An ecosystem based biomimetic theory for a regenerative built environment

M. Pedersen Zari & J.B. Storey
Centre of Building Performance Research, School of Architecture, Victoria University of Wellington, Wellington, New Zealand.

ABSTRACT: Biomimicry, where flora, fauna or entire ecosystems are emulated as a basis for design, has attracted considerable interest in the fields of architectural design and engineering as an innovative new design approach and importantly as a potential way to shift the built environment to a more sustainable paradigm. The practical application of biomimicry as a design methodology, particularly in the built environment, remains elusive however. This paper seeks to contextualise the various approaches to biomimicry and provides an integrated set of principles that could form the basis for an ecosystem based design theory. This would enable practitioners to reach beyond sustainability to a regenerative design practice where the built environment becomes a vital component in the integration with and regeneration of natural ecosystems as the wider human habitat.

1 INTRODUCTION

Approaches to biomimicry as a design process typically fall into two categories: Defining a human design problem and looking to the ways other organisms or ecosystems solve this (design looking to biology), or identifying a particular characteristic in an organism or ecosystem and using it to provide a solution to a human problem (biology influencing design) (Biomimicry Guild, 2007). Within these two approaches, there are three levels of mimicry: Organism level, behaviour and ecosystem levels as detailed by Pedersen Zari (2007).

Through an examination of existing biomimetic technology and literature it is clear that markedly different approaches to biomimetic design have evolved and can have different outcomes in terms of an increase in overall sustainability. Examples of biomimicry are typically of products or materials, and tend to mimic a single organism. As Reap et al. (2005) demonstrate, products or materials that are organism biomimetic without also being ecosystem biomimetic are not inherently more sustainable when analysed from a life cycle perspective. An example given by Baumeister (2007) is Velcro. While Velcro mimics how burs of certain plants attach to animal fur, the product itself is made from petrochemicals and is not typically recycled or recyclable, nor does it take into account any of the other principles of ecosystems.

An ecosystem based approach to architectural design will be discussed in this paper, however the social, psychological and aesthetic implications of such an approach are not explored in this context. The potential relationships with biophilia, evolutionary psychology (Storey & Pedersen Zari, 2006) and integration or interface with non-human-dominated ecosystems are acknowledged with ecosystem based biomimicry. The possible links with Construction Ecology (Kibert et al., 2002) and Building Ecology (Graham, 2003) are also acknowledged.

2 ECOSYSTEM BASED BIOMIMICRY

Humans affect ecosystems and evolutionary processes at great rates and in multiple ways (Imhoff et al., 2004). Despite traditional approaches in the study of ecology where systems tended to be studied as unaffected and separate from human influence, it may be as Alberti et al, (2003) suggest, impossible to look at ecosystems as separate from human systems.

Despite the fact that there may not be any ecosystems that are truly unaffected by humans, and that humans are inherently part of the natural world, there are some obvious and essential differences in the way that non-human-dominated and human-dominated systems work. Non-human-dominated ecosystems, particularly those that are k-strategists (more complex and longer lived), tend to function in way that is conducive to dynamically sustained and ongoing life (Benyus, 1997, Berkebile and McLennan, 2004). In this particular period of human existence, there are perhaps some valuable observations humans can make of 'natural' ecosystems in the creation of human habitat that is able to integrate with and regenerate rather than damage the ecosystems they are part of.

3 BIOMIMICRY AND ARCHITECTURAL DESIGN

Biomimicry, particularly at the ecosystem level has yet to be meaningfully explored in built form, with few examples existing beyond an aesthetic metaphor. A documented example that does go beyond a simple mimicking of form is Mick Pearce's Eastgate Building in Harare, Zimbabwe and the CH2 project in Melbourne, Australia based on the mimicking of the building behaviour of certain termites. The temperature regulation observed in the mounds is achieved through careful orientation, spatial organisation and techniques of passive ventilation. Aldersey-Williams (2003) also details a number of buildings that mimic animals in various ways. Although most do not go beyond the form level, a notable exception is the Waterloo International Terminal. Designed by Nicholas Grimshaw & Partners, the terminal is able to respond to changes in air pressure as trains move through it. Its glass panel fixings mimic the flexible, scaly Pangolin making them able to move in response to imposed forces.

4 BIOMIMICRY FOR REGENERATIVE DESIGN

While biomimicry at the organism level may be inspirational for its potential to produce novel architectural designs, the possibility exists that a building as part of a larger system, that is able to mimic natural processes and can function like an ecosystem in its creation, use and eventual end of life, has the potential to contribute to a built environment that goes beyond sustainability and starts to become regenerative (Van der Ryn, 2005; Reed, 2006).

Although the authors are not aware of any built architectural examples that demonstrate comprehensive ecosystem based biomimicry, there are proposed projects that display aspects of such an approach such as the Lloyd Crossing Project proposed for Portland, Oregon. The project's design team including Mithūn Architects and GreenWorks Landscape Architecture Consultants use estimations of how the ecosystem that existed on the site before development functioned, termed by them *Pre–development Metrics*™ to set a wide range of goals for the ecological performance of the project over an extended time period.

5 ECOSYSTEM RESEARCH

Ecology literature typically does not offer sets of generalised principles but tends to explore the complexities of certain aspects of ecosystems. While there is considerable overlap in how ecosystems are described between sources, not all authors are in agreement. Because of the interconnected nature of ecosystems and the ways in which they function, it is difficult to organise generalised principles into a neat list which accurately encapsulates the complexity of the relationships between each principle (Charest, 2007). It is however considered that an examination of the relationships between each principle has potential to offer additional insights into how human design could be based on ecosystems and that the development of a comprehensive relationship diagram could be a useful step in the evolution of a model that is able to portray this. A recent iteration of the Biomimicry Guild's *Life's Principles* remains the only non-linear model of this type that the authors are aware of (Biomimicry Guild, 2007).

In this case, Pedersen Zari conducted a comparative analysis of related knowledge of ecosystem principles in the disciplines of ecology, biology, industrial ecology, ecological design and biomimicry and used this to formulate a group of ecosystem principles aiming to capture cross disciplinary understandings of ecosystem functioning. It is intended that this biomimetic theory in the form of a set of principles based on ecosystem function could be employed by designers, to aid in the evolution of methodologies to enable the creation of a more sustainable built environment.

An initial matrix (available from the authors upon request) was used to compare information from explanations of generalised ecosystem principles. From this, an inventory was complied encompassing as much of the information as possible. The following sources were used: Benyus (1997), Berkebile & McLennan (2004), Biomimicry Guild (2007), Copeman (2006), de Groot et al. (2002), Faludi (2005), Hastrich (2006), Hoeller (2006), Kelly (1994), Kibert et al. (2002), Korhonen (2001), McDonough & Braungart (2002), Reap et al. (2005), Thompson (1942), Vincent (2002), Vincent et al. (2006) and Vogel (1998). Additional sources, typically from the discipline of ecology were used to expand upon each principle.

6 ECOSYSTEM PRINCIPLES

The ecosystem principles provided here are proposed as a set of generalised norms for the way most ecosystems operate rather than absolute laws and should be taken as a starting point for further research to fully understand the different and important aspects of each simplified principle. Without comprehensive explanations of each principle, which is beyond the scope of the paper, the effectiveness of simplified lists of ecosystem principles aimed at use by designers with little background ecological knowledge are likely to remain at the level of metaphor. While Korhonen (2001) points out that mimicking at the metaphoric level is not insignificant in terms of increasing overall performance of the built environment, opportunities exist for design to be positively integrated with global biogeochemical cycles through a thorough understanding of ecology beyond the metaphoric level.

The principles provided in Table 1 should not be taken as a comprehensive explanation of the ways ecosystems function, but are intended to give designers with limited knowledge of ecology a set of operating principles which, if employed, could significantly improve the sustainability of the human built environment. A brief explanation of each principle follows Table 1.

Ecosystem principles listed can be applied to the design process by transforming them into a set of questions that are asked of the project at each stage of the design (Biomimicry Guild, 2007, Charest, 2007).

Table 1. Ecosystem Principles

1. Ecosystems are dependant on contemporary sunlight.
    -Energy is sourced from contemporary sunlight.
    -The sun acts as a spatial and time organising mechanism.
2. Ecosystems optimise the system rather than its components.
    -Matter is cycled and energy is transformed effectively.
    -Materials and energy are used for multiple functions.
    -Form tends to be determined by function.
3. Ecosystems are attuned to and dependant on local conditions.
    -Materials tend to be sourced and used locally.
    -Local abundances become opportunities
4. Ecosystems are diverse in components, relationships and information.
    -Diversity is related to resilience.
    -Relationships are complex and operate in various hierarchies.
    -Ecosystems are made up of interdependent cooperative and competitive relationships.
    -Emergent effects tend to occur.

-Complex systems tend to be self organising and distributed.

5. Ecosystems create conditions favorable to sustained life.
   -Production and functioning is environmentally benign.
   -Ecosystems enhance the biosphere as they function.
6. Ecosystems adapt and evolve at different levels and at different rates.
   -Constant flux achieves a balance of non-equilibrium
   -Limits, tend to be creative mechanisms
   -Ecosystems have some ability to self heal

6.1 *Sunlight.*

Solar radiation is the only input into the closed loop ecosystem of earth and except for gravitational effects of the moon, is the only source of energy either directly or indirectly available to organisms. The majority of ecosystems exist through utilising contemporary sunlight (recently received from the sun) that has been converted by photosynthesis into biomass, which forms the basis of the food chain (Kibert et al., 2002). In contrast, humans currently source a large proportion of energy from ancient sunlight in the form of hydro carbon based fossil fuels.

Oxygen production, the hydrological cycle, wind currents, and drivers for certain ocean currents and other cycles are all caused by or are intimately linked with solar radiation (Xiong, 2002). As Baumeister (2007) points out, organisms tend to use 'free energy'. Examples are wind dispersed seed pods using air currents, or marine mammals exploiting water currents in migration. Ultimately this resourceful use of 'free' energy is also the harnessing of converted energy from the sun but by means other than directly through the food chain.

The sun also acts as a timing and directional orientation or spatial organisation mechanism. Biological rhythms such as diurnal and annual (or longer) cycles are determined by the sun's gravitational effect and the rotation of the earth. Migration patterns or flowering seasons in some species in response to these cycles are examples of the role the sun (or the earth's relative position to it) has in timing mechanisms in ecosystems. Many plants are able to sense the direction of the sun and therefore grow or move towards (or away) from it, enabling greater photosynthesis efficiency or other advantages (Benyus 1997). Wind and rain patterns, are also indirectly linked to solar radiation and are important organisational factors in ecosystems, determining where and in what formation organisms are able to inhabit a microclimate.

If the built environment was based on this one principle alone as is advocated by sustainable design theory in general, where it's energy was derived from contemporary sunlight and it was sited and organised according to climate, detrimental environmental impacts would be considerably less and there may be consequent significant positive physical and psychological health impacts (Kellert, 2005).

6.2 *System optimisation*

Ecosystems use energy and materials in a way that optimises the whole system rather than individual components (Kelly, 1994). What would appear to be inefficiency in individual organisms can sometimes equate to effectiveness for the entire system (McDonough & Braungart, 2002). Ecosystems tend to cycle matter in large closed loop systems, where the wastes of one organism become the nourishment of the next, through connected food webs at different scales. Detritus becomes a fundamental part of the health of the system (Odum, 1969).

Although matter can be cycled, energy will flow through a system (Korhonen, 2001). Benyus (1997) points out that *'the pyramid of life is quite literately an energy distribution chart, a record of the sun's movement through the system.'* Allen (2002) discusses the way that biological systems degrade energy in a large number of small steps, rather than in a small number of large steps, as tends to be the case in human systems and that these pathways of dissipation tend to be highly deliberate and important to the overall system. This allows energy that is left after one organism has done work to be utilised by another, so energy use is maximised.

In an example of both materials and energy effectiveness, organisms in ecosystems tend to use materials for more than one function (Benyus, 1997). This means less energy is expended and can be used for other functions such as health, growth and reproduction for example.

Reap et al. (2005) describe the characteristic of form fitting to function as *'the use of limited materials and metabolic energy to create only structures and execute only processes necessary for the functions required of an organism in a particular environment.'* Geometry and relative proportions found in nature are further offered as examples of materials and energy efficiency by various authors (Vogel, 1998, Faludi, 2005).

A built environment that mimicked this aspect of ecosystems through multifunctional use, closed loop functionality and overall system optimisation to ensure effective material cycles and careful energy flow would beneficially challenge conventional attitudes to building boundaries and the idea of waste.

6.3 *Local context.*

Species that make up ecosystems tend to be linked in various relationships with other organisms in close proximity (Allenby and Cooper, 1994, Korhonen, 2001). They typically utilise resources and local abundances from their immediate range of influence, and tend to be well adapted to their specific microclimatic conditions (Reap et al., 2005).

The Gaia hypothesis proposed by Lovelock posits that living communities may not be passively dependant on the local environment but may influence their microclimate as part of their initial adaptation to the environment (Harding, 2001). Both Gaian theory and the conventional ecology view that life adapts to local environment, point to ecosystems and the organisms in them seeming to be attuned to and suited to the climate and environment that they exist in.

The functions required for an ecosystem to continue and remain in dynamic balance, including the cycling and production of materials, are usually carried out by species within the system, existing in specific niches and linked with each other (Benyus, 1997). The ecosystem as a whole is able to be responsive to local conditions through extensive feedback loops created by the relationships between these organisms.

Incorporating this principle into the built environment implies that a thorough understanding of a particular place would be required of the design team and that local characteristics of ecology and culture would be seen as drivers and opportunities in the creation of place.

6.4 *Diversity*

A diverse system is often described in biomimicry literature as a robust and stable one capable of adapting to change. In certain levels of ecosystems and in individual organisms there may be a level of redundancy to allow for adaptation to changing conditions at different rates. Some ecologists describe this as the 'insurance effect' (Shear McCann, 2000). This concept is usually expanded upon in ecology literature, and it should be noted that there is considerable historical debate about the relationship between diversity, complexity, resilience and stability in ecosystems. What is clear from the literature is that the number and strength of relationships between species in systems is more important to dynamic stability than actual numbers of species (Shear McCann, 2000). Through this kind of cooperative networking, one element (or organism) can fail without disrupting the entire system.

Ecosystems are organised hierarchically (Kibert et al., 2002), and at different scales may be governed by different physics principles (Vogel, 1998, Thompson, 1942). In complex ecosystems both cooperation and competition between individuals and species are important in the creation of ecosystem dynamics (Kibert et al., 2002). Organisms will occupy non-competing niches and species in the same niche may use tactics such as defining territories or having non-overlapping feeding times to avoid competition. Reap et al. (2005) discusses life existing in a cooperative framework as relating to *'the diverse web of interactions that effect populations, facilitate resource transfers, ensure redundancy and generally maintain the biosphere.'*

Emergence in ecosystems is the phenomena of novel and unexpected organisation in complex systems. Allen (2002) asserts that it is through new relationships of control and constraint that emergence appears, allowing systems to become more complex. Ecosystems tend to be made up of distributed and decentralised networks of feedback loops dependant on relationships between organisms, and between the living system and the rest of the environment, making them rapidly responsive and adaptable to change (Vincent et al., 2006). Kibert et al. (2002) describe this aspect of ecosystems as *self-organisation*. This kind of organisation, based on multiple feedback mechanisms, tends to incorporate high amounts and transfer rates of information (Allenby and Cooper, 1994).

Translating this into the built environment implies a systems approach to architectural design where considering the facilitation of relationships between buildings or components is as important as designing the individual buildings themselves.

6.5 *Life enhancement.*

The growth and activities of organisms tend not to damage the ability of the overall system they are a part of to exist and continue (Benyus, 1997, Rosemond and Anderson, 2003). Organisms must manufacture or process the materials or chemicals they need in the same environment that they live in and concentrated toxins, such as snake venom for example tend to be produced and used and locally (Kibert et al., 2002). This is in direct contrast to the typical human approach towards manufacturing. Allenby & Cooper (1994) point out that chemicals including nutrients are toxic in natural systems if in high concentrations, and that living systems typically do not have clusters of high energy and materials transformations and that high fluxes in the use of energy and materials are avoided. Natural materials are all produced at ambient temperature and often use water as the chemical medium (Reap et al., 2005). Benyus (1997), contrasts this with the human tendency to produce materials in high energy, pressure and chemically intensive conditions; the *'heat beat and treat'* approach rather than allowing *'the physics of falling together and falling apart – the natural drive towards self – assembly'* to do the work.

Ecosystems may do more than avoid polluting and in fact may regenerate, and strengthen the system as organisms in it live and die. *'Life on Earth alters Earth to beget more life'* (Kelly, 1994). Rosemond & Anderson (2003) point out that classifying the effects of species in ecosystems as beneficial or detrimental is largely a subjective human interpretation, but may include facilitating the presence of other species and increasing nutrient cycling and mutually beneficial relationships. As ecosystems shift from development stages to more complex stages through time and through the combined activities and interactions of the organisms within them, the system tends to become more adaptable to change and is able to support more organic matter and organisms with longer and more complex life cycles (Odum, 1969, Faludi, 2005).

Mimicking this aspect of ecosystems would require the built environment to be considered as a producer of energy and resources and that it be designed to nurture increased biodiversity in the urban environment. An understanding of ecology in the creation of the built environment would form the basis of it being able to participate in the major planetary cycles (such as the hydrological and carbon cycle etc) in a way which reinforces and strengthens them rather than damages them.

6.6 A*daptation and evolution*

Adaptation and evolution allow organisms and whole ecosystems to persist through the locally unique and constantly dynamic, cyclic environment they exist in. Reap et al. (2005) describe adaptation as the means by which an organism adjusts (behaviourally and physically) to change throughout a lifetime. Evolution is referred to as the process by which genetic changes happen though successive generations in species or ecosystems through the medium of the gene.

Ecosystems are essentially in a constant state of flux and it is this very state of flux that keeps an ecosystem dynamically stable (Allen, 2002). Allenby & Cooper (1994) point out that *'mature communities* [are] *highly dynamic systems, and many subsystems will be in flux at any given time (for example, exhibiting spatial 'patch dynamics'). Maturity is not stasis'*.

Benyus (1997) touches on the idea that nature *'curbs excesses'* from within systems (internal feedback) as well as from external events or changes (external feedback). Feedback mechanisms, or the way that changes in one part of the ecosystem are communicated throughout the entire community are cited as a factor in the ability of ecosystems to adapt and evolve (Allenby and Cooper, 1994). Limits existing in ecosystems are also often discussed in terms of carrying capacity and intensity of flows of materials and energy (Berkebile & McLennan, 2004).

The implications of applying this principle to architectural design could range from a redefinition of when a building is considered to be finished, designing it to be more dynamic over time (applying techniques for additive and adaptable design and design for disassembly for example), to designing systems that incorporate some level of redundancy to allow for added complexity to evolve over time, increasing the ability of the built environment to be able to respond to new conditions and possibly to become self-maintaining.

7 CONCLUSIONS

Since the industrial revolution, esteemed examples of architecture have typically been based upon the metaphor of the machine of the industrial age as demonstrated by Le Corbusier's famous quote: *'The house is a machine for living in'*. Korten, (2007) discusses the importance of changing the metaphors, or 'stories' cultures are based on, while Gould & Hosey (2007) elaborate on the expansion of the conversations communities must have if humans are to become more sustainable. If ecosystems rather than machines are to become the philosophical design metaphor and the practical metric for architectural design, the built environment may come to be considered less as a collection of distinct buildings that behave like objects set in an arbitrary landscape, but rather as nodes in a system that become conduits, and ultimately producers of energy and nutrients (materials) in a complex, cyclic system. This is in contrast to the current status of the built environment as a heavy consumer and polluter. Such an approach is ultimately rooted in the design team having a deep and intimate understanding of the context of the place a design is sited in, as well as an understanding of basic ecology.

The importance of architectural design based on an understanding of ecology is discussed by researchers advocating a shift to regenerative design (Reed, 2006). This discourse tends to be theoretical at present and as such many of the ideas expressed in this paper have yet to be tested in realised built form.

Such an ecosystem based biomimicry is likely to be dependant on a collaborative approach to design that includes both design professionals and ecologists. Even with increased collaboration, achieving success in such an approach may be dependant on design professionals understanding basic concepts of ecology and ecologists understanding basic concepts of design. Only then perhaps will designs based on ecosystem principles transcend the level of metaphor and incorporate a 'deeper' form of biomimicry, able to imbue buildings with the ability to become a functioning part of ecosystems.

An ecosystem based biomimicry operating formatively in setting the initial goals and in establishing the performance standards by which the appropriateness of changes to the built environment are evaluated, has the potential to create a significantly more sustainable and ultimately regenerative built environment, transforming ideas about what the built environment is and how it relates in a mutualistic way with the ecosystems it is part of, particularly if humans collectively begin to behave like a species that intends to remain on earth.

REFERENCES:

Alberti, M., Marzluff, J. M., Shulenberger, E., Bradley, G., Ryan, C., & Zumbrunnen, C. (2003). Integrating humans into ecology. *BioScience, 53*(12), 1169-1179.

Aldersey-Williams, H. (2003). *Zoomorphic - new animal architecture*. London: Laurence King.

Allen, T. F. H. (2002). Applying the principles of ecological emergence to building design and construction. In C. J. Kibert, J. Sendzimir & G. B. Guy (Eds.), *Construction Ecology*. London: Spon Press.

Allenby, B. R., & Cooper, W. E. (1994). Understanding industrial ecology from a biological systems perspective. *Total Quality Environmental Management, Spring*, 343-354.

Baumeister, D. (2007). Presentation at the University of Washington, Seattle, WA. 8 May.

Benyus, J. (1997). *Biomimicry - innovation inspired by nature*. New York: Harper Collins Publishers.

Berkebile, B., & McLennan, J. (2004). The living building. Biomimicry in architecture, integrating technology with nature. *BioInspire 18*.

Biomimicry Guild (2007). *Innovation inspired by nature work book*: Biomimicry Guild.

Charest, S. (2007). Ecosystem principle research. Personal Communication, May.

Copeman, D. (2006). Permaculture for urban sustainability - draft chapter for the book steering sustainability: Royal Melbourne Institute of Technology.

de Groot, R., Wilson, M. A., & Boumans, R. M. J. (2002). A typology for the classification, description and valuation of ecosystem function, goods and services. *Ecological Economics, 41*, 393-408.

Faludi, J. (2005). Biomimicry for green design. *World Changing*.

Gould, K., & Hosey, L. (2007). *Women in green*. Bainbridge Island: Ecotone Publishing.

Graham, P. (2003). *Building ecology - first principles for a sustainable built environment*. Oxford: Blackwell Publishing.

Harding, S. (2001). *Complexity and stability in a Gaian ecosystem model.* Paper presented at the International School Earth and Planetary Sciences, Earth Science System, Siena.

Hastrich, C. (2006). The biomimicry design spiral. *Biomimicry Newsletter, 4*(1), 5 - 6.

Hoeller, N. (2006). Patterns in nature: Sustainability Innovation Network. Unpublished work.

Imhoff, M. L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., & Lawrence, W. T. (2004). Global patterns in human consumption of net primary production. *Nature, 429*, 870 - 873.

Kay, J., & Schneider, E. (1994). Embracing complexity: The challenge of the ecosystem approach. In L. Westra & J. Lemons (Eds.), *Perspectives on Ecological Integrity* (pp. 49-59). Kluwer: Dodrecht.

Kellert, S. R. (2005). *Building for life*. Washington DC: Island Press.

Kelly, K. (1994). *Out of control - the new biology of machines*. London: Fourth Estate.

Kibert, C. J., Sendzimir, J., & Guy, G. B. (2002). *Construction ecology*. New York: Spon Press.

Korhonen, J. (2001). Four ecosystem principles for an industrial ecosystem. *Journal of Cleaner Production, 9*, 253-259.

Korten, D. (2007, April 25-27). *Presentation* at the Living Future Conference, Seattle, WA.

McDonough, W., & Braungart, M. (2002). *Cradle to cradle - remaking the way we make things*. New York: North Point Press.

Odum, E. P. (1969). The strategy of ecosystem development. *Science, 164*, 262-270.

Pedersen Zari, M. (2007 June 1-3). *Biomimetic approaches to architecture.* Poster presented at the Toronto Sustainable Building Conference 07, Toronto, Canada.

Reap, J., Baumeister, D., & Bras, B. (2005). *Holism, biomimicry and sustainable engineering.* Paper presented at the ASME International Mechanical Engineering Conference and Exposition, Orlando, FL.

Reed, B. (2006) Shifting our Mental Model - "Sustainability" to Regeneration. *Rethinking Sustainable Construction 2006: Next Generation Green Buildings.* Sarasota, Florida.

Rosemond, A. D., & Anderson, C. B. (2003). Engineering role models: Do non-human species have the answers? *Ecological Engineering, 20*, 379-387.

Shear McCann, K. (2000). The diversity-stability debate. *Nature, 405*, 228-233.

Storey, J. B., & Pedersen Zari, M. (2006). *Factor X - well being as a key component of next generation green buildings.* Rethinking Sustainable Construction Conference, Sarasota, Florida.

Thompson, D. W. (1942). *On growth and form* (2nd ed.). Cambridge: Cambridge University Press.

Van der Ryn, S. (2005). *Design for life: the architecture of Sim Van der Ryn*. Salt Lake City: Gibbs

Vincent, J. (2002). Systematic technology transfer from biology to engineering. *Philosophical Transactions of the Royal Society, 360*, 159-173.

Vincent, J. F. V., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A.-K. (2006). Biomimetics - its practice and theory, *Journal of the Royal Society Interface*: The Royal Society.

Vogel, S. (1998). *Cat's paws and catapults*. New York: Norton and Company.

Xiong, J., & Bauer, C. E. (2002). Complex evolution of photosynthesis. *Annual Review of Plant Biology, vol. 53*, pp. 503 - 521.