Reference:
Pedersen Zari, M. and J. B. Storey (2007). An ecosystem based biomimetic theory for a regenerative built environment Lisbon Sustainable Building Conference 07, Lisbon, Portugal.

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 and comprehensive application of biomimicry as a design methodology and benchmarking tool, particularly in the built environment, remains elusive. One reason identified for this is the lack of a comprehensive and rigorous general theory of biomimicry that could be applied to the architectural design process and its outcomes over entire building lifecycles. This paper attempts to clarify various approaches to biomimicry and provides a set of principles that could form the basis of an ecosystem based biomimicry. It is posited that such an approach could become a vehicle for creating a built environment that goes beyond simply sustaining current conditions to a restorative 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

The term *biomimicry* originates from the 1960s, and was popularised by the publication of *Biomimicry - Innovation Inspired by Nature* in 1997 by Benyus. Vincent (2006) points out that the *mimicry* part is not intended to a slavish copying of organisms, but instead an interpretation, adaptation or derivation from biology. This process of translation often results in designs that are not immediately similar to the organism that inspired them, but utilise the same functional concepts. An example is Sto's Lotusan paint, inspired by the lotus flower. Because the flower emerges from swampy waters clean, it has long been an ancient symbol of purity. By studying the nano-structure of the lotus leaf, scientists observed that due to its rough texture, water beads on the leaves, drawing dirt from the leaf as the droplets roll off. The paint does not resemble the lotus, but allows surfaces to be self-cleaning in a way similar to the lotus.

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 translating that into a human need (biology influencing design) (Biomimicry Guild, 2007).

Within these two approaches, there are three levels of mimicry: The organism level, the behaviour level and the ecosystem level (Pedersen Zari, 2007). The organism level refers to a specific organism and may involve mimicking part or the whole of the organism. The second level refers to mimicking behaviour, and may include how an organism does things. The third level is the mimicking of whole ecosystems and the common principles that allow them to successfully function. Within each of these levels, are a further five possible dimensions to the mimicry: what it looks like (form), what it is made out of (material), how it is made (construction), how it works (process) and what it does (function). Pedersen Zari (2007) provides examples of the differences.

Commonly cited examples of biomimicry are typically of products or materials rather than buildings, and tend to mimic a single organism. Biomimetic examples where an ecosystem process has been mimicked are less common. There are however examples of waste water filtering based on how wetlands or soil based decomposition works (Todd, 2004; Allen, 2005).

2 BIOMIMICRY FOR REGENERATIVE DESIGN

While biomimicry at the organism level may be inspirational for its potential to produce novel designs, the possibility that biomimicry could transform architectural design from a paradigm of sustainability to one of regeneration (Van der Ryn, 2005) is less well understood or explored.

Through an examination of existing biomimetic technology and literature it is clear that markedly different approaches to biomimetic design have evolved and can have clearly different outcomes in terms of an increase in overall sustainability. As Reap et al. (2005) demonstrate, products or materials that are organism biomimetic without also being system 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 a 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.

Pedersen Zari (2007) elaborates on the impact different approaches to biomimicry can have on the overall sustainability of the product or system. Examples provided demonstrate the deepening of the levels of biomimicry in terms of regenerative potential. A building that is stylistically based on an organism, but is made and functions in a conventional way for example is unlikely to be a truly sustainable building. A building that is able to mimic natural processes and can function like an ecosystem in its creation, use and maintenance has the potential to be part of a regenerative built environment.

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 the mimicking of form. A documented example is Mick Pearce's Harare Building in Zimbabwe and CH2 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 a mimicking of form. An example is the Waterloo International Terminal. Designed by Nicholas Grimshaw & Partners, it is able to respond to changes in air pressure as trains move through the terminal. It's glass panel fixings mimic the flexible, scaly Pangolin so they are able to move in response to imposed forces.

The authors are not aware of any architectural examples that demonstrate comprehensive ecosystem based biomimicry. There are aspects of existing and proposed projects that display concepts of such an approach such as the Lloyd Project proposed for Portland, Oregon by a design team including Mithūn Architects and GreenWorks Landscape Architecture Consultants. The project uses estimations of how the ecosystem that existed on the site before development functioned, termed by them *Pre–development Metrics*™ to set goals for the ecological performance of the project.

4 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 humans, it may be as Alberti et al, (2003) suggest, impossible to look at ecosystems as separate from humans.

Despite the fact that there may not be many 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 or are type three (more complex and longer lived), tend to function in way that is conducive to sustained and ongoing life (Benyus, 1997). In this particular period of human existence, there are perhaps some valuable observations humans can make in the creation of human habitat that is able to integrate with rather than damage ecosystems they are part of.

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

5 ECOSYSTEM RESEARCH

By conducting a comparative analysis of related knowledge of ecosystem principles in the disciplines of ecology, biology, industrial ecology ecological design and biomimicry, a group of ecosystem principles aiming to capture cross disciplinary understandings of ecosystem functioning was formulated. 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 lists or explanations of generalised ecosystem principles. From this, a list 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.

It should be noted that ecology literature typically does not offer sets of generalised principles but tends to explore the complexities of certain aspects of ecosystems, and that there are a number of controversial theories in ecology, such as the exact process and mechanisms of evolution and ecological succession for example (Kay & Schneider, 1994).

There are a number of different ways of organising the information, as evidenced by the diversity in aspects of ecosystems that authors in different disciples discuss and the ways they categorise them. 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 thought 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 network diagram could be a step in the evolution of a model that is able to portray this. A recent iteration of the Biomimicry Guild's Life's *Principles* is the only non-linear model that the authors are aware of (Biomimicry Guild, 2007).

6 ECOSYSTEM PRINCIPLES

The ecosystem principles provided here are 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 may remain at the level of metaphor. Korhonen (2001) points out, the '*direction we should follow when striving towards sustainable development is to learn from the ecosystem, although this effort may still be only at a metaphoric level.*' While this is not insignificant in terms of increasing overall performance of the built environment, opportunities to be positively integrated with global biogeochemical cycles through a thorough understanding of ecology may exist.

The ecosystem principles provided here are in a list format (with a brief explanation following) in order to be an easily usable set of generalised principles that if employed by designers with limited background knowledge in ecology could significantly improve the sustainability of the human built environment. They are not intended to be a comprehensive and complete explanation of the way ecosystems function that are able in the present form to encapsulate the varying opinions and exact mechanisms of functioning discussed in ecology literature.

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

6.1 *Ecosystems are dependant on contemporary sunlight.*

-Energy is sourced from contemporary sunlight.

-The sun acts as a spatial and time organising mechanism.

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 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 be 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 still harnessing converted energy from the sun in 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, (dependant in part on solar radiation as established) are also 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 its energy was sourced from contemporary sunlight (including wind, hydro and biomass) and it was sited and organised according to climate, environmental impact would be considerably less and there may be consequent significant positive physical and psychological health impacts (Kellert, 2005).

6.2 *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.

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 a global closed loop system, 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 etc.

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 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 increased communication and organisation to ensure effective material cycles and careful energy flow would challenge conventional attitudes to building boundaries and the idea of waste.

6.3 *Ecosystems are attuned to and dependant on local conditions.*
-Materials tend to be sourced and used locally.
-Local abundances become opportunities.

Species that make up ecosystems tend to be linked in various relationships with other organisms in close proximity (Allenby & Cooper 1994). 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 *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.

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 (Harding 2001). 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, Kelly 1994). Kibert et al. (2002) describe this aspect of ecosystems as *self-organisation*. This kind of organisation, based on multiple feedback mechanisms, tends to have high amounts and transfer rates of information (Allenby & Cooper 1994).

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

6.5 *Ecosystems create conditions favourable to sustained life.*

- Production and functioning is environmentally benign.
- Ecosystems enhance the biosphere as they function.

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 (Rosemond & 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 used and produced 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 to have clusters of high energy and materials transformations and avoid high fluxes in the use of energy and materials. Materials (both internal such as organs and external such as shells) are produced at ambient temperature and often use water as the chemical medium (Faludi 2005). Benyus (1997), contrasts this with the human tendency to produce in the energy and materials intensive *'heat beat and treat'* method 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 potential mutualisms. 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 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 *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

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 slower 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 & Cooper, 1994). Limits existing in ecosystems are 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, allowing it to be more dynamic over time (applying techniques for additive and adaptable design and design for disassembly for example), to designing mechanisms into building systems 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 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 as sculptures in an arbitrary landscape, but as nodes in a system that become conduits, transformers 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.

An ecosystem based biomimicry forming the initial goals and metrics and final evaluation for the appropriateness of changes to the built environment 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, J. (2005). Global winner, Biolytix is taking on effluent society. *ECOS, 5*(Oct-Nov), 127.
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.
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, FL.
Thompson, D. W. (1942). *On growth and form* (2nd ed.). Cambridge: Cambridge University Press.
Todd, J. (2004). Restorer eco-machines for the culture of aquatic animals and the restoration of polluted aquatic environments. *BioInspire 19*.
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.