# USING BIOLOGY AS A MODEL FOR SUSTAINABILITY: INSIGHTS FOR ECODESIGN AND BIOINSPIRED DESIGN PRACTITIONERS

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## Abstract

Numerous authors in the bioinspired design and ecodesign research communities conceive of biology as a model for sustainability and use biological systems, organisms, and features as analogies when designing environmentally friendly products and systems. The purpose of this paper is to dig deeper into the issue of sustainability in biology, to better understand the ways biology is – and is not – sustainable and discuss the implications of these findings for ecodesign and bioinspired design researchers and practitioners.

**Keywords**: Bio-inspired design, biomimetics, Ecodesign, Sustainability

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# 1 INTRODUCTION

In some sense, the underlying goal of environmentalism is to avoid environmental problems caused by humans, such as acid rain, chemical releases, and climate change. While there are a wide range of perspectives within this community, environmental problems are frequently presented in the context of a greater story of human development, in which the industrial revolution profoundly changed human impact on the environment, new technology promoted the growth of the human population, and a culture of consumerism developed in wealthier regions, increasing the impact of individuals on the environment - all resulting in significant, human-caused environmental problems both locally and globally. These impacts have been deemed 'unsustainable' because, if the current relationship between humans and the environment continues unaltered, it threatens the viability of human life - and perhaps even life in general.

To some extent, non-human biology is depicted in this narrative as a naturalist's idyllic landscape teeming with healthy plants and animals that, in recent times, have fallen victim to humans who are destroying ecosystems and obliterating species. Within the environmental dialogue, there is a sense that humans, technology, and their impacts are 'bad' and everything else is 'good.' Hence, the job of the ecodesigner in this context is to eliminate human impacts and help humanity return to a 'sustainable' impact level while still maintaining a high quality of life for people globally through the development of low-impact designs. This conception of the origin of environmental problems has also prompted many to view non-human biology as the model for environmental sustainability.

The purpose of this paper is to investigate the extent to which non-human biology can serve as a model for sustainability. Section 2 provides evidence that ecodesign researchers frequently utilize biology as a model for sustainability and make specific assertions about the relationship between biology and sustainability. Section 3 investigates the most common of these assertions in the context of biological literature. Section 4 summarizes the results of this work and discusses the implications of these results for bioinspired design and ecodesign practitioners and researchers.

# 2 LITERATURE REVIEW OF SUSTAINABILITY IN BIOINSPIRED DESIGN

Many ecodesign practitioners and researchers refer to 'sustainability in biology' and describe biology as a model for sustainability. In an effort to understand more clearly how researchers view the relationship between biology and sustainability, a study was conducted of bioinspired design literature to identify the most common ways of expressing that relationship.

The literature review encompassed 128 different sources from the bioinspired design domain, all of which touched upon the theory behind bioinspired design or the benefits of bioinspired design in the introduction, conclusion, or abstract. These sources represent the work of 257 different authors, published in 17 journals, 4 conferences, 14 academic books, and 14 non-academic publications. Different sources written by the same author were analysed separately in the study. Hence, large numbers of sources containing a particular type of statement likely indicate that the statement is widely accepted and/or is considered important by a small number of prolific authors. Although it is not possible to provide citations here due to length constraints, full references for all 128 sources analysed in this study are available in O'Rourke (2013).

Of the 128 sources examined, 53 – over 40% – cite ‘sustainability in biology' in their accounts of bioinspired design; in other words, sustainability is cited as a motivating factor for or positive outcome of bioinspired design. Quotations from the accounts that referenced ‘sustainability in biology’ were categorized further into the eight assertions listed in Table 1. These assertions are generalized versions of the statements authors make when referencing a particular idea concerning sustainability in biology. For instance, the specific statement that the optimized topography of the skin of a ball python "relates to… possible economy of energy consumed in combating frictional transactions during locomotion” (Abdel-Aal and Mansori, 2011) was counted under the generalized claim 'Biological organisms are efficient.' Many sources referred to more than one assertion.

*Table 1. The 8 most frequently-made assertions concerning biology and sustainability*

| # | Assertions Concerning Sustainability in Biology | Number of Sources |
|---|---|---|
| 1 | Biology has withstood the test of time. | 9 |
| 2 | Biology is environmentally sustainable. | 9 |
| 3 | Biological organisms use renewable and abundant inputs. | 9 |
| 4 | Biological materials are nontoxic. | 2 |
| 5 | Biological organisms employ sustainable manufacturing processes. | 15 |
| 6 | Biological organisms are efficient. | 42 |
| 7 | Biological organisms do not pollute. | 5 |
| 8 | Biological materials are recycled. | 6 |

## 3 ANALYSIS OF SUSTAINABILITY ASSERTIONS USING LITERATURE FROM BIOLOGY

Here, the assertions identified in the study of bioinspired design literature are unpacked, interpreted, and discussed in the context of peer-reviewed research from biology. This analysis provides a richer understanding of the ways in which biology - and biological systems, organisms, and features - are - and are not - sustainable. It also provides insight into how the sustainability advantages present in biology could be used as models for ecodesign.

### 3.1 Has biology 'withstood the test of time'?

Sustainability in the biological world is frequently related to life’s ability to endure and persist over billions of years, with authors referencing the ‘lasting’ solutions in biology or the fact that biology has ‘withstood the test of time.’ Life has indeed persisted for billions of years. Biological organisms’ ability to collectively survive and remain on earth for such an extended period of time indicates that biology has the ability to sustain itself.

However, although life as a whole has endured over this time period, individual species for the most part have not. Most estimates of the average length of time a species survives on earth are 10 million years or less, and it is widely accepted that almost every species that has ever lived is now extinct (Raup, 1981), with some indicating that the percentage of earth's biota that is now extinct is greater than 99.999% (Novacek and Wheeler, 1992). The environment has changed dramatically since the first organisms, and the types of biological organisms that inhabit the earth - and the types of features they possess - have likewise changed.

Additionally, biological processes are not necessarily inherently sustainable. Tendency toward unsustainable population growth and the resulting competition for resources is a fact of life and a main driver for natural selection (Starr et al., 2006). Many organisms, including plants and animals, have a reproductive capacity so great that it would result in unlimited population growth if left unchecked (Sadava et al., 2008). Because resources are limited, organisms are forced to compete. In the process, the fittest typically survive and are reproductively successful, and the least-fit die. Without natural selection, species would not become better suited to their environments, and the prevalence of desirable traits that have allowed some form of life to continue on the planet would not have arisen.

Finally, it is important to note that sustainability of biology in this sense is very different from the sustainability sought in ecodesign. Biological systems that have remained unchanged for long periods of time are not necessarily the ones with the smallest environmental impact.

### 3.2 Is biology environmentally sustainable?

As discussed previously, 'environmental sustainability' is frequently associated with having a small environmental impact. Hence, this section explores the topic of environmental impacts in biology - whether biological organisms can be considered 'bad' for the environment, under what conditions biological organisms typically have their environmental impacts quantified using life cycle assessment (LCA), and when organisms in the wild can be said to have a negative environmental impact from a biological perspective.

The public frequently perceives some biological organisms to be 'good' and have positive environmental impacts, while other organisms are considered to be 'bad' and have negative environmental impacts. Many biological organisms are seen as 'good', and the introduction, preservation, or flourishing of these organisms is seen as having a positive environmental impact. For instance, the preservation of endangered species is typically regarded as ‘good for the environment’ (Jolliet et al., 2004). Additionally, tree planting and forest preservation is seen as part of many carbon control strategies in the face of climate change (COMEST, 2010) and can even earn carbon credits under the Kyoto Protocol (United Nations, 1998). However, biology also includes ‘non-desirable’ organisms that are seen as ‘bad for the environment.’ For instance, the proliferation of parasites, bacteria, and viruses harmful to humans - regardless of whether they are endangered or not - is frequently viewed as 'bad.' In addition, the proliferation of invasive species is typically considered to have negative environmental impacts (Crooks, 2002).

LCA practitioners sometimes account for the negative environmental impacts of biological organisms if they are directly or indirectly caused by humans. For instance, invasive species can be considered a damage indicator in LCA if the invasion is caused by humans (Jolliet et al., 2004), and organisms used by humans as resources commonly have their negative environmental impacts quantified, such as corn used in the production of ethanol, feed, and food (Kim et al., 2009, Pimentel and Patzek, 2005). However, it is highly uncommon for LCAs to be performed on wild organisms whose environmental impacts are not caused by human intervention.

Some biologists, however, conceive of biology's environmental impacts somewhat differently than the common public and LCA practitioners in that they allow for the possibility that biological organisms have negative environmental impacts in their own right - even when their impacts do not negatively affect humans and are not caused by humans. Two pivotal papers published in 1994 (Jones et al.) and 1997 (Jones et al.) introduced the concept of 'ecosystem engineers,' organisms that alter the availability of resources in their environments, both creating and destroying habitats. The environmental impact of ecosystem engineers can be both positive and negative, where positive impacts enhance “species richness and abundance” and negative impacts reduce these traits (Jones et al., 1997). Interesting examples include corals, which change the environment through the presence of their physical structures, and beavers, which affect the environment though the structures they build (Jones et al., 1994).

On a global scale, some organisms besides humans have had a significant and lasting impact on the environment (Starr et al., 2006), and at least some of these impacts could be considered negative. For instance, a mass extinction not unlike the one anticipated to be caused by climate change occurred during the Great Oxygenation Event, when prokaryotes began to produce food via photosynthesis, introducing oxygen into the atmosphere, which was toxic to the vast majority of organisms on earth at that time (Sadava et al., 2008). Also, evidence suggests that methane emissions from sauropod megaherbivores in the Mesozoic Era were on a scale large enough to significantly warm the climate (Wilkinson et al., 2012).

In conclusion, biological organisms frequently are considered to have negative environmental impacts, and occasionally these negative environmental impacts have significant implications for species worldwide. Using the framework from biology, organisms are considered to have negative environmental impacts when they diminish species diversity locally or globally. However, in the LCA community, biological organisms are frequently only considered to have negative environmental impacts if they are used as resources by humans or their impact is otherwise caused by human intervention. Common perceptions, on the other hand, see some organisms as 'good' and others as 'bad,' with positive and negative environmental impacts, respectively, associated with the success of these organisms.

### 3.3 Is biology a good model for providing specific environmental advantages?

The remaining assertions relate to specific types of environmental advantages offered by biological organisms. The literature review in this section indicates that many of these claims frequently - or even generally - hold true, meaning there are numerous examples of biological organisms that possess each of the environmental advantages of interest. However, there are also important exceptions for each environmental advantage analysed, where a number of biological organisms, features, or processes do not have the advantage of interest and would make poor models for environmental sustainability. Designers selecting biological analogies to use as inspiration during ecodesign should be aware that these advantages are not universally applicable to biology and that these important exceptions exist.

### 3.3.1 Using Renewable and Abundant Inputs

Biological organisms are generally fuelled by renewable and abundant inputs. In the commonly-accepted concept of a food chain, sunlight is the only initial energy input typically considered; for instance, solar insolation during the growing season is the only energy input included in Golley's (1960) analysis of the energy dynamics of a food chain in old-field community. From a global perspective, the raw materials needed for photosynthesis - sunlight, water, and carbon dioxide - are widely available, and successful organisms are likely to rely on food found in abundance that is grown or produced through other biological processes, such as photosynthesis, and is, hence, also renewable. However, there are a number of exceptions where organisms consume nonrenewable or rare resources, including hundreds of species of bacteria, cyanobacteria, and fungi that use hydrocarbons as a source of carbon and energy (Yakimov et al., 2007); organisms that live in locations where the raw materials for photosynthesis are not abundant, such as in deserts, caves, and deep-sea environments; and organisms that require the presence of potentially-rare species in their environments, such as *Oenothera deltoids* ssp. *howellii*, a highly endangered plant, that requires hawkmoths or other effective pollinators in the environment to reproduce at high rates (Pavlik and Manning, 1993).

### 3.3.2 Avoiding Toxic Materials

There are numerous examples of non-toxic biological materials and substances, suggesting to some that biology may be a good model to help engineers avoid toxic materials. However, there are also many examples of biological organisms that produce chemicals toxic to other organisms, such as algal blooms that release toxins poisonous to marine organisms and people (Kalaitzis et al., 2012), bodies of some types of cyanobacteria that are toxic to zooplankton (Ferrao-Filho et al., 2000); the venom of the wasp *Eulophus pennicornis* which is toxic to tomato moth larvae (Price et al., 2009); plants used to make botanical insecticides that contain compounds toxic to insects (Akhtar et al., 2012); seeds of the tree *Aesculus californica* which are toxic to vertebrates (Mendoza and Dirzo, 2009); and *Sistrurus* rattlesnakes with venom toxic to their prey (Gibbs and Mackessy, 2009).

### 3.3.3 Employing Sustainable Manufacturing Processes

Many manufacturing processes in biology, including those producing spider silk (Vollrath and Knight, 2001) and coral reefs (Biello, 2008), occur at ambient temperatures and pressures, unlike competing engineered materials. Hence, these processes are considered ‘sustainable’ by a number of authors. Nearly all of the 15 sources referring to 'sustainable manufacturing' in biology directly state that it is the low-temperature and low-pressure aspect of biological manufacturing that makes it sustainable. However, some biological organisms do produce materials at high temperatures and pressures. For instance, bombardier beetles heat a mixture of noxious chemicals and water to 100 °C which they spray on predators (Beheshti and Mcintosh, 2007). In addition, piezophilic bacteria, such as deep-sea *Shewanella violacea*, (Kato and Nogi, 2001), and the thermophilic bacteria, such as *Bacillus stearothermophilus* (Yayanos et al., 1983), grow or 'manufacture their bodies' at high pressures and temperatures, respectively.

### 3.3.4 Maximizing Efficiency

Literature from biology discusses a number of examples of efficiency in biological organisms. For instance, shark skin has placoid scales with arrangements that reduce frictional drag (Raschi and Tabit, 1992) and, hence, energy loss. In addition, jellyfish are able to attain high swimming speeds while minimizing energy consumption by creating beneficial vortices when water is ejected through their velum during swimming (Dabiri et al., 2006). However, biological organisms and systems are not all exceptionally efficient. Many organisms waste materials and energy on body parts that are ‘useless’ and are present only as a result of the history of the evolutionary process; for instance, humans have tailbones although we do not have tails (Starr et al., 2006). Additionally, some significant biological energy conversion processes have seemingly poor energy conversion efficiencies; e.g., the average conversion efficiency of photosynthesis globally is only 0.3% (Tester et al., 2005). Furthermore, when energy conversion efficiencies of biological and engineered processes are compared directly, it does not appear that biological processes are more efficient than engineered ones. For instance, Blankenship et al. (Blankenship et al., 2011) conducted an in-depth study comparing the efficiencies of natural photosynthetic and photovoltaic-driven electrolysis and found that the manmade solar PV system was far more efficient; they go so far as to propose that solar PV systems could be used to inspire genetic engineering and the development of plants with higher yields for the production of biofuels. Also, Smil (1999) lists a wide range of anthropogenic and biological energy conversion efficiencies, the most efficient of which are anthropogenic.

#### *3.3.5 Minimizing Pollution*

Many waste streams from biological organisms might not typically be viewed as pollutants because they are used by other organisms or provide a habitat for them. However, non-human biological organisms do emit wastes commonly regarded as 'pollutants,' and these emissions can have a large-scale effect on the atmosphere and environment globally. One of the primary examples of pollutants emitted by biological organisms is methane, a greenhouse gas produced by both anaerobic decay in wetlands and anaerobic fermentation in the digestive tract of ruminants (Crutzen et al., 1986). Methane emissions from animals are recognized as having an environmental impact on par with those of human pollutants. For instance, estimates indicate that four camels, each emitting 45kg of methane annually, or five cows, each emitting 35 kg methane annually, have approximately the same carbon dioxide-equivalent emissions as a car being driven 20,000 km annually (Clark, 2011). In addition, numerous other materials emitted by biological organisms could be considered pollutants, such as the introduction of faeces from animals into water bodies (Geldreich and Kenner, 1969, Parveen et al., 1999).

#### *3.3.6 Recycling, Repurposing, and Reusing Waste*

As mentioned above, many of the waste streams from biological organisms can be used by other organisms. Hence, materials in biology could be said to be ‘recycled’ when they are eaten by other organisms through predation or decomposition and their bodies are broken down into chemical components and become a different body. When this occurs, the biological material is broken down and reused in another organism over a short time frame, the same way the material in a recycled aluminium can is broken down and used again. Along a similar vein, birds using fallen twigs for building nests could be considered an example of repurposing in biology, and the use of abandoned shells by hermit crabs (Fotheringham, 1976) could be considered an example of reuse.

However, there are numerous cases in which biological materials are not recycled, repurposed, or reused by other organisms. For instance, the destruction of organic material by fire cannot be accurately likened to recycling, repurposing, or reuse. Fires volatilize carbon and nitrogen, causing a significant portion of biological material to become unusable by other organisms (D'Antonio and Vitousek, 1992), and hence, more closely resemble the wasting of a potential energy source, such as the flaring of unwanted natural gas from an oil well. Even though fires serve important ecological and evolutionary roles (Bond and Keeley, 2005), they destroy the material they are burning and make it unusable by other biological organisms. A chemical process that takes aluminium cans and brakes apart the aluminium atoms for some benefit - such as enabling the resultant material to be stored in a smaller landfill because of an increase in density - would not be considered 'recycling', 'repurposing', or 'reuse' if the resultant material was unusable by humans. So too, the destruction of organic material by fire should not be considered 'recycling', 'repurposing', or 'reuse'.

## 4 DISCUSSION

This section summarizes the main findings from Sections 2 and 3 and examines the implications of the analysis and results presented in these sections for bioinspired design and ecodesign practitioners.

### 4.1 Summary of Findings

The study presented in Section 2 clearly established the importance of the connection between biology and sustainability in the field of bioinspired design, with 53 of 128 sources examined citing such a connection. In addition, these 53 statements were then organized and synthesized into 8 specific assertions that demonstrate the many aspects of sustainability that might be embodied in biology.

The study presented in Section 3 examined each of the 8 assertions in the context of literature from biology. At a general level, the results demonstrated that biology and biological systems are sometimes - but not always - sustainable. More specifically, it was shown that while biology as a whole has persisted for billions of years on earth and thereby 'withstood the test of time', individual features and species have not. In addition, although the success of biological organisms is typically seen as 'sustainable', biological organisms are seen as having negative environmental impacts in various contexts - such as in ecology, when they have impacts that diminish biodiversity locally or globally; in the LCA community, when they are used as resources or their environmental impact is cause by humans; and in the general public, when they are harmful to humans or classified as invasive species. Finally, it was shown that while many biological organisms use renewable and abundant inputs, avoid toxic materials, employ sustainable manufacturing processes, maximize efficiency, minimize pollution, and recycle, repurpose, or reuse waste, in all cases important exceptions exist where biological features and system do not exhibit these specific environmental advantages.

### 4.2 Insights for Bioinspired Design Practitioners

For those interested in bioinspired design, the results of Sections 2 and 3 demonstrate that there are many sustainable biological systems and features that could be used as analogies in the design process to achieve a variety of sustainability-related design goals. These results also show, however, that not all biological organisms and systems are sustainable and, more specifically, that many organisms have large negative environmental impacts. Hence, the results highlight the importance of carefully screening and selecting biological analogies with particular sustainability-related features.

When selecting potential biological analogies, bioinspired design practitioners face the challenge of ensuring that the selected analogy is sustainable, and that it is sustainable in the sense that they intend (it is low-impact or energy efficient, for instance). Consequently, a better understanding of the types of sustainability solutions present in biology is needed. Future work in this area should include the careful study of the types of sustainable solutions present in biology. If these solution types were better understood, tools to aide designers in creating sustainable products could be created. With the assistance of tools that categorize sustainability solutions or make low-impact biological analogies more readily available, designers would be able to more quickly and easily locate sustainable biological analogies and use them to inspire more sustainable engineering designs.

### 4.3 Insights for Ecodesign Practitioners

The finding from Section 3 that non-human biological organisms and systems are sometimes unsustainable calls into question the assumption that non-human biology is necessarily 'good' for the environment and that humans and their impacts are 'bad'. Consequently, it casts doubt on the notion that the identity of the actor causing an environmental impact has a bearing on its overall environmental effect. This conclusion seems reasonable; after all, one kg of methane emitted to the atmosphere from an electric plant has the same negative impact on the climate as one kg methane emitted from the digestive tract of ruminants, for instance.

The realization that biological impacts can be 'bad' for the environment prompts the questions of whether, conversely, anthropogenic environmental impacts might be good in some contexts, and whether humans are simply an example of a high-impact biological organism, with no fundamental difference between anthropogenic and non-anthropogenic impacts. Jones et al. argue this point, claiming both that humans are ecosystem "engineers par excellence" (1994), and that ecosystem engineering - presumably including anthropogenic engineering - frequently has a positive effect on species diversity (1997), because engineering impacts are likely to provide microenvironments that could potentially can serve as habitats for organisms that might not otherwise be able to live in a particular region.

If this is indeed the case, future work in ecodesign might explore the benefit of focusing not only on minimizing the negative environmental impacts of humans but also on maximizing beneficial environmental impacts - through the creation, preservation, or reclamation of microenvironments that can provide valuable habitat. For instance, thermal waste from the cooling systems of two power plants on the San Gabriel River near Los Angeles has created a habitat that supports a population of green sea turtles (Totten, 2015), an endangered species (Fund, 2015); artificial reefs can be constructed out of wrecked ships or waste dredged material (Yozzo et al., 2004); and urban wildlife refuges can be established on the sites of old landfills (Robinson and Handel, 1993). In addition, biological models for environmental impact - such as the one developed around ecosystem engineering (Jones et al., 1994, Jones et al., 1997) - could be applied to human-engineered designs to provide a new lens through which to consider anthropogenic environmental impacts and generate interesting insights for ecodesigners.

## 5 CONCLUSION

Numerous authors in the bioinspired design and ecodesign research communities conceive of biology as a model for sustainability and use biological systems, organisms, and features as analogies when designing environmentally friendly products and systems. This paper delved into the issue of sustainability in biology, to investigate the ways biology is – and is not – sustainable and to discuss the implications of these findings for ecodesign and bioinspired design researchers and practitioners. First, statements from 53 sources concerning sustainability in biology were organized and synthesized into 8 specific assertions. Second, each of these assertions was evaluated in the context of literature from biology, finding that many biological organisms frequently have large negative environmental impacts and that many of the claims related to specific environmental impact advantages (e.g., Materials in biology are nontoxic) may generally hold true, but have important exceptions that should be considered. The final section of this work summarized the results and discussed the implications of these findings. Specifically, the results suggest that there may be a large pool of sustainable biological processes, features, and systems that could serve as analogies for bioinspired design practitioners. However, those seeking to achieve ecodesign goals through bioinspired design need to take care when selecting potential analogies to ensure that the biological analogy is sustainable, and is sustainable in the sense that is desired in the final design. In addition, ecodesign practitioners might be inspired by the results of this work to focus more on maximizing humans' positive environmental impacts and to consider the potential benefits of applying biological models of environmental impact to ecodesign.

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