Environmental Science

http://www.aimspress.com/

AIMS Environmental Science, 2(4): 950-969.
DOI: 10.3934/environsci.2015.4.950
Received date 26 May 2015,
Accepted date 26 November 2015,
Published date 10 December 2015

Review

Biophilic architecture: a review of the rationale and outcomes

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Abstract: Contemporary cities have high stress levels, mental health issues, high crime levels and ill health, while the built environment shows increasing problems with urban heat island effects and air and water pollution. Emerging from these concerns is a new set of design principles and practices where nature needs to play a bigger part called "biophilic architecture." This design approach asserts that humans have an innate connection with nature that can assist to make buildings and cities more effective human abodes. This paper examines the evidence for this innate human psychological and physiological link to nature and then assesses the emerging research supporting the multiple social, environmental and economic benefits of biophilic architecture.

Keywords: biophilia; biophilic design; urban heat island; stress reduction; productivity; air quality; cities; green roofs; living walls

1. Introduction

Biophilic architecture is based on the assertion that humans have an innate connection with nature that should be expressed in their daily lives, especially in cities. This has not been a strong feature of architectural principles (even though there has been a long tradition of landscape architecture), yet potentially offers great rewards if the assertion is true. This paper reviews the psychological and physiological evidence that explains the human-nature connection. If the innate connection is real, then there should be evidence whenever biophilic architecture is practiced for significant social, environmental, and economic benefits. Although it will use some of the evidence for how landscaping between buildings impacts on the human connection with nature, this paper will emphasize how the new biophilic architecture associated with landscaping buildings using green roofs, green walls, indoor plants, and features such as fractal patterns in materials, is creating new human nature connections. The literature supporting the benefits of such architecture will then be reviewed. The goal is to establish a scientific basis for biophilic design using the human, natural, economic, and social sciences.

2. Background—the emergence of biophilic design

Biophilia was a term first brought to life by the psychoanalyst Fromm in his exploration of the "*Essence of Man*", that which defines humanity [1]. He saw that humans' awareness of their "beingness," their mortality, separates them from nature, instilling a deep anxiety and conflict. In the quest to overcome this anxiety two paths can be taken, a regressive path of narcissm, incestuous symbiosis, violence and necrophilia or a progressive path of altruism, freedom, and biophilia. "Biophilia" was defined as a love of life and living processes [1].

The concept of the biophilic human being was then examined and popularized in 1984 by the sociobiologist, Wilson in his book *Biophilia*. Wilson defined biophilia as "the innate tendency to focus on life and lifelike processes" [2]. He utilized the term "biophilia" to describe his deep feelings of connection to nature during a period of exploration and immersion in the natural world. Wilson's unique insight was that this biophilic propensity developed as part of evolutionary survival and, thus, encompasses certain characteristics that remain with humans even in modern cities. He posited that a love of life is an innate human tendency and to "explore and affiliate with life is a deep and complicated process in mental development" [2].

Scholars from diverse fields collected together a decade later to collaborate their thinking and debate the concepts presented by Wilson. From this assemblage of intellectuals, emerged the book *The Biophilia Hypothesis*. Together, Wilson and a fellow ecologist, Kellert, hypothesized that nourishment of this innate love and connection to nature is essential for modern urban human wellbeing, going far beyond a basic provision of sustenance. They suggested that humans are biologically designed to respond positively to contact with nature, and, as Fromm first postulated, this affiliation can assist in humans' intellectual, emotional, and spiritual fulfilment [3].

In 2006, a conference at Rhode Island in the US drew together interested participants from academia, industry, government, finance, and civil areas to further discuss *The Biophilia Hypothesis.* The focus was on practical implementation of the benefits of biophilia into urban design and architecture. From this conference emerged another book *Biophilic Design: The Theory, Science, and Practice of Bringing Buildings to Life* [4], which established cross-disciplinary foundations for a biophilic design approach to the built environment.

3. Current urbanity

A core theme from the biophilic design literature is that humanity has lost something in its approach to building design in modern times [5]. Human affiliation with nature is seen to be historically reflected in organic building designs and materials, in patterning and spaces that mimic those of nature, and in traditional living with close, but respectful proximity, to the natural environment. Greening of roofs and walls was common place in traditional architecture, providing insulation, food, and aesthetics. However, modern architecture has lost this scope. Advancements in industry and technology not only provided the means to mechanize and sterilize buildings and design, but also the ability to influence humans' psychological attitude to nature. Salingaros and Madsen proposed the following three "conceptions of human beings":

1. The Abstract Human Being—humans are regarded as a component in a mechanical world;
2. The Biological Entity—the human being is an organism made of sensors that interact with its environment; and
3. The Spiritual Being—humans are something more than a biological neural system, connected to the universe in ways that other animals are not [6].

They suggested that the contemporary, mechanistic, and sterile urban world has fostered an increase in the abstract human being, of people living without direct connection to nature. They live as "an inert passenger in a fundamentally sterile and non-interactive world" [6].

Societies have been able to transcend the need to accommodate direct connections with nature, modifying the environment to perceptually suit human needs, whilst encouraging a separation and disconnect from the natural world [7,8]. Modernist designs encouraged a fear of nature (due mostly to waterborne diseases and parasites) that led to very sterile urban environments [9]. The contention is, therefore, made by biophilic design writers that contemporary cities are places not designed for mental health and wellbeing. What biophilic designers see as the missing evolutionary element in modern cities is the need to re-establish an innate connection to nature in everyday life. As Beatley stated "we need a daily dose of nature," which means nature must be integrated into all parts of our buildings, not separating people in buildings from people in nature [10]. As biological beings, humans have not adapted physiologically, emotionally, or psychologically to the current sterile urban technological cities. This "mis-match," where the environment that humans occupy is so removed from the one in which humans have evolved, could be the disjuncture that has led to much of modern stress and mental health issues [11,12]. The evidence for such associations will be assessed below, but first the kind of design approaches suggested to enable nature to be better incorporated into cities will be outlined.

4. Biophilic design attributes

The ability of architectural design to influence individuals' physiological and psychological states is an extension of the biophilic connection to nature. Expression of this connection through biophilic design in architecture has occurred throughout history, not always consciously, or even acknowledged, conveying a subjectiveness that testifies to its inherent quality in humans. Nature can be mimicked by using the patterning, forms, materials, symbols and spaces that represent nature and evoke similar responses. Alexander recognized this in his seminal book *Pattern Language*, although not using the term biophilia, he expressed similar insights: "Many of the patterns here are archetypal—so deep, so deeply rooted in the nature of things, that it seems likely that they will be a part of human nature, and human action, as much in 500 years as they are today" [13].

As with biophilic design theory, Alexander believed that the pattern language of the nature of things in the environment "can make people feel alive and human"[13]. When people cannot surround themselves with nature, then architecture and landscapes that contain some archetypal natural elements have found expression in urban design. Similar to Wilson [2] , Appleton considered that human's aesthetic reactions to landscape and architecture "are in part inborn" and, therefore, people cannot stray too far from the natural patterning before destroying their "aesthetic experience" [14]. He posited that humans must seek to recreate something of the primitive connection with nature to maintain an experience of wellbeing. The prospect-refuge theory conceived by Appleton suggests that individuals feel good when safe in a place of refuge, a feeling enhanced when they have a window overlooking life and the happenings around them. This reflects the innate protective need to survey for hazards from a place of safety [14]. Either refuge or prospect on their own can still contribute to a sense of wellbeing, but Appleton suggested that the two together are most appealing.

Wilson [2] also considered prospect (vantage points) and refuge attributes that contribute to positive human feelings. In addition, he theorized that humans' evolutionary beginnings in the African savannah similarly led to a positive psychological response to environments with shade trees, waving grasses, and far vistas. This is now commonly known as the "savannah effect" and is demonstrated in a design example by Lloyd Wright with his iconic Johnson-Wax building.

Proponents of biophilic design have elaborated these design concepts, finding validity through experience, intuitive knowing, and historical examples [15-17]. Contributors to the book, *Biophilic Design: The Theory, Science, and Practice of Bringing Buildings to Life,* recognized the need to define the dimensions of biophilic architecture as the beginning of a toolkit for architects and developers [4]. Heerwagen and Gregory [15] categorized seven major attributes, whereas Kellert [5] listed six elements with seventy design attributes.

Ryan et al. [19] refined these elements of biophilic design with supportive qualitative and quantitative research in both the physiological and the psychological. Browning [18] recognized that previous design attribute lists were unwieldy and potentially confronting for designers, consolidated the design attributes to the following fourteen patterns within three categories (Table 1).

Table 1. Patterns of biophilic design.

Nature in the space: incorporation of plants, water, and animals into the built environment, especially with movement	**Natural analogues:** one degree of separation away from true nature; patterns and materials that evoke nature	**Nature of the space:** the way humans respond psychologically and physiologically to different spatial configurations
1. Visual connection with nature—plants inside and out, green roofs, and living walls, water, nature artwork	8. Biomorphic forms and patterns—organic building forms, structural systems (savannah effect)	11. Prospect—views, balconies, 6 m and above focal lengths, open floor plans
2. Non-visual connection with nature—sun patches, textured materials, bird sounds, weather, nature scents	9. Material connection with nature—organic building forms, structural systems (savannah effect)	12. Refuge—protected spaces, overhead canopies or lowered ceilings, places providing concealment
3. Non-rhythmic sensory stimuli—clouds, shadows, nature sounds, water reflections	10. Complexity and order—fractal patterns, sky lines, plant selection, and variety, material textures, and colors	13. Mystery—winding paths, obscured features, flowing forms
4 Access to thermal and airflow variability—shade, radiant heat, seasonal vegetation		14. Risk/peril—floor to ceiling windows, water walks, high walkways
5. Presence of water—rivers, fountains, water walls, ponds, daylighted streams		
6. Dynamic and diffuse light—light from different angles, ambient diffuse lighting, circadian lighting		
7. Connection with natural systems—seasonal patterning, wildlife habitats, diurnal patterns		

(Adapted from Ryan et al. [19])

Kellert [20] recently revised and simplified his seventy design attributes. Twenty-four design attributes were headed by three categories of experience similar to Ryan et al.: direct experience of nature, indirect experience of nature, and experience of space and place.

Biophilic architecture is emerging as a new design theory around better contact with nature within and on buildings. But does the biophilic urbanism literature generate confidence that there is evidence to support the need for this design approach?

5. Evidence for the human psychology and physiology rationale

In the last 30–40 years, advancements in human psychology and physiology have begun to test whether there is an innate human relationship with nature that is the fundamental rationale for biophilic urbanism. The biochemical underpinnings of human psychological and physiological responses was a little examined area until the work of neuroscientist Pert and her colleagues. Pert's discovery in 1972 of humans' opiod receptors [21] and the subsequent discovery of the natural opiate of enkephalin (endorphin) by Hughes and Kosterlitz (as published by Pert [22]), pioneered the ability to test for feelings of pleasure and wellbeing. In this way, the link between psychological wellbeing and physiological responses became established.

In 1979, Ulrich began investigating links between psychological wellbeing and physiological responses when individuals are exposed to nature or even views of nature. Psychological testing of responses to projected slides revealed that stressed individuals feel considerably better when exposed to views of nature [23]. In 1984, Ulrich decided to test this response with hospital patients' analgesic usage and recovery times with and without a view of nature. Recovery times were faster for the patients with a view of nature, along with less need for pain relief [24].

Kaplan and Kaplan were also researching the potential benefits of the human relationship with nature, and in 1989 presented a psychological perspective of experiencing nature. They built on the 1892 work of James, who identified two types of attention: voluntary and involuntary. Involuntary attention is what we give to things that "catch our eye", often moving, patterned, bright, and stimulating. Voluntary attention is where a focus is held, blocking out unwanted stimuli (it can be exhausting). Aggressive, irritable, and antisocial behavior plus slow responses can result from directed attention fatigue. Restoration is important and involves involuntary attention. Kaplan and Kaplan suggested that exposure to nature, over a range of environmental choices can fulfil the criteria for directed or voluntary attention restoration [25].

In 1991, Ulrich employed electrocardiograms (EKG) and measured pulse rates, frontal muscle tension and skin conductance plus self-ratings of emotional states to further investigate the physiological relationship with nature. Both physiological and verbal results indicated that recovery from stress was faster in a natural setting than an urban one. The physiological results also suggested an involvement of the parasympathetic nervous system [26]. Ulrich proposed a psycho-evolutionary theory that nature restores through increasing positive feelings, positive physiological responses, and sustained involuntary attention [26]. Ulrich's stress reduction theory was perceived to contradict Kaplans' restorative theory, which suggests that peoples' directed attention relaxes in nature due to an involuntary (fascination) attention and is, thus, restorative. Kaplan's investigation of this apparent dichotomy led to an integrative understanding that deepened the theoretical exploration of the human-nature connection and formed the attention restoration theory [27].

Since Pert's early work, other physiological markers of psychological feelings and moods have been established, enabling quantifiable physiological analysis. Cortisol and cortisone are hormones released when the body is stressed. Cortisol is now widely used as a stress marker. Blood pressure, heart rate, skin moisture conductivity all increase when individuals are anxious or stressed. Studies have emerged from Japan on the effects of the traditional Shinrin-yoku, or forest bathing. These and other research have shown that exposure to nature reduces heart rate variability and pulse rates, decreases blood pressure, lowers cortisol, and increases parasympathetic nervous system activity, whilst decreasing sympathetic nervous system activity [28-33]. These responses contribute to improved cognitive functioning, working memory, and learning rates. Forest walking has also revealed that levels of the hormone DHEA tend to increase [28].

Both Kaplans' and Ulrich's theories have been put to the test in the years since they were first proposed, either directly or by studies revealing supporting results. Berto [34] undertook three experiments involving 32 participants, and concluded that restorative environments and experiences that involve nature do greatly support mental fatigue recovery. She suggested that in a "world overflowing with information," mental fatigue is endemic and much could be done, especially in institutions, to help cognitive wellbeing [34]. Following the increasing interest in Kaplan's restoration theory, Ivarsson and Hagerhall [35] also began investigations into the restoration values between differing forms of natural environments amongst built environments, such as gardens. The varying results between gardens suggested that greater understanding of the form of the natural environment, and its potential to be restorative, was needed [35]. Hartig et al. [36] supported the theoretical evidence for restorative environments. They discuss the relationship between restorative environmental design and biophilic design, suggesting that restorative design encompasses more than biophilic design by taking into account low-impact technologies, people's activity cycles, and varying needs for restoration plus the impact of cultural experience on peoples' receptivity to biophilic influences.

Salingaros and Masden suggest that "environments devoid of neurologically nourishing information mimic signs of human pathology. Drab minimalist surfaces reproduce symptoms of strokes and macular degeneration, for example" [6]. Environments that are devoid of any representation of nature can not only make people psychologically unwell and regressive in their behavior, but people can also display physical symptoms and responses. A recent study that examined human responses to design stimuli, concluded that the primal flight or fight response is increased when individuals are exposed to hard edged architecture rather than curving contours [37]. They also suggested that this response is heightened when a person is already in a stressful environment, such as a hospital [37].

Increasing greenery in housing estates resulted in less violence and aggression, less crime, and better interpersonal relationships [38]. Further research by Kuo also suggested that greener environments in poorer public housing estates reduces mental fatigue and assists "residents' psychological resources for coping with poverty" [39]. Studies by Guègan and Stefan observed that short immersions in nature elicited a more positive mood and a greater desire to help others [40].

Berman et al. [33] investigated the interaction with nature on direct attention restoration and improved cognitive functioning by comparing urban and natural environments. Their results further validated Kaplan's restoration theory, and showed that even viewing pictures of nature can improve cognitive functioning, mood, and working memory [33]. Raanaas et al. [41] conducted controlled laboratory experiments on attention restoration with and without plants. Although only four pot plants were utilized there were improvements in performance in the room with plants than the room without plants [41]. Their results suggest that exposure to nature could be a valid supplement to treating depression and other disorders, with improvements to mood and memory span [29,32].

Park and Mattson [42] suggested that, with further supporting evidence, plants should be used in hospitals as a supplementary healing mode. Their research had confirmed Ulrich's early studies on the positive effects that nature has on a patients' recovery period and analgesic need. Park and Mattson found that indoor plants "enhance patients' physiological responses, with lower ratings of pain, anxiety and fatigue, and more positive feelings and higher satisfaction with their hospital rooms" [42]. A study in Michigan revealed a 24% less frequency of healthcare visits for prison residents with views of nature [43]. Measurements of elderly women exposed to a green rooftop forest on a hospital showed that they were more physiologically relaxed and restored [30].

Research of the physiological and psychological responses of office workers to a vase of roses by Ikei et al. [44] has demonstrated the use of both psychological and physiological markers. Heart rate variability, pulse rate, and subjective responses, evaluated through a Profile of Moods (POMS) questionnaire, were measured. Heart rate variability is a physiological indicator of the human nervous system and, thus, can be used to reflect parasympathetic and sympathetic nervous system activity [28,30,31]. The study showed that by simply viewing roses, parasympathetic nervous system activity increases, indicating lower stress and a greater sense of wellbeing [44].

A Finnish study investigated the psychological effects (restorativeness, vitality, mood, and creativity) and the physiological effects of short term immersion in nature [32]. The physiological response was measured using salivary cortisol as an indicator of stress. Results suggested that even short-term exposure to nature had positive effects on stress compared to the urban built environment [32]. Nieuwenhuis et al. [45], noticing two opposing trends in offices, conducted studies of the comparison: lean versus green. They concluded that lean is "meaner than green," not only because it was less pleasing to the workers, but also because organizational output and productivity was significantly less in the lean offices [45].

It is not just direct exposure to greenery that has positive human responses. Research by Ivarsson and Hagerhall [35] suggested that there may be different human responses to different natural forms. People respond both psychologically and physiologically to natural patterning and the spaces of nature. Prime amongst these are the fractal patterns of nature (self-replicating patterns that occur at increasingly smaller magnification are found throughout nature), especially those with "high randomness and mid to low fractal dimension." Research suggests that these patterns relax and de-stress people [46,47]. Viewing nature, especially the richer patterns, is literally pleasurable due to the stimulation of the mu-opioid receptors in the human brain and greater endomorphin release [48]. Although seen throughout architecture and art and intuitively appreciated, it is only recently that measurement of the psychological and physiological responses to fractal patterns has occurred [49-51]. It was found that certain fractal dimensions trigger more intense physiological responses, with many of these responses indicative of stress reduction [51]. Taylor suggested how incorporating a rich variety of fractal patterns into buildings can be useful in situations where "people are deprived of nature's fractals" [51]. Varying sounds, colors, and light can produce similar pleasurable physiological responses, as can movement such as waving grasses, especially when viewed in the eyes' periphery.

Thus, there is strong evidence for an innate human response to nature. The conclusion to this section is that psychological and physiological evidence is now emerging to suggest that there is a scientific basis for biophilic design. If this is the case, then there should be strong economic, environmental, and social outcomes associated with such design. The next section seeks to find and present this evidence.

6. Socio-psychological benefits

From the research already reviewed a list of socio-psychological benefits can be compiled:

- Improved mental health [23,26,29,32];
- Reduced stress [28-33,44,46,51];
- Attention restoration [27,34,35,41];
- Increased wellbeing [28,29,32-44,46];
- Decreased violence and crime [38];
- Faster healing rates in hospitals [24,42,43]; and
- Greater altruistic behavior [40].

Such benefits are not isolated; but interact with all aspects of human settlements. The evidence will be assessed for the environmental and economic benefits that flow from a better connection between humans and nature in architectural design.

7. The environmental benefits

Decreased biodiversity, urban heat island (UHI) effects and pollution have become current and urgent environmental issues that challenge the resilience of cities. Kellert, Heerwagen and others in the biophilic design movement from the 2006 conference and beyond, recognized the potential environmental benefits of restoring and enhancing nature in architectural design. These emergent biophilic design advocates primarily focused on the human-nature connection though they acknowledged the possible benefits, not only with the human-nature relationship, but also environmentally that a shift towards a design approach that integrates nature into cities could bring. Following this time, the biophilic design movement, especially with Beatley [10] and his research group [52], have emphasized environmental restoration and regeneration.

In the last decade, research on the environmental benefits of biophilic architecture has focused on the benefits of direct greenery, predominantly on roofs. Green roofs have a historical place in urban design with the early sod roofs of European architecture, but have now developed new engineering techniques to enable green roofs to become a major architectural feature of innovative buildings [53]. For instance, in Toronto, Canada, a relatively recent bylaw (since 2009), requires the installation of green roofs. Vertical greenery has also progressed from vine-covered facades to vertical living walls since the aesthetic designs and constructions of innovative French botanist Blanc [10,54]. As a result, a range of environmental benefits have been evaluated, including improvements to water, air, biodiversity, and heat.

7.1. Water management

The global expansion of urbanized, paved, and concreted regions has contributed to stormwater runoff being a significant management problem in many cities [55-57]. The ability of vegetation, including the growing medium, to uptake and absorb water is proving to be a successful strategy to manage runoff and associated waterway pollution [58,59]. Quantifying research of the efficacy of this is consistently showing that significant reductions of stormwater runoff can be achieved, especially through the use of green roofs [56-58], and to a lesser extent green walls [60]. Variance in retention occurs due to climate, seasons, plant type, slope of roof, and substrate depth, but the appropriate combination can achieve average retention rates of 70% or more [55-57]. Biophilic design in the form of green roofs and rain gardens are significantly aiding stormwater reduction by utilizing plant uptake and absorption of rain water. Green roofs are particularly appealing as they potentially utilize previously unused or underused areas so they do not compete with public space [56]. Vertical green walls also have the feature of utilizing “unused” facades, having minimal footprint and significantly adding, through their visibility, to the aesthetics of the urban environment. Aside from reducing stormwater runoff, they have the potential to reuse water from reclaimed wastewater plus recirculating any excess drainage water for the vertical wall [61].

7.1.1. Water pollution

Gravity encourages water to flow down a living wall and through the plant’s growing medium and, depending on the living wall system, can act as a biofilter for the water used. The large vertical root zone typical of a living wall can also efficiently purify water through the phytoremediation processes of phytofiltration and rhizofiltration [61]. In many US cities, stormwater management is a significant issue. This is due to heavy rainfalls along with urban hard surfaces that collect impurities. A substantial contributor to water pollution in the US are the combined sewer systems (CSSs) that are commonplace in the Northeast, Great Lakes, and Pacific Northwest areas and as urban stormwater runoff increases so does the problem. Combined sewer systems originated in Hamburg, Germany, and were first implemented in the US in Chicago and Brooklyn, with their adoption continuing through the perception of their cost effectiveness [62]. In these systems, a single conduit carries both stormwater and household sewage and wastewater. Heavy rain events are resulting in more frequent combined sewage overflows (CSO), carrying both household pollutants and surface pollutants into waterways [63,64]. The US government has introduced regulations and policies to mitigate waterway pollution through control of stormwater runoff [62]. Washington's Clean River Act is an example of the outcome of one of these policies, an initiative that has catalyzed the introduction of green roofs throughout the city [65].

Research on the effectiveness of green roofs in lessening pollutants in runoff varies in results. While, overall, the research suggests that green roofs can help mitigate water pollution [58,63], there are difficulties quantifying the results due to variance in substrates, plant selection, roof age, and weather events [63,66]. However, there is little doubt that reducing or slowing water runoff through biophilic initiatives, such as green roofs and green walls, does reduce the overall amount of pollutants entering waterways [58].

7.2. Air pollution

7.2.1. Carbon reduction

With high concern about climate change the sequestration of carbon from the atmosphere has received attention. Plant photosynthesis in cities is able to assist in airborne carbon reduction as long as carbon sequestration in roots and stems is able to last long enough to meet recommended standards [67-69]. Carbon can also make its way into the soil from the plant when the plant dies or goes dormant. A deepening of the understanding of this process has led to terrestrial sequestration being examined as a potential aid in atmospheric carbon reduction through managed land practices that impede the stored carbon from being exposed to oxygen and re-entering the atmosphere [70]. It is possible to use the same principles in biophilic design initiatives, especially with green rooftops and living walls [68,69,71-73]. Carbon sequestration by urban street trees can be significant in reducing a city's CO_2 level, with each 50 m^2 crown of trees sequestering 4.5–11 kg of carbon [67]; thus, it is likely that biophilic architecture can also demonstrate carbon sequestration, although large scale demonstrations are still required.

7.2.2. Phytoremediation

Phytoremediation refers to the use of plants and associated soil microbes to reduce the concentrations or toxic effects of contaminants in the environment; it is the ability of plants to "clean" or remediate the surrounding air, soil or water [68,69,71,74]. Pollutants, such as O_3, NO_x, SO_2, NH_3, HNO_3, CO and particulates, can be remediated by urban vegetation [68,75]. Vegetation planted on streets between highrises (street canyons) can reduce particulate matter by as much as 60% and nitrogen dioxide by 40% [74]. Particulate matter adhering to leaf surfaces is absorbed into the plant, or at least diluted, when it is released. In the root area, contaminants are broken down due to interactions between plants and the soil. In the plant tissue, compounds are chemically transformed [71,73]. Phytoremediation involves different mechanisms and different processes, so particular plants are suited more than others for particular pollutants [71,73]. Although few studies have yet appeared, this well-known science would suggest that mechanical filtration and phytoremediation could enable gray water to be used to irrigate green roofs and living walls in hot areas with little water and substantial reduction of pollutants [71].

Ongoing research conducted at the National Aeronautics and Space Administration (NASA) on the potential of plants to assist air purification in closed systems has evolved from a focus on air quality in space stations and closed-system buildings, with particular attention to the removal of formaldehyde and other volatile compounds [76]. Wolverton et al. [76] concluded that plants, particularly the spider plant, were effective in pollutant removal. Studies conducted in a primary school that monitored temperature, CO_2, CO, VOCs, carbonyls, and particulate matter with and without plants corroborated NASA's findings [77]. NASA's research also revealed that the soil, particularly if it contained activated carbon, played an important part in the absorption of pollutants, storing them until the plants are able to utilize the pollutants for food [76,78]. The US Environmental Protection Agency's chief of Indoor Air critiqued NASA's research, however, arguing that it would take 680 plants in a typical house to achieve the same results as the tests.

The University of Guelph in Ontario, Canada furthered NASA's research in conjunction with Canadian and European Space Agencies. They also concluded that it was the soil microbes which removed indoor air pollution. Living walls provide the solution. They can support a large number and variety of plants, thus also a variety of microbes, and be hydroponic and thereby supporting beneficial microbes. Combined with fans circulating air through the wall of plants, an effective indoor biofilter is created. The University of Guelph's Controlled Environment Systems Research Facility designed their first one in 2001, installing the first wall at the University in 2004. Toronto now has a number of indoor biofilter living walls and the number is growing. With successful outcomes and responses, architects are discovering that developers are cost cutting in other areas to pay for the installation of a biofilter green wall. These indoor green walls complement the green roofs now required to be installed on applicable developments since the passing of the 2009 by-law.

7.3. Biodiversity

With declining biodiversity, increasing habitat in cities through increased urban vegetation is receiving focus in many countries. Biodiversity loss is a worsening global issue, galvanizing agreements by governments at the United Nations 2012 conference on biodiversity to increase commitment and spending to halt the rate of the loss [79]. With increasing urbanization the importance of biodiversity conservation in cities increases [80]. Green roofs and green walls, with the appropriate plant species selection, have the potential to mitigate "the loss of ecosystem services in urban areas" [81,82]. Cities in Switzerland, particularly Basel, have been studying the progression of biodiversity associated with their green roofs with encouraging results, resulting in mandatory green roofs on new flat-roofed buildings [83], similar to Toronto. Some bird species are beginning to colonize Swiss green roofs [84]. In a study of 115 "wild colonised" green roofs in northern French cities, 86% of the colonies were found to be native plants [85]. This suggests that, once established, biophilic architectural features could act as important sites for biodiversity colonization from the surrounding bioregion.

Singapore's KTP hospital incorporated greenery and biophilic design throughout the hospital in the hope that this initiative would encourage butterflies back. A goal of 100 butterfly species was set. After three years, 102 species were sighted at the hospital, indicating that the goal had been reached [86]. Newman [86] in his assessment of Singapore's biophilic urbanism suggests that the value of high density cities for biodiversity is the high labor and much greater variety in the structure of habitats (especially vertical sites, i.e. forests in highrise areas).There is much more scientific work to be done in designing and evaluating biophilic architecture for its biodiversity, but the early signs are encouraging and a whole new set of ecological techniques could be emerging.

7.4. Urban heat island effect reduction and reduced energy consumption

With increasing urbanization, urban vegetation is being replaced by low albedo surfaces, such as concrete and asphalt, which alongside less evapotranspiration leads to a phenomenon known as the UHI effect [87]. The appropriate use of vegetation in the built environment can adjust the urban microclimate and improve thermal behavior of building envelopes [88].

Akbari [67] reported that a 25% reduction in net heating and cooling energy use can be achieved in urban areas by planting street trees. For example, 16 shade trees saved 30% energy cooling [68]. These results suggest that biophilic architecture could have a similar impact.

Studies done with models suggest that vegetated facades can reduce the UHI effect around 2 ºC, improve air quality, thermal comfort, and human health, with savings in electricity consumption of 5–10% [89,90]. Shading heat-absorbing surfaces with vegetation may reduce daily temperature fluctuations by 50%, while evapotranspiration can convert large amounts of solar radiation [87]. Vegetated facades also reduce interior temperatures and delay solar heat transfer, leading to reductions in energy consumption used in air conditioning [91].

Green roofs are capable of reducing the use of energy for cooling and heating [90]. French studies concluded that a green roof reduced summer indoor air temperatures by 2 ºC, with the annual energy demand reduced by 6% [92]. Hong Kong research revealed a maximum temperature decrease of 8.4 ºC if both green walls and green roofs are used to create a green urban canyon. City-wide this could reduce energy needed to cool buildings by between 32 and 100% [93]. Sproul et al. [94] examined the economics of green, white, and black roofs. They concluded that either white or green were far more beneficial and, therefore, economical than black. Biophilic green roofs save in energy costs through insulating effects and evapotranspiration, but contribute less to cooling than white roofs.

8. The economic benefits

Figure 1 summarizes the core argument and flow of the paper that the innate human-nature connection should show in direct measurements of human and nature interactions, it should also show in how cities work in environmental measurements, and that together these two should lead to economic improvements. Socio-psychological and environmental benefits are likely to combine to contribute to significant economic benefits, as set out in Figure 1. Research has provided some quantifiable data that has enabled the economic case to be made, yet the research has tended to focus on the economics of either an individual benefit or a few connected benefits. The article by Browning et al. [95], although still in grey literature, specifically focuses on making the economic case for biophilic initiatives, but restricts itself to the social benefits in workplaces, health facilities, retail, schools, property value, and crime reduction. With biophilia originating in the human-nature connection, this is justifiable, and Browning et al. supported this further by pointing out that "today productivity costs are 112 times greater than energy costs in the workplace," and that by daylighting schemes in offices can "save over $2000 per employee per year in office costs" p.3 [95]. The economic gains to be made from environmental benefits such as reduced energy costs, extended building life, and decreased water management costs are apparent. Extrapolating the quantitative figures to support this is particular to location and local costs, but nevertheless presents an area of research needing further attention.

The evidence for economic benefits from biophilic design are set out to include better workplace productivity, improved health and healing, increased retail potential, decreased crime and violence, increased property values and employee attraction, and increased liveability in dense areas.

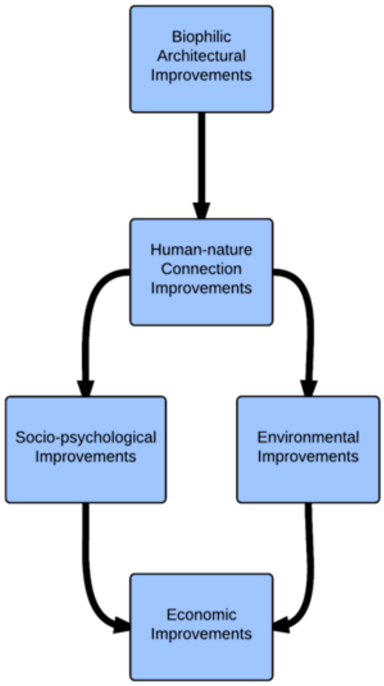

Figure 1. Biophilic architectural benefit flow.

8.1. Increased worker productivity

With productive salaries and benefits, absenteeism and presenteeism (being at a work station but mentally removed) contributing to more than 90% of a company's operating costs, worker performance and the workplace environment is receiving increasing attention as the productivity gains associated with high quality interior environments is supported by mounting research [96].

Thermal comfort and daylighting work environments have both been increasingly linked to productivity [97]. Workers with greater control over their internal environment, with both air-conditioning and natural ventilation, have been found to have increased productivity, less illness, and less absenteeism [96]. The Herman-Miller research project utilized an existing worker population with known productivity, who were being moved from their old windowless factory with no skylights to a newly designed building with extensive daylighting, internal skylights and plants, and operable windows. With the night time shift, there was no gain in productivity, while the daytime shift, who enjoyed the benefit of seeing outside, had significant gains. The swing shift had mixed results that were found to be seasonal. In summer, productivity was increased. The workers felt more positive about coming to work, and job satisfaction increased [95,96].

Studies on the effects of lighting on productivity and wellbeing have been undertaken by Heschong and the California Energy Commission. Schools, shops, and offices have been involved in the studies [98]. In one of the studies in a call center, researchers revealed that workers with window views handled calls 6–7% faster than those without views. Spending $1000 per worker to angle desks so a natural view was available, plus providing operable windows, achieved annual productivity savings of $2990 per employee delivering a payback period of four months [95].

Furthermore, a study conducted by the University of Oregon found that employees with views of nature took less sick days [95]. Browning et al. [95] concluded that productivity, health, worker wellbeing with decreased absenteeism, and presenteeism were significantly affected by light, air quality and variance, indoor plants, and dynamic views of nature. Heerwagen [96] agreed suggesting that a growing body of evidence supports that the presence of positive, up-lifting features can promote greater wellbeing and increased tolerance to other stresses. These features include "daylight, sun patches, window views, contact with nature, and overall spatial design" [96]. Contact with nature and window views of nature can be both psychologically and physiologically beneficial, reducing stress and enhancing wellbeing [26,27,99]. Stress reduction in the workplace is not only beneficial to the organization's productivity, but also to worker health. Viewing nature also restores attention, as expounded by Kaplan's attention restoration theory [27]. With focused office and computer work particularly, attentional fatigue results so a view of nature, especially dynamic views, renews attention, restores cognitive functioning and increases productivity and sense of wellbeing in the workplace. For instance, increases in productivity through biophilic workplace environments have the potential to contribute $470 million towards economic benefits in New York City [95].

8.2. Health and healing

Quality workplace conditions, not only increase productivity, but can also reduce absenteeism and healthcare costs by increasing employee wellbeing [96,100]. Direct healthcare cost benefits can be calculated utilizing research regarding healing rates, anesthesia usage, and psychological benefits gained from the incorporation of biophilic design in healthcare facilities. Ulrich's research from 1984 [24] that revealed increasing healing rates in hospitals with views of nature, has been corroborated by ongoing research. Increased daylight in patients' room can reduce depression and pain [101,102]. This can lead to shorter hospital stays, from 2.6 to 3.67 days, particularly with patients suffering from bipolar disorder or depression [101,103].

As well as daylight, views of nature, pictures of nature, and hospital healing gardens, all have the ability to reduce the need for anesthesia, increase the satisfaction of the hospital stay with both patients' and their families, reduce stress, and improve clinical outcomes [30,42,104]. Browning et al. [95] have incorporated these studies with statistics of hospital and medication costs in the US to conclude that by reducing the average length of a hospital stay by 0.41 days with daylighting and views of nature would result in $93 million in reduced hospital costs [95].

8.3. Increased retail potential

A consumer study of varying biophilic initiatives in store design and retail streets ranging from streets with no visible vegetation, streets with scattered vegetation, to streets with a high level of street trees that even obscured shopfronts, revealed that the more vegetated streets attracted a greater number of shoppers who were prepared to spend up to 25% more and travel further [105]. Joye et al. [106] introduced the concept of biophilic store design in a 2010 research article. They hoped that the paper would reinforce the awareness of the beneficial effects of vegetation for retail stakeholders and affirm that commercial practices, greater profits, and greenery are "mutually reinforcing practises" [106]. A later study, which explored the consumer impact of in-store greenery, discovered that shoppers were less stressed and enjoyed more feelings of pleasure [107]. The same study also suggested that shop employees responded to in-store greenery with less stress, more positive moods, and improved customer service and job satisfaction [107]. In 1995, a *Wall Street Journal* article reported that Walmart, after adding skylights to one of their stores, found that sales in the sky lit part had significantly risen. Erwine and Heschong [97] on behalf of their energy consulting firm, decided to investigate this further utilizing a different chain store with surprising results. With 99% statistical certainty they analyzed that skylighting one of the chain's stores would result in a 40% sales increase, ± 7% [97].

8.4. Decreased violence and crime

There are many studies of crime and the causes of violence, but few have yet included biophilic design parameters in their analysis. In 2001, Kuo and Sullivan [38] undertook a 2-year study of crime rates in Chicago public housing with and without greenery, finding a 52% reduction in felonies. Browning et al. [95] calculated that this would save $162,000 per year for the Illinois Department of Corrections. Biophilic landscapes could save New York City $1.7 billion through crime reduction [95]. More research is needed in this area.

8.5. Increased property value and employee attraction

It can be anticipated that biophilic design features will increase the value of properties and also attract higher staff attraction and retention rates. Some research is now showing this. Specifically, Eichholtz et al. found that buildings with a "green rating" attracted higher rental prices, 3%/ft^2 or 7% in effective rents, selling at prices 16% higher [108]. Green buildings, however, may or may not incorporate biophilic features to attain their rating. Studies such as Benson et al. [109] on real estate prices, have concluded that people are willing to pay more for views of nature. It is known that gentrification tends to occur where there are parks and greenery in dense urban spaces and more affluent neighborhoods comprise more greenery. This has been recently experienced by property owners and tenants, for example in the vicinity of the New York Highline vegetated walkway [10]. Coupling this phenomenon with the research on productivity and the workplace environment, it makes sense that higher rental prices would be valid in biophilic buildings.

Employee turnover is costly and companies are finding building design that contributes to employee wellbeing is attracting and retaining high-quality workers [96]. Major companies, such as the Bank of America with a Manhattan office building, utilize views of nature and green buildings to entice and retain top candidate employees. The Bank of America ensures that 90% of their employees have river, park, or green roof views [95]. There is much anecdotal evidence for the economic benefit of biophilic features, but not enough research has been done yet to quantify this.

8.6. Increased livability—enabling higher density and reduced footprint

Perhaps the most significant economic gain from biophilic architecture is for enabling higher density to be attractive. Denser cities have much lower footprints and enhanced economic productivity due to reduced costs of sprawl, improved agglomeration economies and greater opportunities for attracting knowledge economy capital [110]. However, cultural and political barriers to density can prevent these economic benefits. By introducing biophilic architectural features into dense buildings, the chances of delivering these economic benefits are greatly increased.

9. Conclusion

The emerging area of biophilic architecture is rapidly growing. This paper finds that there is a strong human psychological and physiological rationale for an innate human-nature connection. As well, there is solid environmental evidence for the value in biophilic architecture. Together, these factors should combine to suggest significant economic advantages, although the formal evidence for this is not yet as strongly developed as the socio-pyschological and the environmental evidence. However, Browning et al. have summarized the expected economic benefits this way: "By assigning value to a variety of indicators influenced by biophilic design, the business case for biophilia proves that disregarding humans' inclination towards nature is simultaneously denying potential for positive financial growth." [95].

There is a lot more research needed to quantify all these benefits, especially the economic benefits; but, the presence of a fundamental theoretical foundation in improving the human-nature connection in daily urban life is likely to achieve multiple benefits in how people live and how cities can, therefore, be managed better. The scale of how much connection to nature is needed in cities, and what different kinds of biophilic architecture produce in their human, environmental, and economic outcomes, is yet to be shown. Nevertheless, the research does suggest that developers, designers, planners, and urban politicians can no longer neglect the value of biophilic architecture.

Conflict of Interest

The authors declare no conflict of interest exists between themselves and the content of this paper.

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