driving mechanical systems to achieve the same internal regulation provided naturally in termite mounds.

By describing and categorizing some of the solutions that termites have developed over millions of years of evolution, this paper proposes that the study of natural habitats can substantively inform the field of structural engineering. In particular, termite mounds present a model of sustainability through both integrated structural and mechanical functions and efficient use of local materials in construction of superstructures.

Mound Form and Function

The structural forms of termite mounds provide multiple functions, such as protection from predators and storage of food material; however, an integral function of an epigeal (aboveground) mound is to provide a homeostatic environment for the nest. The internal and external topologies of the mound's structure facilitate the necessary mechanical functions. This approach is quite different from modern structural design in which the structural forms on which humans rely the most, (e.g., beams, columns, trusses, and walls) are generally not well suited to adjusting the internal environment of the building, and are typically designed to be isolated from the systems that make a building habitable. As described by Turner and Soar (2008)

> In most building designs, walls are erected as barriers to isolate spaces: internal spaces from the outside world, internal spaces from one another and so forth. Yet spaces, if they are to be occupied and used, cannot be isolated. Resolving this paradox is what forces building designs to include infrastructure—windows, fans, ducts, air conditioning, heating etc.—all essentially to undo what the erection of the walls did in the first place.

The rest of this section provides some specific examples of termite mounds found across the world that adapt structural form to their local conditions. These cases demonstrate that topology of the mound structure is not wholly dependent on genetic characteristics of the builders, but is influenced by local availability of materials and adaptation to climate.

Temperature is one of the most significant environmental characteristics which can place strain on the survival of an organism. Regulating the temperature of buildings to make them suitable for human comfort accounts for about 48% of US energy use in residential buildings and 36% in commercial buildings (US EIA 2009, 2012). In contrast, termites achieve the same end result with only their mound's structure.

In colonies of *Macrotermes bellicosus* in Côte d'Ivoire, termite mounds were observed in two nearby environments with different average temperatures: a shaded tropical monsoonal forest and an open savannah. Under the hotter conditions of the savannah, the termites were observed to create complex mound structures with thin walls and a large surface area exposed to the outside. Only a few kilometers away, termites mounds in shade generally had a simpler, dome shape. The dome mounds had thicker walls and less surface area, which were shown to have an effect on the mound temperature, providing insulation and reducing heat loss (Korb 2003). As described subsequently in this paper, the soil conditions also varied across these two microclimates.

Similarly, a species of termite in Kenya, *Pseudacanthotermes spiniger*, appears to regulate the temperature of their nests as well, but through an entirely different mechanism. Biologists noted that termites that lived in hotter areas constructed mounds which were often twice as tall as those in colder conditions, despite similarities in species and geographic location (Kooyman and Onck 1987). The termites also placed the inhabited portions of their nests low within the mound, or even underneath it, whereas termites in colder environments often lived entirely in the aboveground portion of the mound.

A significant challenge which both humans and termites face is the impact of water on both form and function. In human-designed buildings, this function is not generally related to the structural system, unlike in termite mounds. The interiors of some mounds have a significant clay fraction, regardless of the composition of the mound skins. Clay can store high volumes of water and is less permeable than sand, allowing it to efficiently maintain higher levels of humidity within the nest (Jouquet et al. 2004). In addition, mounds built by *Coptotermes brunneus* have been shown to include impermeable clay collecting cups to store water that has condensed on the inside walls of the mound for later reuse (Aspenberg-Traun and Perry 1998).

Termites have developed multiple mechanisms by which they can prevent erosion from water. Termites of the genus *Cubitermes* are known for building mounds across Central Africa with a distinctive mushroomlike shape (Fig. 2). In addition to their shape, these mounds have fingerlike tendrils on the edge of their upper surface which shed excess water even more effectively (Emerson 1938). Arboreal termites in South America build mounds with a similar need, but manage to prevent erosion by building small diversion structures which redirect water away from the mound (Emerson 1938). In areas prone to flooding, termites have been observed to build taller mounds with aboveground nests (Wango and Josens 2011).

Fig. 2. Mushroom mound in Congo. (Image © Lucy Keith-Diagne, reprinted with permission.)

Meta-Analysis of Mound Structures

It has been suggested that the form of a termite mound is dependent on some combination of the following three components; material, climate, and behavior (Harris 1956). The same observation is largely true for the form of human-built structures as well. Although literature on nest construction and ecological impact is extensive, literature related to mound structures is significantly less prevalent. Based on the literature review, it can be argued that the reasons may be that the resulting structural topology is more interesting to architects and engineers than to biologists and ecologists, who are more focused on behavior and ecological impacts.

The diversity of termite mounds makes large-scale comparisons of termite mounds across species and regions extremely challenging. As a result, no substantive effort has been made to holistically discuss the relationship between environmental conditions and the structural form of mounds; any conclusions that have been drawn have been over a limited georgraphic region or limited to a single species (e.g., Korb 2003; Jouquet et al. 2015). The only known online reference available that covers multiple geometric areas is devoted to nest structures (Mesomorph 2017).

This research begins an effort to develop a database from the diverse field of published information on termites to allow for holistic consideration of termite construction and the resulting mound shapes. The information has been collected and stored in an online database (Claggett et al. 2017); the long-term goal is to allow continuous updating by researchers and the scientific community to inform a larger understanding of termites and habitat construction. This paper presents a meta-analysis based on this database that considers 71 mounds built by dozens of termite species across four continents.

Termite Mound Shape Classes

With more than 2,500 species of termites in existence with different geographic distributions, feeding habits, and nesting strategies, it seems that there are as many types of termite mounds as there are species that build them. However, common configurations have emerged across species; a single species may build more than one type of mound, and multiple species may build similarly shaped mounds.

This study grouped mounds into five primary shape classes (Figs. 3–5):

- Conical mounds, distinguished by a height:width ratio typically greater than 3, a strong conical shape, and a discernable peak at the top of the mound (Figs. 1 and 3);
- Dome mounds, which are similar to conical mounds but with less-defined shapes, lower height:width ratios, and more-rounded mound tops (Fig. 4);
- Cathedral mounds, featuring complex forms, buttresses, and multiple peaks [Figs. 5(a and b)];
- Meridian (or compass) mounds, found in Northern Australia, featuring a specific geographic orientation and bilateral (rather than circular) geometries; and
- Mushroom mounds, with distinctive stem and mushroom cap–type appearance (Fig. 2).

These labels are commonly used descriptors in the literature on termites and mounds.

Fig. 3. Example of conical mound outside Otjiwarongo, Namibia. (Image by Andrea Surovek.)

Fig. 4. Example of dome mound in Agombe, India. (Image by P. Bardunias, with permission.)

Conical and dome mounds may be difficult to distinguish because many mounds often display properties of both, may be described as subconical in the field by biologists, and immature mounds of either shape class may be relatively undistinguishable. Because of these complications, the cone shape class was subdivided based on size and a subjective estimate of how strongly the mounds exhibited a conical appearance.

Despite the commonality of the labels in the literature, not all termite mounds can be represented using these class descriptors. Among those that were omitted from the study are small mounds of primitive termite species; mounds that do not develop any significant structural features; pavement mounds, which are predominantly flat; and arboreal termite mounds.

Methodology and Data Collection

In order to determine relationships between termite mound shapes, local soil and local climate data were collected on several environmental variables, including the soil composition, temperature, and rainfall. Relatively few works on termite mounds provide detailed discussion of these environmental properties, and what little information is available is often inconsistent and/or incomplete. Conveniently, it is standard practice within the scientific community researching termites to provide coordinates for the sampling locations and testing sites. Supplemental data on climate and local soils were obtained from geographic information system (GIS) data using these coordinates. Although information from the literature was used preferentially, the use of soil and climate databases made it possible to obtain local environmental data for the rest of the samples.

The soil composition at each mound site was defined by percentages of sand, silt, and clay contents at the site. The database of mounds considers both mound composition and site composition when those data were available; correlations are based on site conditions as a means to examine the effects of local material availability on the resulting shape.

Temperature has often been shown to have a considerable impact on the activity of termites and has been used to describe the impetus for the variable structure often seen in termite mounds (Korb 2011). Termites function best within a range of acceptable temperatures, especially termites which cultivate fungus as a food source (Bignell et al. 2011). Mean annual temperature was collected, as well as the minimum and maximum mean monthly temperatures representing the extremes for which each species would have to design. Annual precipitation data and wettest-quarter data were collected because mound differences have been attributed to their locations in arid or wet environments. These data were provided by the 30-arcsecond 1950–2000 temperature and precipitation data set compiled by Hijmans et al. (2005).

Additionally, to represent the local ecological biomes of the various sites, the study leveraged the classical Köppen (1918, 1936) climate regimes by which regional climates over the globe are partitioned into their seasonal temperatures and precipitation as well as their net local water deficit to produce climate zones that correspond to recognizable biomes such as rainforest, savannah, steppe, desert, and subtropical landscapes. This study used a Köppen-Geiger global climate region analysis produced by Peel et al. (2007). The analysis was generated using the Peterson and Vose (1997) Global Historical Climatology Network (GHCN) version 2.0 data set resampled from monthly temperature and precipitation observations over the full period of each available point station to a 0.1° grid-spaced global analysis.

Mounds as Response to Soil Condition

The soil conditions observed through GIS suggest that there is a correlation between three of the shapes considered and the soil. Fig. 6 presents a box-whisker plot indicating the interquartile range, median, and extreme values of clay and sand content for each of the shape classes. The mushroom, cathedral, and meridian mounds each appeared to be partially dependent on the sand and clay contents of the soil. Although the differences may not be large, there is a preference among the termites to build their mounds in areas which better fit the final soil characteristics of the mound.

(a) (b)

Fig. 5. (a) Emerging and (b) mature cathedral mounds in Bangalore, India. (Images by Andrea Surovek.)

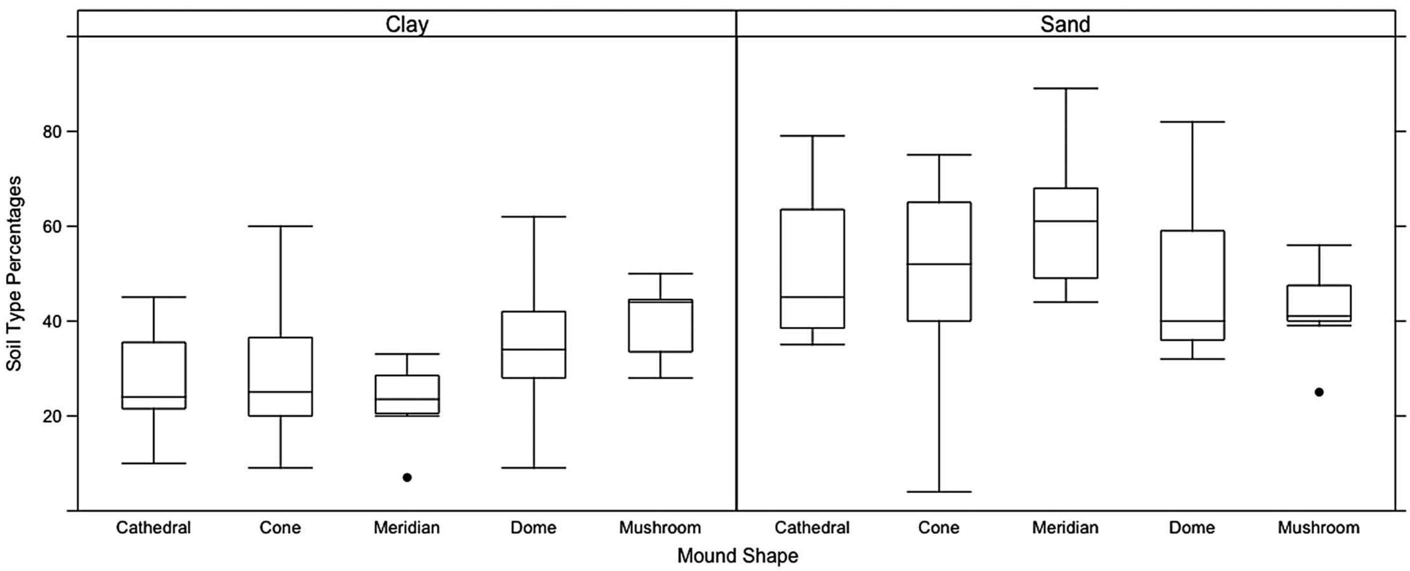

Fig. 6. Distributions of sand and clay contents for mound shapes: interquartile range (box), median (thick horizontal line), 1.5 times interquartile range or maximum/minimum value, and outliers beyond 1.5 times interquartile range (solid circle).

For example, mushroom mounds seem to preferentially appear in locations that have the highest amounts of clay, which closely matches the final composition of the mounds, whereas cathedral and meridian mounds show the opposite trend, appearing to be more abundant in areas with lower clay contents and higher sand. The data shown represent 71 mounds total mounds, including 24 cone, 21 dome, 11 cathedral, 8 meridian, and 7 mushroom mounds. Because some geographic areas are well represented in termite literature and other areas are not, mounds were selected that came from distinct locations, so that several reported termite mounds from different sources but from one location did not skew the data in favor of a single soil condition. Because of the limited geographical range of some of these mound shapes, i.e., meridian and mushroom, this meant that available data were limited compared with data for cone and cathedral mounds.

Mushroom mounds are typically constructed of fine-grained soil particles, predominantly built in soils richer in clay. Mounds of the genus *Cubitermes* demonstrate why this might be the case. The interiors of these mushroom mounds are made up of small, thin-walled chambers that likely benefit from the cohesion and small diameter of clay particles (Perna et al. 2008a). The caps that cover the mounds and give them their distinctive shape may also require strong cohesion among particles to prevent deterioration from rain, wind, and internal stresses.

Cathedral and meridian mounds are typically much taller than mushroom mounds and tend to have a high percentage of sand in their construction. This may improve the porosity of the structure and facilitate permeability of gases through the often thick exterior walls that surround the hive. Sand provides significantly more bearing strength and is more volumetrically stable, especially under varying water conditions. This is significant, because cathedral and meridian mounds are often among the most massive of termite mounds (Korb 2011).

In the remaining two mound shapes, cones and domes, the potential relationship between soil particle size and structure is less clear. Both of these shapes are highly variable in sand and clay

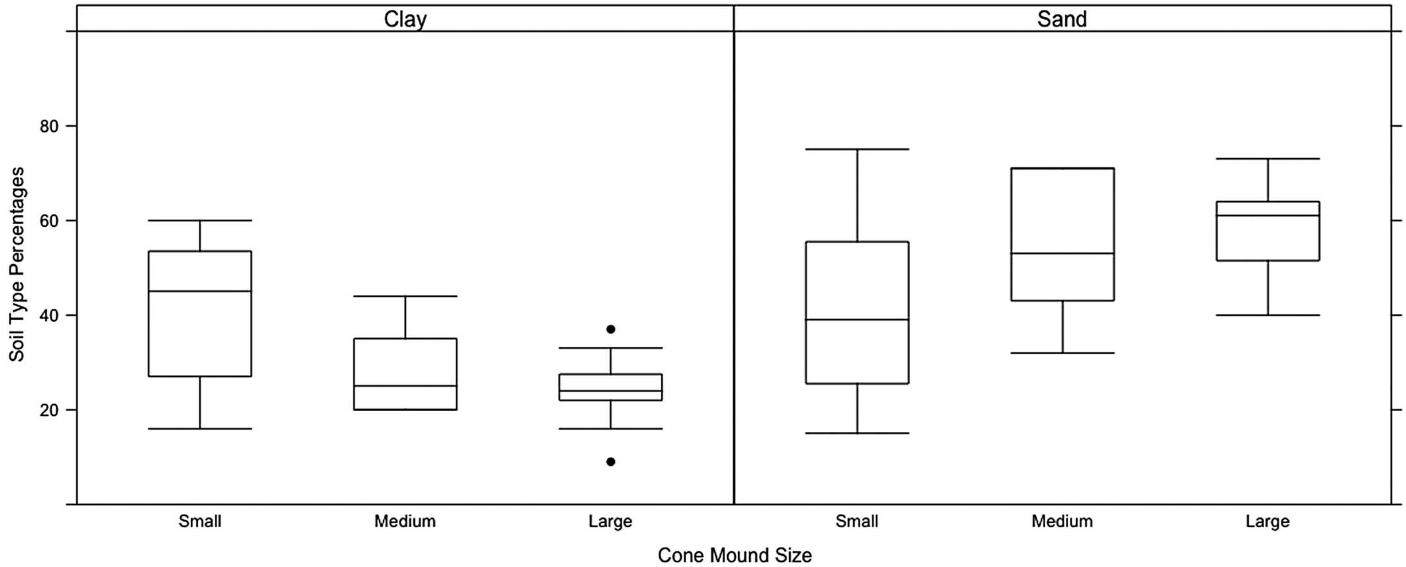

Fig. 7. Sand and clay content correlated with size and shape of conical mounds; small <0.5 m height and large >1.5 m in height.

composition between mounds of different species and locations. When considered as a whole, there is a slight affinity among cone mounds toward regions with higher sand content and lower clay, but it is relatively weak. The inverse may to be true for domes, although the relationship seems to be even weaker. Dome-shaped and cone-shaped mounds are very common throughout the world, and may be suitable shapes for survival in a variety of different soil conditions, requiring less-specific soil properties than the other shapes.

Conical mounds proved to have the most obvious diversity among their shapes, varying widely in size and in how much they subjectively looked like cones; conicality is generally determined by height:width ratio and linearity of the side angles of the mound. As cones became taller, and as they began to display a more distinctly conical appearance, more pointed and less rounded, they tended to be located in soils with higher sand and lower clay contents, similar to the cathedral and meridian mounds (Fig. 7).

Mounds as Response to Climate

Despite the common assertion that climate has a strong influence on termite construction, and the specific instances described previously which implied a strong relationship between climate and structure, the data collected in this study do not imply a significant correlation between differences in temperature or rainfall and the mound shape class.

Despite a wide range of variability in rainfall among the mounds observed, on average the shapes were not tied to differences in mean annual rainfall (Fig. 8). As is often asserted due to their appearance, the mushroom-shaped mounds correlated with the highest mean rainfall, but mounds of other shapes were also found to experience as much or more rainfall. Seasonally, the compass mounds experienced high rainfall, but this result is biased by their limited geographic distribution. The cone and dome mounds had very high deviation within their samples for mean and season rainfall.

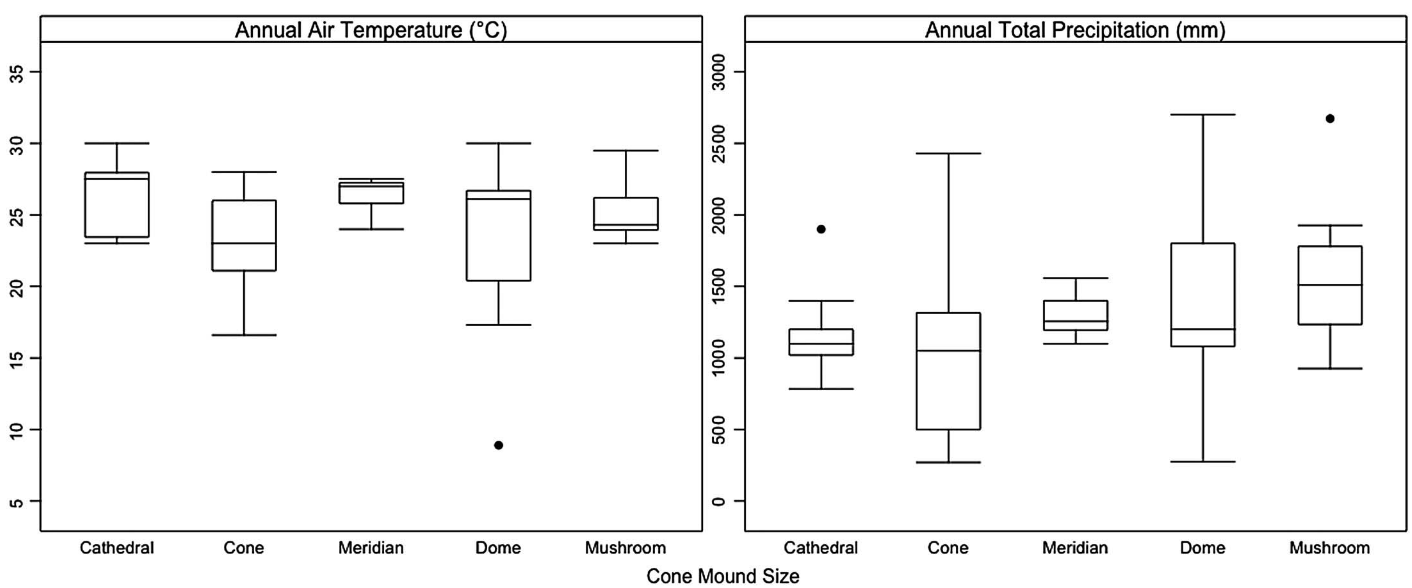

Fig. 8. Impact of annual air temperature and precipitation on shape class.

Temperature seems to have somewhat more significance than rainfall. Mounds of the meridian and cathedral shapes tend to be located in areas with higher mean temperatures in the warmest month; however, no such relationship seems obvious for the mean temperature of the coldest month. The geographic distribution of mound-building termites does not include areas prone to freezing temperatures, so adaptability to extremes is limited to high temperature ranges.

Although temperature and rainfall may influence the mound-building behavior of termites, it is likely that they have a more profound impact on aspects of the mound other than the shape. For example, the mounds of *Pseudacanthotermes spiniger* in Kenya maintain the same archetypal shape, that of a cone, but experience dimensional changes as a result of the temperature of their environment (Kooyman and Onck 1987).

Much of the literature on termite mounds points to climate as the primary factor affecting the form of the termite mound. Only recently, Jouquet et al. (2015) suggested that mound shape complexity was impacted more by soil properties than by climate influences. This meta-analysis suggests that, although climate is correlated with the size of mounds, available soil types may have a stronger influence on the resulting mound shape.

Implications, Limitations, and Conclusions

Although the structural forms of termite mounds may not be readily suitable for human buildings as they are found in nature, the termites' adaptations of the structural form to suit conditions may be informative in considering new paradigms in integrated structural forms that consider highly localized environmental effects. The most noted example of termite mounds as a design inspiration is the Eastgate Centre in Harare, Zimbabwe (Fig. 9) designed by architect Mick Pearce (2018). The Eastgate Centre is able to operate without the need for traditional air conditioning through the incorporation of an efficient system of ventilation and thermal regulation that was based on the prevailing theory of the termite mound function at the time of construction. The design uses large fans that force cool air through the structure at night when ambient temperatures are lower, dissipating the heat collected during the day in the form of warm air which escapes through large chimneys. The building, like termite mounds, encourages the movement of hot air through the difference in density between hot and cool air. It is also similar to mounds in that the high thermal capacity of the materials used in its construction maintains a more constant temperature throughout the day (Dahl 2013). Although current theories on termite mound ventilation suggest that the Eastgate Centre may not ventilate in the same fashion as termite mounds (Turner and Soar 2008), taking inspiration from termite mounds to develop a structure that is integrated with the mechanical function and uses approximately 10% of the energy of a similar-sized building in the region suggests that sustainable design can be informed by considering natural examples.

Fig. 9. Eastgate Centre, Harare, Zimbabwe. (Reprinted from Pearce 2018, with permission.)

Studying the ability of termites to regulate their environment through the topology of the load-bearing structure can be a starting point for structural engineers to learn new paradigms for sustainable design. Lessons may also be learned from termites in how they adjust construction to their local environment and their ability to efficiently and adaptively use local materials.

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