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Beyond biomimicry: What termites can tell us about realizing the living building.

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Abstract. Termites and the structures they build have been used as exemplars of biomimetic designs for climate control in buildings, like Zimbabwe's Eastgate Centre, and various other "termite-inspired" buildings. Remarkably, these designs are based upon an erroneous conception of how termite mounds actually work. In this article, we review recent progress in the structure and function of termite mounds, and outline new biomimetic building designs that could arise from this better understanding. We also suggest that the termite "extended organism" provides a model to take architecture "beyond biomimicry"—from buildings that merely imitate life to buildings that are, in a sense, alive.

Keywords: biomimicry, termite, Eastgate Centre, *Macrotermes*, termite mound, gas exchange, temperature regulation, homeostasis, rapid manufacturing, free-form construction, extended organism

1 The Eastgate Centre. A biomimicry watershed

Harare's Eastgate Centre, which opened in 1996, deservedly stands as an iconic biomimetic building (Figure 1). Mick Pearce, the project's lead architect, wanted the building to reflect two tenets of his philosophy of "tropical architecture"—first, that design principles developed in the temperate northern hemisphere are ill-suited to tropical climes like Zimbabwe's; and second, that effective design should draw inspiration from local nature [1].

Where Pearce drew *his* inspiration was from the remarkable mound-building termites of southern Africa (Figure 1). These creatures are themselves architects of sorts, building massive mounds that in some instances tower several meters high. The mound serves as climate-control infrastructure for the termite colony's subterranean nest. Pearce reasoned that the architectural principles of the termite mound, honed to sleek efficiency by the relentless refining of natural selection, could inspire buildings that perform equally well. By all measures, his vision succeeded brilliantly.

For the past several years, we have been studying the structure and function of the termite mounds that inspired Mick Pearce. In the process, we have learned many things, among them something quite remarkable: the Eastgate Centre is modeled on an erroneous conception of how termite mounds actually work. This is not intended to be a criticism, of course: Pearce was only following the prevailing ideas of the day, and the end result was a successful building anyway. But termite mounds turn out to be much more interesting in their function than had previously been imagined. We believe this betokens expansive possibilities for new "termite-inspired" building designs that go beyond Pearce's original vision: buildings that are not simply inspired by life—biomimetic buildings—but that are, in a sense, as alive as their inhabitants and the living nature in which they are embedded.

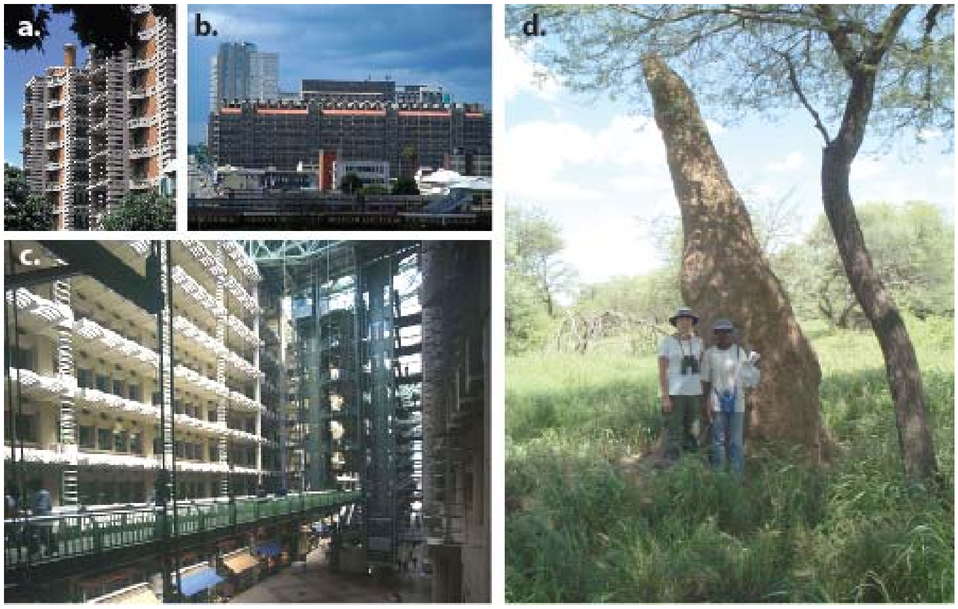

Fig. 1. The Eastgate Centre and a *Macrotermes* mound. a-b. The exterior of the Eastgate Centre, showing chimneys along the roof[1]. c. The interior atrium of the Eastgate Centre[2]. d. A mound of *Macrotermes michaelseni* in northern Namibia.

2 How the Eastgate Centre is like a termite mound

If Eastgate was inspired by termite mounds, what precisely about them was the inspiration? This is not as simple a question as it might seem. Termite mounds are structurally diverse—some are festooned with one or more large vents, others have no obvious openings to the outside, and shapes range from cones to pillars to hemispheres [2-6]. Most biologists believe this structural diversity betokens a diversity of function [7]. As we shall show, this turns out mostly to be incorrect. What makes Eastgate all the more remarkable is that it melds many of these diverse, and in some instances contradictory, design features into a single functional building.

The earliest model for termite mound function was Martin Lüscher's thermosiphon mechanism, in which the mound is a venue for metabolism-driven circulation of air [8]. Here, the colony's production of heat (roughly 100 watts) imparts sufficient buoyancy to the nest air to loft it up into the mound and to drive it eventually to the mound's porous surface. There, the spent air is refreshed as heat, water vapor and respiratory gases exchange with the atmosphere across the porous walls. The higher density of the refreshed air then forces it downward into open spaces below the nest and eventually through the nest again. This mechanism was thought to operate in mounds with capped chimneys, those that have no obvious vents.

[1] www.archpaper.com/features/2007_14_imitation.htm
[2] http://blog.miragestudio7.com/wpcontent/uploads2/2007/12/eastgate_centre_harare_zimbabwe_interior_mick_pearce.jpg

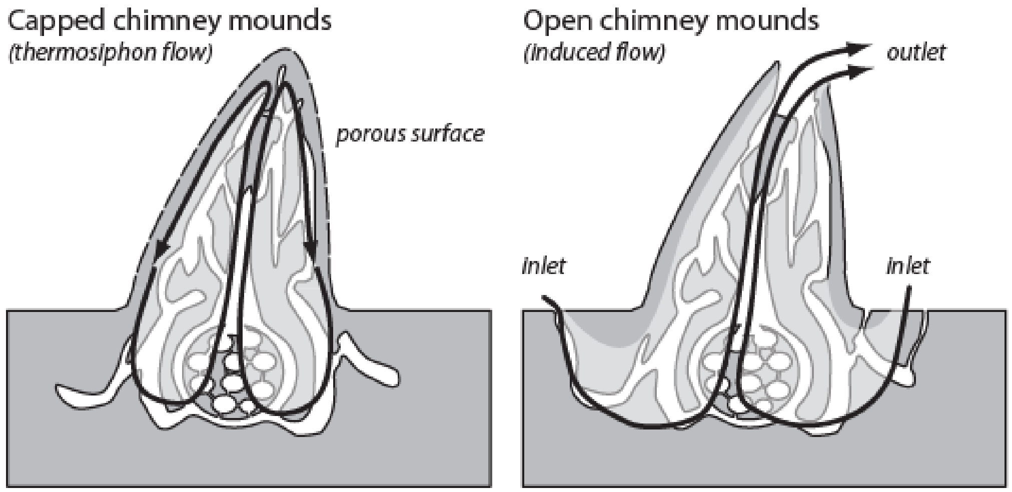

Fig. 2. Two early models for mound ventilation. Left. Thermosiphon flow thought to occur in capped chimney mounds. Right. Induced flow thought to occur in open-chimney mounds.

The second model is known to biologists as induced flow [9-11], but it is probably better known to architects and engineers as the stack effect. This mechanism was thought to occur in open-chimney mounds [12]. Because the mound extends upward through the surface boundary layer, the large chimney vent is exposed to higher wind velocities than are openings closer to the ground. A Venturi flow then draws fresh air into the mound through the ground-level openings, then through the nest and finally out through the chimney. Unlike the thermosiphon model's circulatory flow, induced flow is unidirectional.

The similarities between the Eastgate Centre and termite mounds now become clear. The induced flow principle is evident in the row of tall stacks that open into voluminous air spaces that permeate through the building (Figure 1). Meanwhile, heat from the building's occupants and machinery, along with stored heat in the building's thermal mass, helps drive a thermosiphon flow from offices and shops upward toward the rooftop stacks. In the climate of Harare, the combination provides for an impressive steadiness of interior temperature, accomplished without resorting to a costly and energy-hungry air-conditioning plant. This is where most of the building's efficiencies accrue.

3 How the Eastgate Centre is not like a termite mound

The design and function of the Eastgate Centre departs from termite mounds in some significant respects, however, and this makes for some interesting design anomalies.

One of the more interesting involves temperature regulation. In the architectural literature, discussions of the Eastgate Centre are often accompanied by encomia to the impressive thermoregulatory abilities of the mound building termites. A few quotes make the point:

> "The Eastgate building is modeled on the self-cooling mounds of *Macrotermes michaelseni*, termites that maintain the temperature inside their nest to within one degree of 31 °C, day and night … "[3]
>
> "Indeed, termites must live in a constant temperature of exactly 87 degrees (F) to survive."[4]
>
> "Termites farm fungus deep inside their mounds. To do so, the internal temperature must remain at a steady 87 degrees F." [5]
>
> "The fungus must be kept at exactly 87 degrees … "[6]

There is just one problem: there is no evidence that termites regulate nest temperature. Indeed, there is good evidence that they do not. In the subterranean nest of *Macrotermes michaelseni*, for example, while temperatures are strongly damped through the day, they also closely track deep soil temperatures through the year (Figure 3). Consequently, the annual march of temperature in the nest ranges from about 14°C in winter to more than

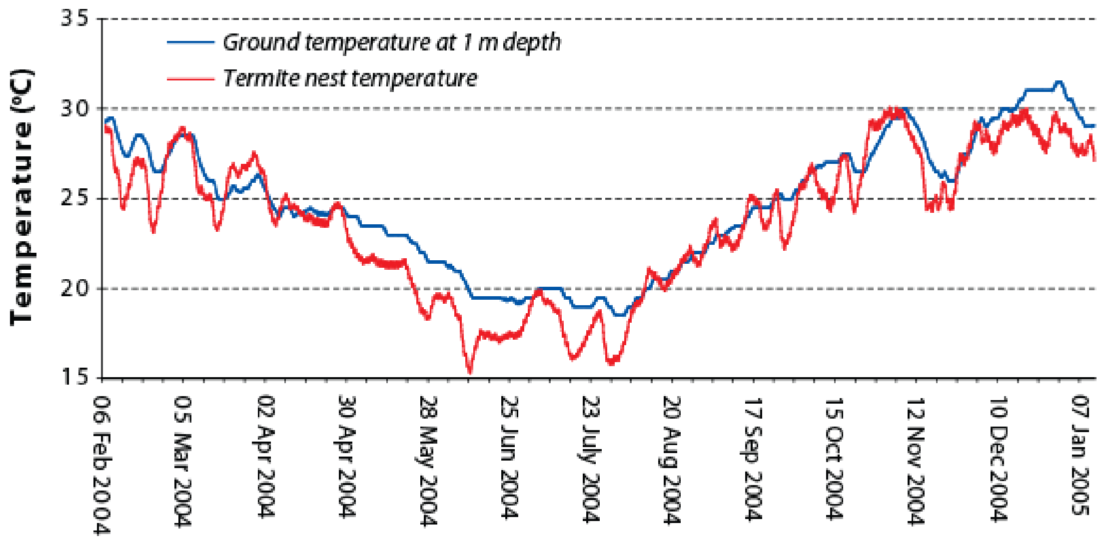

Fig. 3. The annual march of temperature in the nest of a *Macrotermes michaelseni* colony in northern Namibia. For comparison, ground temperature 15 m away and at 1 m depth is also plotted.

31°C in the summer, a span of nearly 17°C. Nor is there any evidence that mound ventilation affects nest temperature. In the nest of *Odontotermes transvaalensis*, which builds open-chimney mounds, eliminating ventilation altogether (by capping the open chimney) produces no discernible effect on nest temperature [13]. These observations have a straightforward explanation: nests are embedded in the capacious thermal sink of the deep soil, and the nest energy balance (and hence its temperature) is strongly driven by this large thermal capacity. This produces the nest's strongly damped temperatures, but the mound infrastructure and nest ventilation has virtually nothing to do with it.

[3] http://www.biomimicryinstitute.org/case-studies/case-studies/termite-inspired-air-conditioning.html
[4] http://www.aia.org/aiarchitect/thisweek03/tw0131/0131tw5bestpract_termite.htm
[5] http://database.biomimicry.org/item.php?table=product&id=1007
[6] http://www.zpluspartners.com/zblog/archive/2004_01_24_zblogarchive.html

This points to one of Eastgate's interesting design anomalies. Like termite mounds, Eastgate uses thermal capacity to damp temperature excursions through the day. Over the long term, however, damping is less effective, as is demonstrably the case in termite nests (Figure 3). To counter this, Eastgate makes clever use of a daily fan-driven ventilation cycle: low-capacity fans operate during the day, while high capacity fans operate at night. During Harare's typically warm days, the low volume turnover of air in the building facilitates heat storage in the building's fabric, keeping internal temperatures cool. During the typically cool nights, the high volume fans are deployed to extract stored heat from the building's high-thermal-capacity walls, essentially "emptying" them to receive a new load of heat the next day. Thus, even though Eastgate can dispense with an air conditioning plant, it still requires a forced-air plant to drive the required daily ventilation cycle. No termite colony does this.

Interaction with wind presents another interesting divergence between termite mounds and buildings like Eastgate. Wind has practical value as an energy source if it is predictable and reliable. Yet wind, by its very nature, is variable and unpredictable [14]. A building design that seeks to harness wind must therefore seek those aspects of the wind resource that maximize reliability. This is why it is common for buildings that tap wind energy to be designed around some variation on the induced flow principle: one of the most predictable features of natural winds is the vertical gradient in wind speed (and hence wind-borne kinetic energy) that comprises the surface boundary layer.

Termite mounds also exploit boundary layer winds, of course, but with some important differences. Natural winds are unreliable in large part because natural winds are nearly always turbulent winds. At a particular location, this means there is a high probability that the wind velocity vector will vary significantly over time, in both the speed and direction components of the vector. Thus, any scheme that aims to capture wind at a particular location will be inherently unreliable. Induced flow works because it has a reliability advantage: the likelihood of a boundary layer *gradient* between two locations is very high compared to the likelihood of a particular wind velocity at one location. This reliability advantage is increased by height difference between the wind capture points, so for a building to be reliably ventilated by induced flow, it must therefore be tall. Termite mounds, in contrast, are comparatively short, usually only a meter or two in height, and this reduces the reliability advantage commensurably. As a result, induced flow rarely operates in termite mounds, even in open-chimney mounds where the structure would seem to strongly favor it [13, 15, 16].

Finally, there is the assumption that mound ventilation also means nest ventilation. This has long been the prevailing assumption in termite biology (and in building designs inspired by termites). Surprisingly, there is no evidence that supports this claim, whether ventilation is driven by wind (induced flow) or heat (thermosiphon flow). Indeed, measurements of actual flows of air in termite nests and mounds (using tracer gases) indicate that air in the mound is almost never driven into the nest [15]. This signifies, among other things, that other mechanisms beside ventilation must be involved in mediating the mound's function, respiratory gas exchange.

Termite-inspired building designs thus depart in some significant ways from the conventional view of how termite mounds work. How, then, do termite mounds actually work?

4 How a termite mound is like a lung

The termite mound is but one part of a larger integrated system that includes the subterranean nest and the complex reticulum of termite-excavated tunnels (Figure 4) that permeate the mound. These both extend upward into the mound and downward to envelop the nest (Figure 4).[7] This system is the functional analogue of a lung, and like the lung, multiple layers of subsidiary function are involved in the global function of colony gas exchange. Previous models for mound function have fallen short because they have not accounted for these functional complexities.

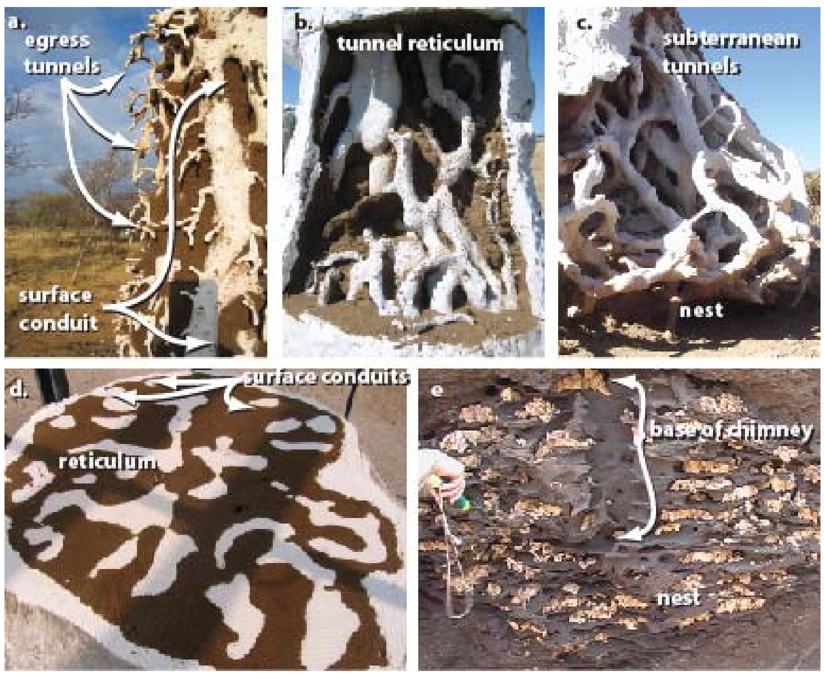

Fig. 4. The internal structure of a *Macrotermes michaelseni* mound. a. Plaster cast of a portion of the superficial tunnel network showing egress tunnels and surface conduits. The mound surface has been partially washed away. b. Plaster cast of the deep tunnel reticulum in a mound of *Macrotermes michaelseni.* c. Plaster cast of the subterranean reticulum that envelops the nest. The nest is just visible behind the reticulum. d. A horizontal slice at roughly 1 m above ground level through a plaster filled mound. The reticulum and surface conduits are indicated. e. Cross section through the subterranean nest, showing the galleries (the fungus combs are the yellowish masses inside the galleries) and the base of the chimney opening into the nest.

Commonly, physiologists describe the lung as a multi-phase gas exchanger (Figure 5, [17, 18]). Ventilation is only one phase, and it operates in the lung's upper airways (the trachea and several branches of the bronchial tree). There, gas exchange is dominated

[7] These tunnels ultimately connect to the extensive array of foraging tunnels that radiate several tens of meters from the nest, and which gives colony's workers access to their food (dried grass, dead wood and dung).

strongly by forced convection driven by the respiratory muscles. In the lung's terminal passages—the alveoli and alveolar ducts—gas exchange is dominated by diffusion, and there is virtually no bulk flow of air there. Sandwiched between these phases is an extensive region of the lung, which includes the fine bronchi and bronchioles, where neither forced convection nor diffusion dominates flux. This mixed-regime region is the site of the overall control of lung function. This is dramatically evident in asthma, which is a constriction disorder of the mixed-regime airways. Small constrictions of these airways during an asthma attack disproportionately compromises lung gas exchange in a way that similar constriction of the upper airways do not.

This casts lung ventilation into a somewhat different perspective from how we normally view it. For example, when respiratory exchange is elevated, as it might be during exercise, increased ventilation (heavier breathing) does not itself enhance respiratory flux, as most might think. Rather, increased ventilation works its effect secondarily by enhancing gas exchange through the limiting mixed-regime phase.

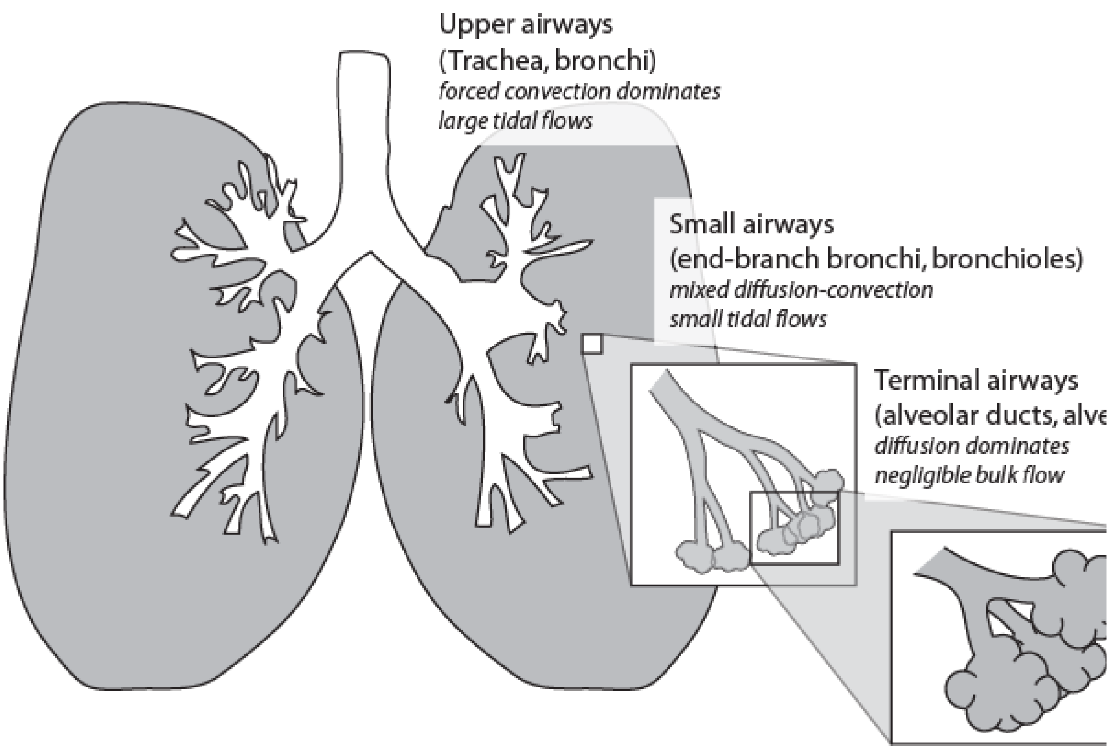

Fig. 5. Functional organization of the lung

Termite colonies have a similar functional organization (Figure 6). As in lungs, there is an ultimate diffusion phase, which is located within the termites themselves: indeed, one can think of the termites as mobile alveoli. The termites, in turn, are embedded within the nest, which comprises numerous galleries separated by thin walls that are perforated by a few large pores (2-3 mm diameter). The nest, meanwhile, is embedded in the larger reticulum of large-diameter tunnels that permeate the mound. The nest galleries connect to the reticulum above the nest via a capacious space, the chimney. The reticulum of subterranean tunnels that envelops the nest appears to connect to the nest at its base. Air

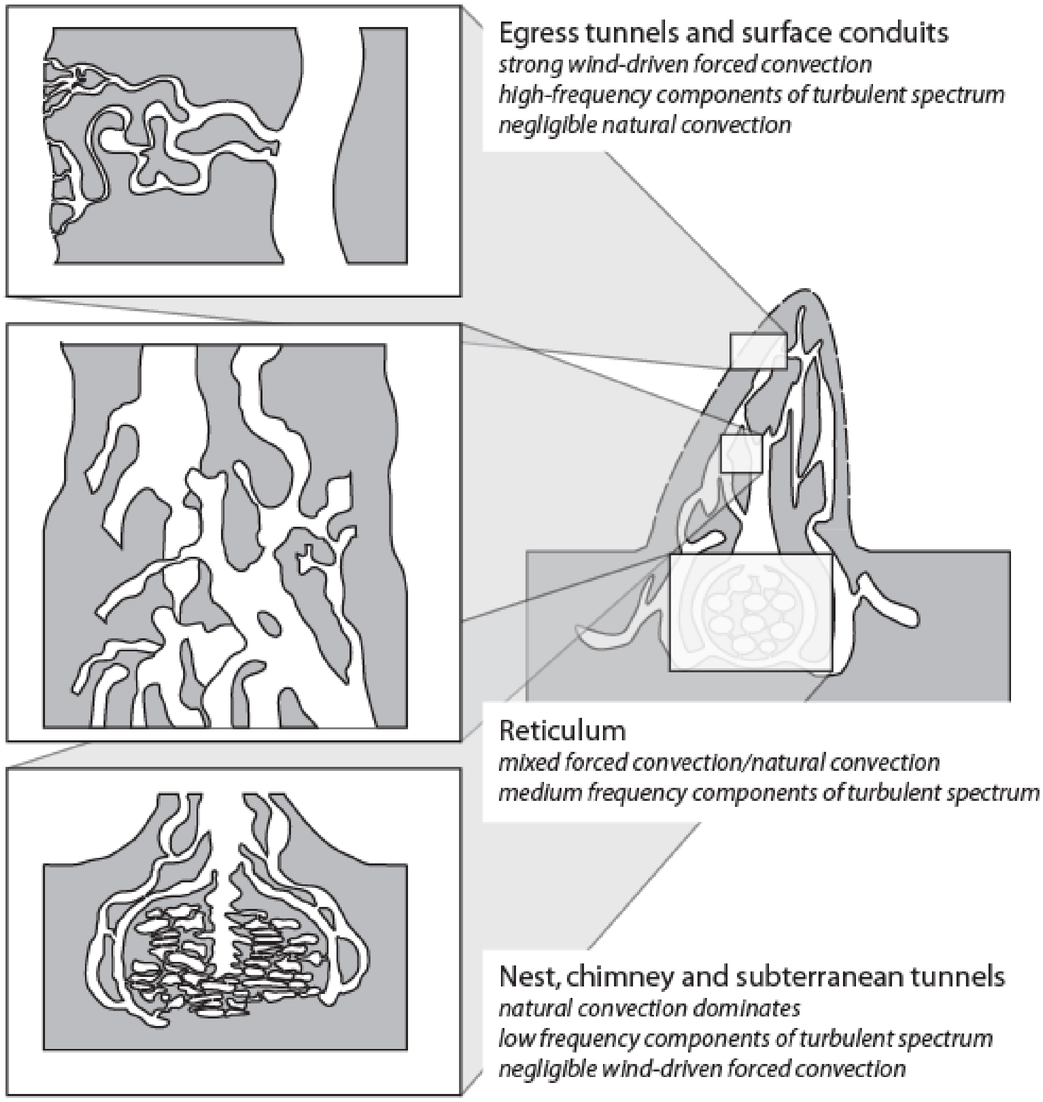

Fig. 6. Functional organization of a termite mound.

movements in the nest and subterranean reticulum appear to be dominated by natural convection, powered by the substantial metabolism that is concentrated within the nest.[8] Finally, the reticulum extends to the mound surface to encompass a web of vertically-biased surface conduits: these ultimately open to many small egress tunnels that project to the surface and serve as zones of mound porosity. In the surface conduits and egress tunnels, air movements are strongly driven by wind. As it is in lungs, the colony's respiratory function is dominated by a mixed-phase regime that is sandwiched between the subterranean structures (where natural convection dominates), and the upper parts and

[8] Each gallery contains a fungus comb where the colony's fungi are cultivated, and a colony can have up to a hundred or so fungus combs. Each fungus comb contributes about a watt to the colony's total metabolism, and the heat and water vapor thus produced impart buoyancy to the nest air. This is the buoyant force that Martin Lüscher believed could drive thermosiphon circulation.

peripheral air spaces of the mound (where wind-driven forced convection dominates). By our best estimates, this mixed natural/forced convection regime occupies the lower parts of the chimney and the deeper parts of the mound reticulum [15].

The mound is the principal interface of this complex with environmental winds. Most thinking about termite mounds (or termite-inspired buildings) has idealized this as a flow-through system driven by idealized gradients in wind energy. It is common, for example, to see diagrams of mounds (or buildings) with winds depicted as a vector with implicitly predictable and well-behaved velocity and direction. To render a useful analogy, there is a tendency to idealize wind as a DC energy source, and to characterize the mound (or building) as essentially a resistance load that spans a DC gradient in potential energy (such as the surface boundary layer). Function is then defined by the DC work done, that is, bulk movement of air through the building's occupied space, as in induced flow.

However, neither lungs nor termite mounds are DC systems and it is inapt to treat them that way. Rather, they are more properly thought of as AC systems, driven by dynamic transients in the energy that powers their function [19]. Lung ventilation, for example, is driven by an AC "motor", namely the tidal movement of air driven by the cyclically active respiratory muscles. What determines lung *function* is the depth to which this AC energy can penetrate and influence exchange across the mixed-regime phase. Similarly, termite mounds capture energy in the chaotic transients that are the defining features of "badly-behaved" turbulent winds. The mound's *function*, however, depends upon how deeply this AC energy can penetrate into and do work in the mound. In both instances, function is essentially AC work, driven by the capture of AC energy across an *impedance*, not a resistance.

Many peculiar aspects of lung (and mound) function can only be understood in this context. One has already been mentioned: how both the lung and the colony-mound complex mediate respiratory gas exchange when ventilation does not extend to the entire structure. In an impedance-driven system, ventilation does not have to: the AC energy need only penetrate deeply enough to modify the mixed-phase region that limits the global function: gas exchange. There are other interesting aspects of AC systems, however, that not only uncover novel mechanisms for how termite mounds work, but that can inspire entirely new kinds of biomimetic designs.

For example. so-called *pendelluft* ventilation (literally, air pendulum) enhances gas exchange across the mixed-regime region of lungs through weakly-driven bulk flows of air between alveolar ducts and between the fine bronchi (Figure 7, [17, 18]). We believe there is a pendelluft in termite mounds as well, driven by an interaction between buoyant forces generated by the colony, slow transients in turbulent wind energy that penetrate to the lower chimney and subterranean tunnels and the rapid transients that drive flows in the superficial tunnels (Figure 8). In the lower reaches of the chimney and deep reticulum, there is a steady upward buoyant force imparted to the air by the colony's excess heat production. In the surface conduits and superficial reticulum, flow is driven by fast transients in turbulent winds. Depending upon wind speed, wind direction and the distribution of surface porosity on the mound, this can impart either a downward or an upward pressure on the peripheral parts of the mixed regime phase. Similarly, slow wind-induced transients can impart either a downward or an upward pressure on air deep within the chimney and reticulum. The end result of these complicated interactions is a

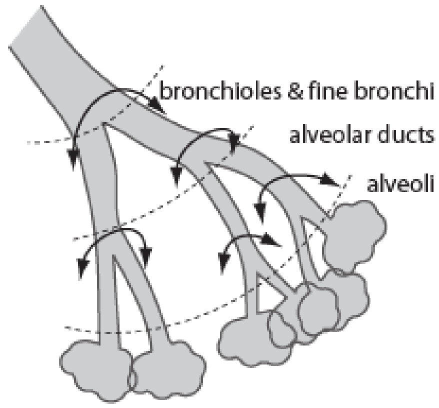

Fig. 7. Pendulluft flow in the terminal and small airways of the lung.

pendelluft that drives slow quasi-tidal air movements in the chimney and lower parts of the mound interior, enhancing exchange between the nest and mound [15].

Another interesting impedance-based mechanism involves so-called high-frequency ventilation, or HFV [20]. This is a respiratory therapy that is used to sustain gas exchange in lungs that have suffered mechanical damage and cannot sustain the large volume changes that normally accompany respiration. High frequency ventilation imposes minuscule volume changes on the lung, but at a much higher frequency, 10-20 Hz as opposed to the normal ventilation frequency of 0.2 Hz. According to one theory, HFV works by driving the lung at the resonant frequency of the airways, enhancing diffusion and promoting pendelluft ventilation [19, 21].

A form of high-frequency ventilation may also occur in termite mounds, but here driven by particular bandwidths of the frequency spectrum of turbulent winds. The extensive array of large-calibre long tunnels in termite mounds can extend for more than 2 meters in length. These resonate strongly at frequencies of about 20-30 Hz, which sits comfortably within the frequency bandwidth of turbulent winds, typically 1-100 Hz. If the mound's tunnels are "tuned" to capture the AC wind energy in this narrow frequency band, it may set air in the tunnels resonating, driving a kind of HFV that could promote gas exchange without large bulk flows of air through the nest. More likely, however, is a structural distribution of wind capture that matches a distribution of resonant frequencies. For example, the air spaces in the mound offer a variety of path lengths for transient wind energy to follow, ranging from a few centimeters in the superficial egress tunnels, to meters in some of the deeper and larger caliber tunnels. Thus, transient winds at the upper end of the frequency spectrum could do work in the shorter superficial tunnels, while lower frequency transients do work in the deeper and longer tunnels.

This opens the possibility for discriminatory mass transfer mechanisms in termite mounds (and termite-inspired buildings) similar to those that operate routinely in lungs. Evaporative cooling through panting works this way, for example. Panting cools a dog by elevating the rate of evaporative mass loss from the mouth and lungs, driven by an increased lung ventilation [22-25]. This poses a physiological quandary: how to increase water vapor flux without simultaneously increasing carbon dioxide flux, which could cause severe upsets of the body's acid-base balance. The quandary is resolved by the lung's impedance. Driving the lungs at the resonant frequency of the thoracic cage

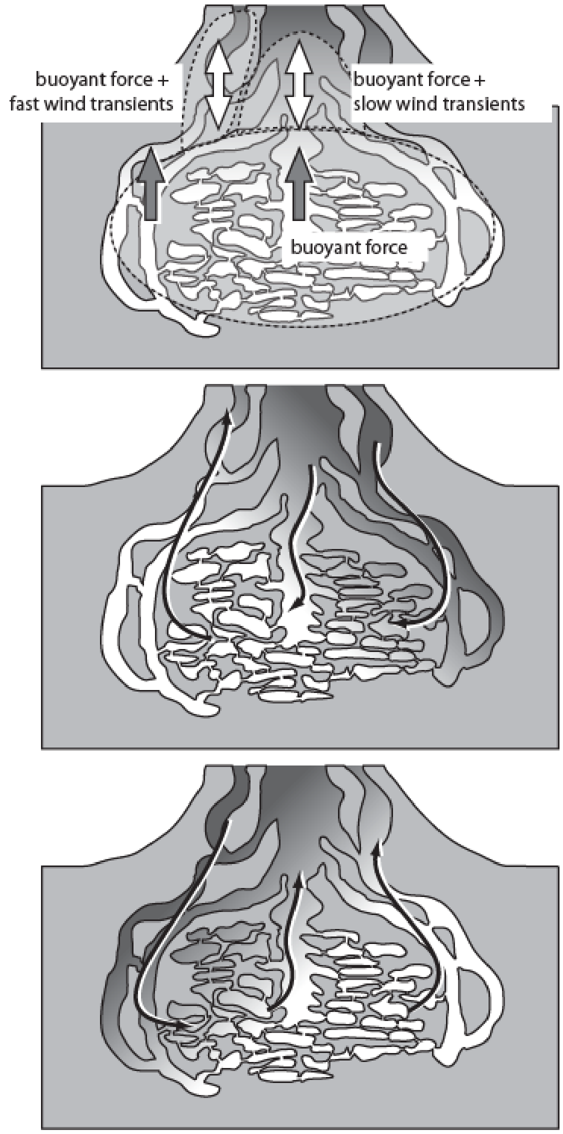

Fig. 8. Hypothetical pendelluft ventilation in the termite mound and nest. Top. Array of forces acting on the deep air masses in the mound and nest. Middle and bottom. Pendelluft flow that arises in response to variation in wind speed and direction.

increases the lung's impedance. Ventilation therefore preferentially enhances evaporation from the upper respiratory passages. The lung's elevated impedance to these high frequencies leaves flux at the deeper, mixed regime level unchanged.

Similar discriminatory schemes may operate in termite mounds too. For example, termites tightly regulate the nest's water balance, which is often undermined by percolation of ground water into the nest following rains [26, 27]. At the same time, termites also tightly regulate the concentrations of oxygen and carbon dioxide within the nest [15]. Termites are thus faced with a physiological quandary similar to that panting dogs must face: how to evaporate water faster from the nest without simultaneously disrupting the balance of respiratory gases. Termites accomplish this by actively transporting water to the superficial parts of the mound in wet soil, where it is deposited around the egress tunnels. Because it is precisely these regions that should be ventilated most strongly by rapid wind transients, evaporation can be enhanced without also increasing respiratory gas flux.

5 How buildings can be like lungs

This enhanced conception of how termite mounds work is immensely liberating because it offers a veritable universe of new termite-inspired building designs. No longer need such designs be constrained by the long-prevailing models of induced-flow and thermosiphon flow: a good thing, since these mechanisms rarely operate in natural mounds anyway. In contrast, a clear vision of how termite mounds actually work literally opens a whole new spectrum of wind energy to explore and exploit.

Consider, for example, the traditional conception of the wall. 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. In short, the paradox forces building design toward what we call the “building-as-machine” paradigm (BAM).

Living systems, which also are avid space-creators, resolve the paradox in a different way: by erecting walls that are not barriers but adaptive interfaces, where fluxes of matter and energy across the wall are not blocked but are managed by the wall itself [28, 29]. This is illustrated dramatically in the complex architecture of the interface that termites build—the mound—to manage the environment in their collectively constructed space—the nest [30].

New rapid manufacturing and free-form fabrication techniques make it feasible to build walls that incorporate some of these design principles. Imagine, for example, porous walls that are permeated with a complex reticulum that, like in the termite mound, acts as a low-pass filter for turbulent winds. In this instance, an interior space of a building could be wind-ventilated without having to resort to tall chimneys, and without subjecting the inhabitants to the inconvenient gustiness that attends to the usual means of local wind capture, namely opening a window. Now, it is the windows that are the barriers and the walls that connect the inhabitants to the world outside. Or, imagine a cladding system that mimics the mound’s complex interface at the surface conduits and egress tunnels (Figure 9). One could employ such claddings as whole-building wind-capture devices, which greatly expands a building’s capacity for wind capture. Or, imagine a wall that is tuned for differential mass exchange where the high-frequency components of turbulent winds can evaporatively cool a porous wall’s surface layers and provide natural cooling for air forced through the walls by wind’s lower-frequency components. The possibilities, we hope you will agree, are large.

Fig. 9. Some imagined biomimetic designs. Top left. The surface conduit-egress tunnel complex. Top right. A rendering of a building enveloped by porous "surface conduits." Bottom. The block elements for an artificial surface conduit.

6 Beyond biomimicry

Indeed, the possibilities may be more than large: they may be vast. This is because the termite mound is not simply a structural arena for interesting function. It is itself a function, sustained by an ongoing construction process that reflects the physiological predilections of the myriad agents that build and maintain it. The mound, in short, is the embodiment of the termites' "extended physiology" [28, 31, 32]. This raises the intriguing idea that building design can go "beyond biomimicry", to design buildings that do not simply imitate life but are themselves "alive" in the sense that termite mounds are.

Realizing the living building is predicated upon there being a clear idea of what distinguishes living systems from non-living ones. Unfortunately, most of the criteria that are commonly put forth by biologists—cellular organization, replication, heredity, reproduction, self-organization, low entropy—are not very informative for building designers. Remarkably, they are not even particularly helpful in the life sciences. Reproduction, for example, is not a useful criterion for recognizing living systems, such as the biosphere, that do not reproduce. Nor is a concept like self-organization much help: many complex non-living systems, like clouds, are self-organizing, so how are these to be distinguished as not-life? Fortunately, there is one feature that reliably distinguishes life in a variety of contexts and scales. That is homeostasis, the tendency of living systems to gravitate toward a particular adaptive state in the face of disruptive perturbations. Realizing the living building therefore means realizing the *homeostatic* building.

The idea of homeostasis is nothing new to architects and engineers, of course: it is standard practice to outfit buildings with systems to regulate particular properties of the built environment: temperature, humidity, air quality and so forth. The focus here is on machines that do work to manipulate a property through negative feedback control (Figure 10). Thus, a property is sensed, its deviation from some desired value is assessed, and a machine is activated that does work to offset the deviation. Such systems range in complexity from simple house thermostats to sophisticated Building Energy Management Systems, but all have in common that they are firmly rooted in the building-as-machine design tradition.

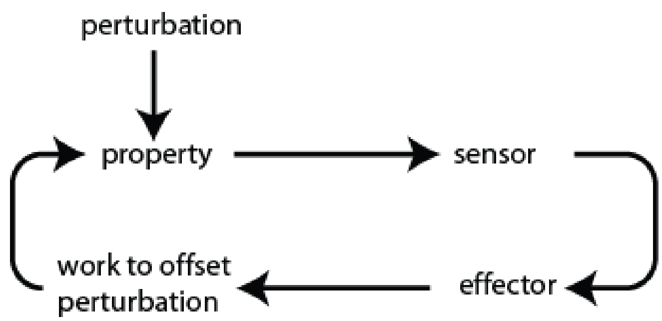

Fig. 10. The standard negative feedback model for regulating the built environment

Homeostasis is more than simply self-regulation, however. It is a fundamental property of life that, among other things, confers upon living systems an impressive capability for emergent self-design [29]. Thus, regulation of an environmental property—the essence of the building-as-machine—is but one of many outcomes of a larger systemic homeostasis that engages every aspect of the system's architecture and function.

The termite "extended organism" is a remarkable example of this capability. A termite colony's oxygen demand varies considerably with colony size: small colonies may comprise a few thousand individuals, while the largest colonies may have populations upwards of two million [33]. Despite this large variation in demand, oxygen concentrations do not differ appreciably with colony size: oxygen concentrations in very large colonies are similar to those in much smaller colonies (Figure 11, [15]). Yet, there is no machine in the termite mound that does the work to offset the perturbation that a negative feedback system might demand. Nor is there any evidence of an "oxygen-stat": termites are not particularly sensitive to quite large oxygen perturbations. How, then, is oxygen concentration regulated?

Part of the answer is that it is not simply the *property* of oxygen concentration that is regulated. What is regulated, rather, is multiphase processes of one outcome is a steady oxygen concentration. Because the mound is an extended organism, this process extends to the mound, which is itself a process. Thus, mound structure is as impressively regulated as oxygen concentration is.

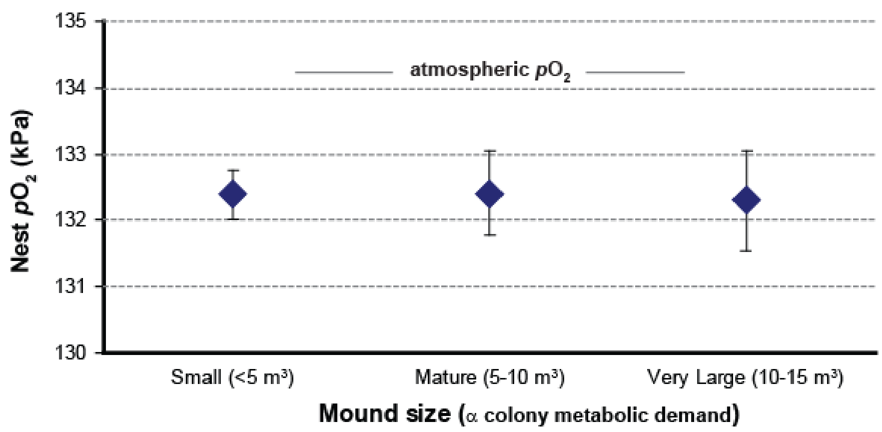

Fig. 11. Oxygen concentration in several nests of *Macrotermes michaelseni*. Symbols represent means +/- 1 standard deviation. Mound size is a surrogate for colony metabolic demand.

How termite colonies manage this seamless integration of structure and function remains largely obscure, but some interesting features are starting to emerge. There is a common link, for example, in the termite-mediated movement of soil that makes the mound both process and structure: this is why it is possible for the mound's structure to reflect the termites' collective physiology. Understanding the termite colony extended organism therefore involves understanding what guides this ongoing termite-driven stream of soil through the mound.

Surprisingly, negative feedback appears to play only a minor role. Rather, there is a kind of swarm intelligence at work. Soil translocation is organized into discrete foci of intense activity that is driven by a multiplicity of positive and negative feedback loops involving termites, the structures they build and the intensity of local AC perturbations of the environment. To complicate matters, the multiple foci compete with one another for workers, with more intensely active foci drawing workers away from less intense foci, the outcome of the competition both determining and being determined by the structures that result. To complicate things further, the entire process is modulated by the availability of liquid water.

The building-as-machine paradigm cannot quite capture this kind of seamless integration, largely because it regards structure as something distinct from function. It is therefore unlikely that the living building can emerge from this design tradition. In living systems, however, no such distinction is possible: structure is function and function is structure. At present, simply stating this offers little practical value in telling us how to realize a living building, but it at least points us the right way: toward buildings that are extended organisms, where function and structure meld, and are controlled by the over-riding demands of homeostasis.

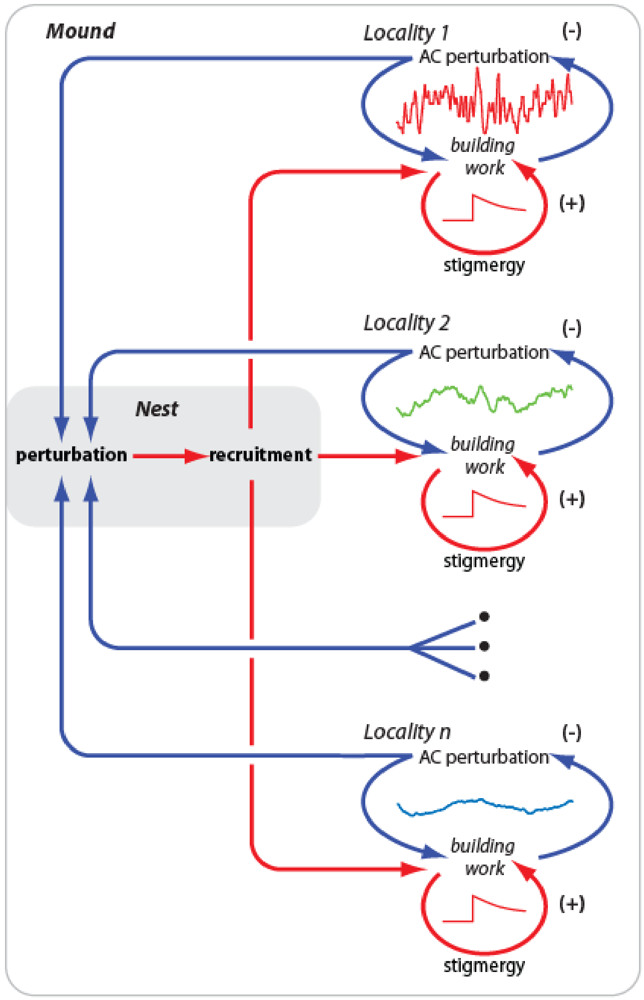

Fig. 12. Model for swarm regulation of the nest environment. Building is driven by multiple foci of intense soil movement that can drive soil transport autonomously. The various foci also compete with one another for building agents (i.e. termites). A focus is initiated by an AC perturbation, and is sustained by a positive feedback loop called stigmergy. AC perturbations also sustain the focus of building. As building proceeds, the level of AC perturbation abates. Building will continue being driven by stigmergy, but this has a natural decay time.

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References

1. Tzonis, A., L. Lefaivre, and B. Stagno, *Tropical Architecture: Critical Regionalism in the Age of Globalization*. 2001, New York: J Wiley and Sons. 320.
2. Collins, N.M., *The nests of Macrotermes bellicosus (Smeathman) from Mokwa, Nigeria.* Insectes Sociaux, 1979. **26**(3): p. 240-246.
3. Darlington, J.P.E.C., *The structure of mature mounds of the termite Macrotermes michaelseni in Kenya.* Insect Sci Appl, 1986. **6**: p. 149-156.
4. Darlington, J.P.E.C., *Mound structure and nest population of the termite, Pseudacanthotermes spiniger (Sjöstedt) in Kenya.* Insect Science and its Application, 1994. **15**(4/5): p. 445-452.
5. Grigg, G.C. and A.J. Underwood, *An analysis of the orientation of "magnetic" termite mounds.* Australian Journal of Zoology, 1977. **25**: p. 87-94.
6. Harris, W.V., *Termite mound building.* Insectes Sociaux, 1956. **3**(2): p. 261-268.
7. Darlington, J.P.E., *How termites keep their cool.* The Entomological Society of Queensland News Bulletin, 1987. **15**: p. 45-46.
8. Lüscher, M., *Air conditioned termite nests.* Scientific American, 1961. **238(1**: p. 138-145.
9. Vogel, S., *Organisms that capture currents.* Scientific American, 1978. **239**: p. 128-139.
10. Vogel, S., *Life in Moving Fluids*. 1981, Boston, Massachusetts: Willard Grant Press. 352.
11. Vogel, S.A. and W.L. Bretz, *Interfacial organisms: Passive ventilation in the velocity gradients near surfaces.* Science, 1972. **175**: p. 210-211.
12. Weir, J.S., *Air flow, evaporation and mineral accumulation in mounds of Macrotermes subhyalinus.* Journal of Animal Ecology, 1973. **42**: p. 509-520.
13. Turner, J.S., *Ventilation and thermal constancy of a colony of a southern African termite (Odontotermes transvaalensis: Macrotermitinae).* Journal of Arid Environments, 1994. **28**: p. 231-248.
14. Sutton, O.G., *Atmospheric Turbulence*. Methuen's Monographs on Physical Subjects, ed. B.L. Worsnop. 1960, London: Methuen & Co, Ltd. 111.
15. Turner, J.S., *On the mound of Macrotermes michaelseni as an organ of respiratory gas exchange.* Physiological and Biochemical Zoology, 2001. **74**(6): p. 798-822.
16. Loos, R., *A sensitive anemometer and its use for the measurement of air currents in the nests of Macrotermes natalensis (Haviland)*, in *Etudes sur les Termites Africains*, A. Bouillon, Editor. 1964, Maisson et Cie: Paris. p. 364-372.
17. Engel, L.A. and M. Paiva, eds. *Gas Mixing and Distribution in the Lung*. Lung Biology in Health and Disease. Vol. 25. 1985, Dekker: New York. 416.
18. Hills, B.A., *Gas Transfer in the lung*. 1974, Cambridge: Cambridge University Press. 176.
19. Rozanek, M. and K. Roubik, *Mathematical model of the respiratory system-comparison of the total lung impedance in the adult and neonatal lung.* Proceedings of the World Academy of Science, Engineering and Technology, 2007. **24**: p. 293-296.

20. Chang, H. and A. Haif, *High frequency ventilation. A review*. RESPIRATION PHYSIOLOGY, 1984. **57**: p. 135-152.
21. Tanida, Y., *Pendelluft effect on gas exchange in high-frequency ventilation.* Japan Society of Mechanical Engineering International Journal. Series B. Fluids and Thermal Engineering, 1996. **39**(2): p. 368-375.
22. Schmidt-Nielsen, K., *Animal Physiology. Adaptation and Environment*. 4th ed. 1990, Cambridge: Cambridge University Press. 602.
23. Crawford, E.C., *Mechanical aspects of panting in dogs.* Journal of Applied Physiology, 1962. **17**: p. 249-251.
24. Goldberg, M., V. Langman, and C. Taylor, *Panting in dogs: Paths of air flow in response to heat and exercise.* Respiration Physiology, 1981. **43**: p. 327-338.
25. Richards, S., *The biology and comparative physiology of thermal panting.* Biological Reviews, 1970. **45**: p. 223-264.
26. Turner, J.S., *Termites as mediators of the water economy of arid savanna ecosystems*, in *Dryland Ecohydrology*, A. Porporato and P. d'Odorico, Editors. 2006, Springer. p. 303-313.
27. Turner, J.S., et al., *Termites, water and soils.* Agricola, 2007. **2006**(16): p. 40-45.
28. Turner, J.S., *The Extended Organism. The Physiology of Animal-Built Structures*. 2000, Cambridge: Harvard University Press. 234.
29. Turner, J.S., *The Tinkerer's Accomplice. How Design Emerges from Life Itself*. 2007, Cambridge, Massachusetts: Harvard University Press. 282.
30. Turner, J.S., *A superorganism's fuzzy boundary.* Natural History, 2002. **111 (6)**(July-August 2002): p. 62-67.
31. Turner, J.S., *Extended phenotypes and extended organisms.* Biology and Philosophy, 2004. **19**(3): p. 327-352. .
32. Turner, J.S., *Extended physiology of an insect-built structure.* American Entomologist, 2005. **51**(1): p. 36-38.
33. Darlington, J.P.E.C. and R.D. Dransfield, *Size relationships in nest populations and mound parameters in the termite Macrotermes michaelseni in Kenya.* Insectes Sociaux, 1987. **34**(3): p. 165-180.