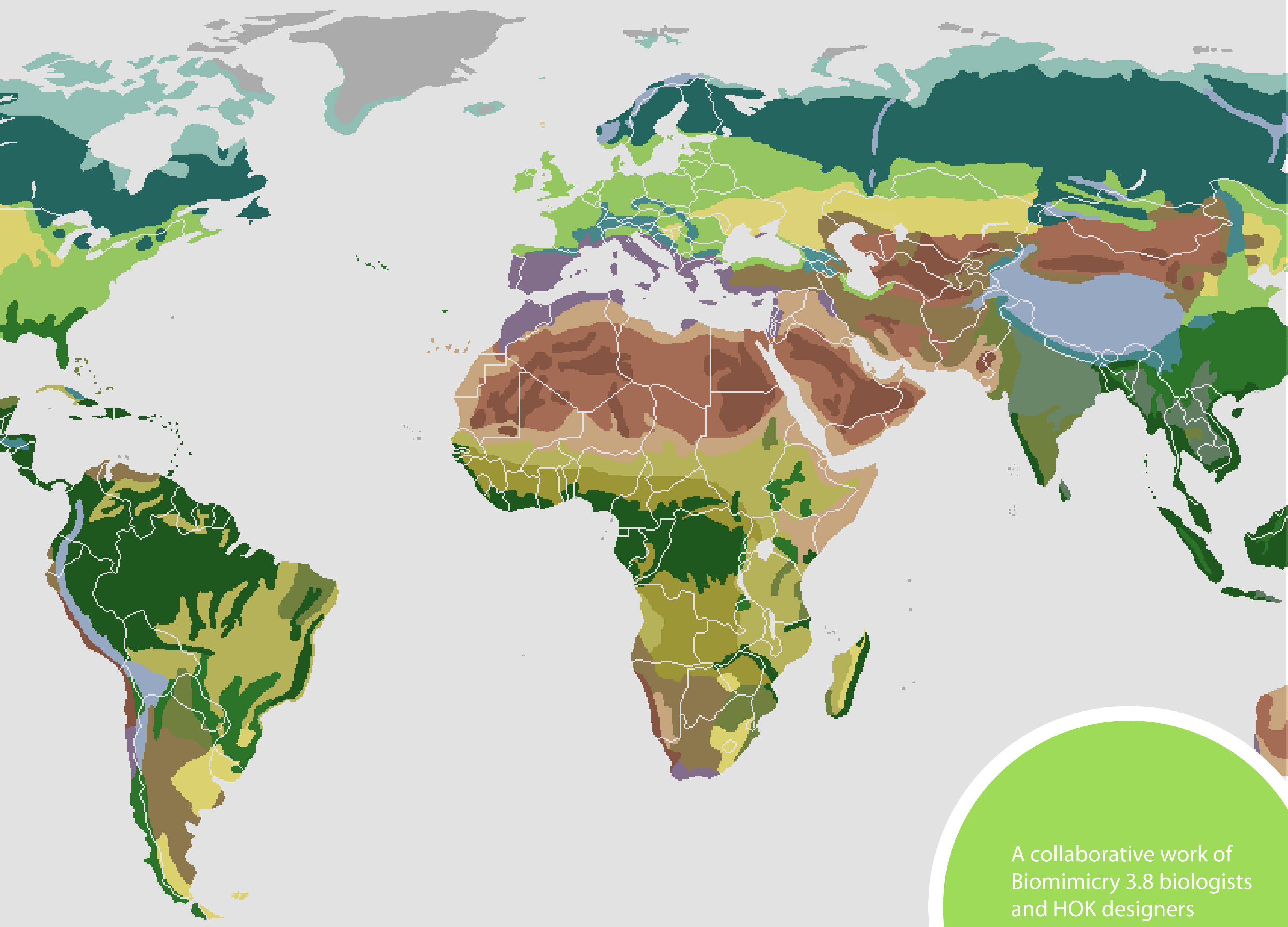
GENIUSOFBIOME

TEMPERATE BROADLEAF FOREST



A collaborative work of
Biomimicry 3.8 biologists
and HOK designers

The information contained in this publication is intended to inspire exploration of how nature can inform or influence place-based design processes and solutions.

Biomimicry 3.8 (a dba of Biomimicry Group, Inc.)
PO Box 9216
Missoula, MT 59807 USA

+1 406 543 4108

HOK Group, Inc
211 N. Broadway, Suite 700
St. Louis, MO 63102 USA

+1 314 421 2000

GENIUS OF BIOME

TABLE OF CONTENTS

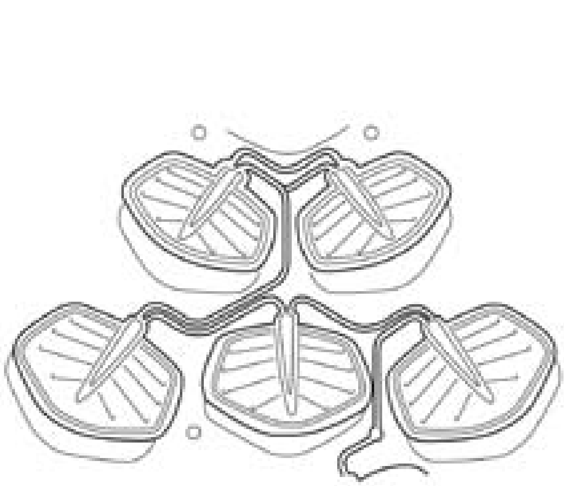
preface

What can we learn from nature's 3.8 billion years of experience? Does the forest hold the answers to sustainable design?

Biomimicry 3.8 partnered with HOK to study how lessons from the temperate broadleaf forest biome, which houses many of the world's largest population centers, can inform the design of the built environment. The result, the *Genius of Biome*, is a highly visual report filled with insightful design strategies and sketches, application ideas, and supporting research.

By examining the strategies that plants and animals have used to thrive over millions of years, we can begin to conceive a completely different built environment – one that's restorative and resilient and that works with nature.

HOK and Biomimicry 3.8's hope is that designers, architects, and planners will use this report to integrate nature's innovations into the design of our buildings, communities, and cities. If we can make these time-tested biological principles part of our design vocabulary, we can define a new standard for what it means to practice sustainable design.



SMIT (Sustainably Minded Interactive Technology)

Ivy

what is biomimicry?

Biomimicry is an innovation method that seeks sustainable solutions to human **challenges** by emulating nature's time-tested phenomena, **patterns**, and principles. The goal is to create well-adapted products, processes, designs, and policies by mimicking how living **organisms** have survived and thrived over the **3.8 billion years** life has existed on Earth.

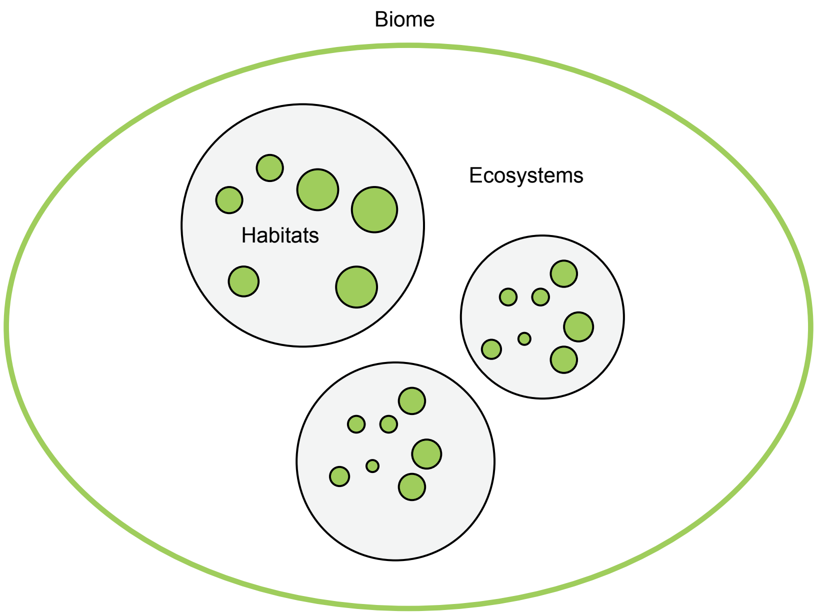
Learning from, modeling, and emulating nature's best designs is the first step to integrating human systems with natural systems. Our biologists showcase elegant and intriguing stories from the natural world that designers can play with as creative fodder.

Ultimately, the deep practice of biomimicry is not just about creating bio-inspired things; it is about emphasizing that humans are a part of, not apart from, nature. It is about viewing and valuing healthy natural systems for their intrinsic worth, not just for what we can glean from them.

Featured AskNature.com Biomimicry Case Study:
SMIT (Sustainably Minded Interactive Technology)
Hybrid Energy System

A Brooklyn-based firm, SMIT, has created a product called Solar Ivy, or GROW. Mimicking the appearance and function of ivy, this technology has wind and solar power-generating photovoltaic leaves that can be attached to building facades.

Solar panels take up a lot of space. GROW Solar Ivy is designed to be placed on building facades, taking advantage of vertical spaces just as ivy does.

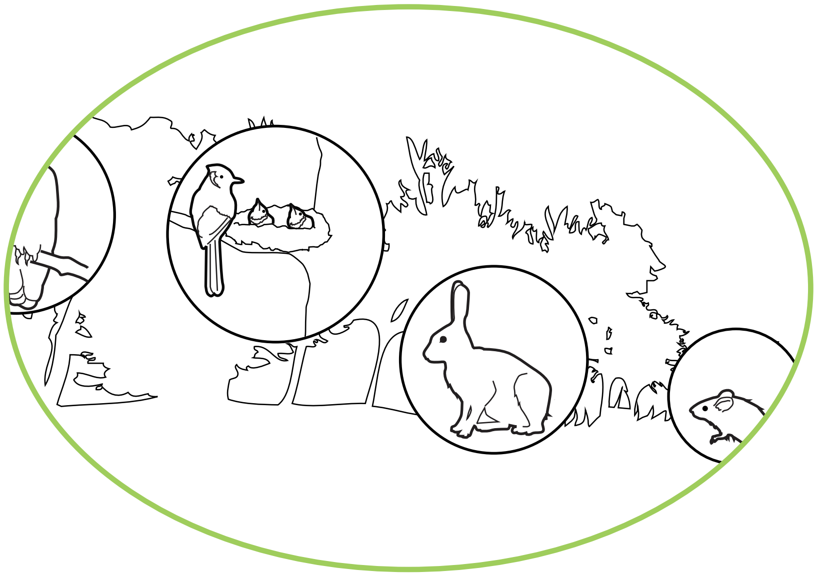


what is a biome?

A biome describes a type of climate and vegetation that exists in specific regions throughout the world. The climate in eastern North America, for example, is similar to the climate in eastern China. The trees that thrive in those conditions are broadleaf trees such as maples and oaks, along with conifers such as pines and firs.

The **habitats** and **ecosystems** found in a biome function in similar ways. The patterns in how they function create relevance for human design. If the living organisms in these biomes are challenged by similar climates and conditions, what design ideas can we learn from their examples of adaptations and survival mechanisms?

There are many biome classification systems. All are similar yet different in how they divide climactic and ecological conditions. Biomimicry 3.8 has selected the best classification system that provides a commonly used biome map that fits its needs. The classification system is a derivative of the World Wildlife Fund classification of terrestrial ecosystems that describes 18 biomes (Hassan et al. 2005; Olson et al. 2011).



what is the genius of biome?

Drawing inspiration from natural systems provides a fresh opportunity to rethink and reimagine how to solve human design challenges. The *Genius of Biome* report offers designers, architects, and planners examples of how organisms and ecosystems have adapted to biome challenges of climate, energy, materials, nutrients, and communication. A biome report can be applied to a wide geographic range of projects with the same or similar climate and vegetation.

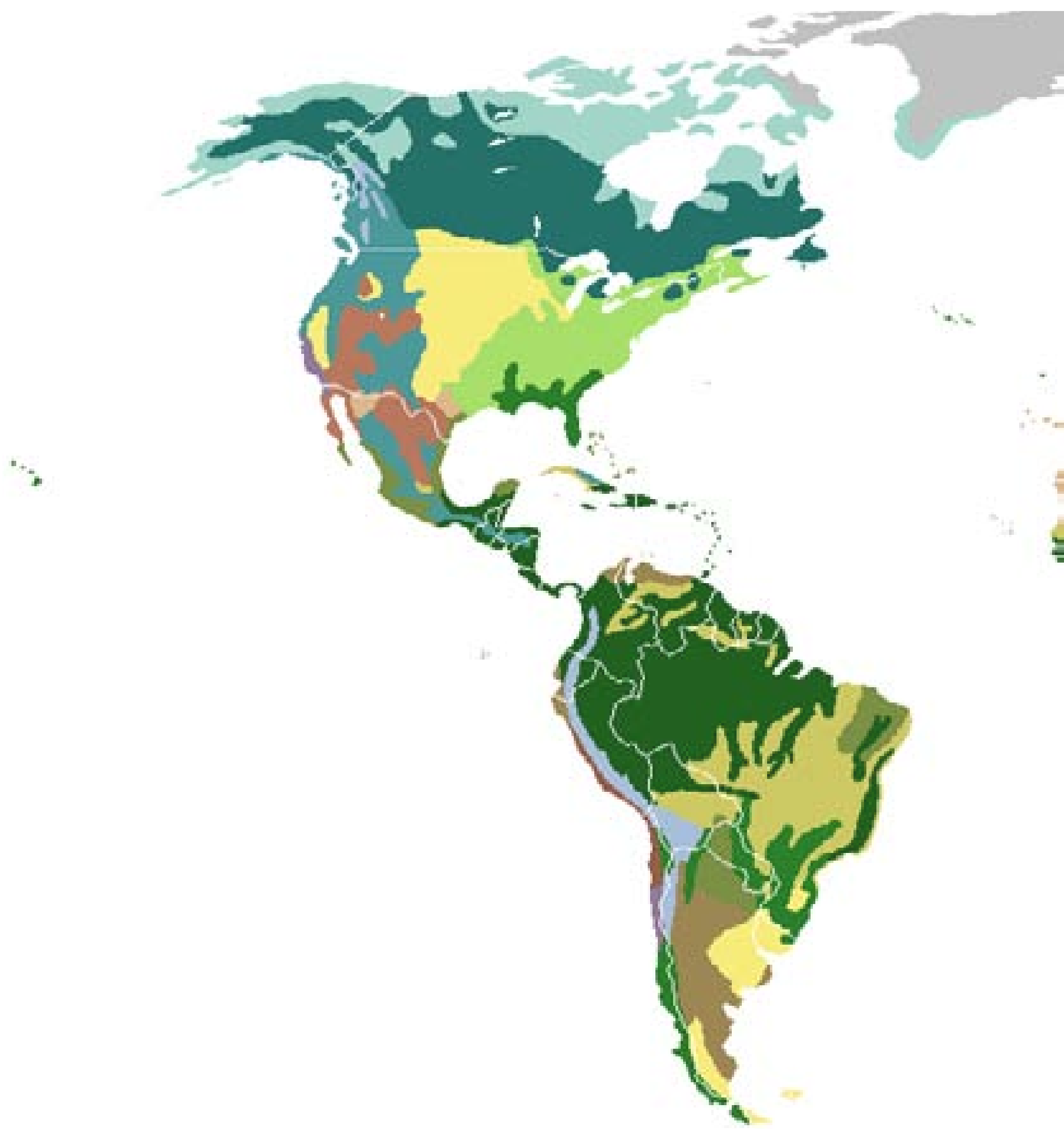
A genius of biome describes the strategies and designs adopted by living organisms found in a worldwide region of similar climate and vegetation. Further, the *Genius of Biome* also investigates and highlights strategies and designs at the ecosystem level. Ecosystems are made up of living entities along with their **abiotic** conditions (climate, temperature, soil types, topography). In a biome, abiotic conditions are just as important as they are to architects, designers, and planners. It is this broad view that the *Genius of Biome* appreciates and illuminates. Ecology offers an additional lens through which we can view nature's genius and learn **design principles** that adapt to a biome's abiotic and **biotic** conditions.

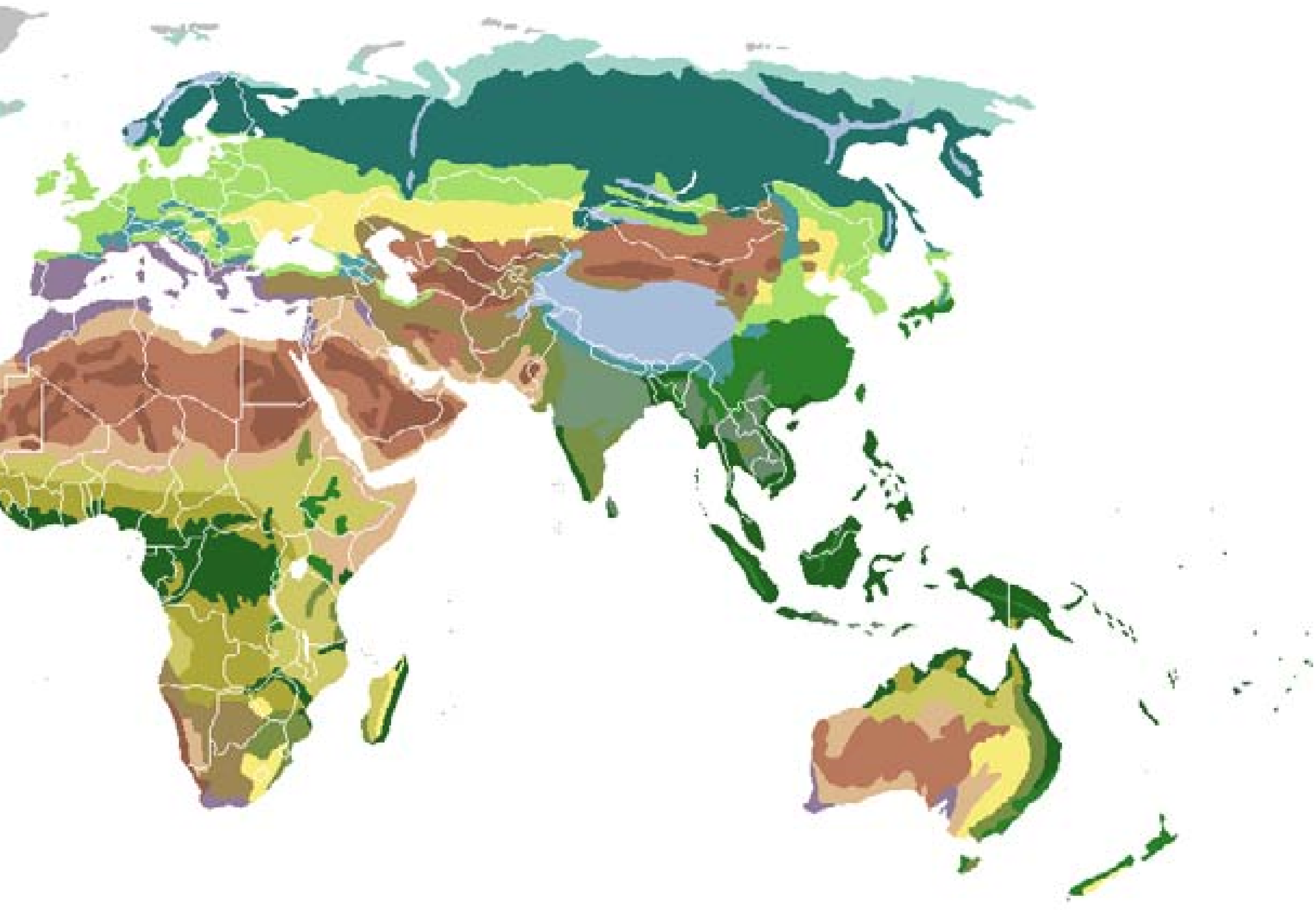
The *Genius of Biome* describes the biological principles and patterns common to organisms and ecosystems within a biome. This biology is then translated into design principles that can be used to inspire design innovations or identify more specific criteria for place-based design.

The goal is to inspire innovation to mimic the successful designs, processes, and patterns found in the larger scale of the natural world—ecosystems. An important part of understanding these biological and design principles and how to mimic them is to know the history of these biomes.

world biomes

- ice sheet and polar desert
- tundra
- taiga
- temperate broadleaf forest
- temperate steppe
- subtropical rainforest
- mediterranean vegetation
- monsoon forest
- arid desert
- xeric shrubland
- dry steppe
- semiarid desert
- grass savanna
- tree savanna
- subtropical dry forest
- tropical rainforest
- alpine tundra
- montane forests





biomimicry process for the genius of biome

This report represents a brief glance at some of the thousands of designs in nature. Nature has had to solve the same challenges as humans. The first step in a biomimetic process is to ask what you want your design to do. What is the function?

The next step is to **biologize** the question. If the problem is how to insulate against heat loss, for example, we would ask, "How does nature insulate?" We identify the functions and study how nature accomplishes that function. A team of biomimetic researchers dives into the scientific literature and asks, "Whose survival depends on solving this problem?"

For the *Genius of Biome*, we identify the operating parameters of the biome:

- Climate conditions (wet, dry, cold, hot, low/high pressure, highly variable, high/low UV)
- Nutrient conditions (poor, rich)
- Social conditions (competitive, cooperative)
- Temporal conditions (dynamic, static, aging)

We identify the core biological principle that is used to accomplish function and describe it without using biological terms to form the design principle. The final step in this process is to **emulate** these principles with sketches for literal, abstracted, or conceptual applications.

The next steps can include a brainstorm session in which we develop a matrix or taxonomy of related elements or principles. We consult expert information for a deeper, broader understanding of the mechanism or process. Our repetitive process of testing the design continuously goes back to the original functions and asks, "Why?"

Nature can act as a **mentor, model, and measure**. Life's Principles can provide a guide to assess the potential success of an innovation or idea. Life's Principles are benchmarks of **sustainability**. Are our designs accomplishing the overarching **pattern** held in common by living organisms on Earth? Life's Principles are the deep patterns of a collection of biological principles abstracted to the broadest level.

Pattern recognition is an art. Developing the ability to identify patterns in nature and then adapt these patterns to solve human problems is a significant step toward seamlessly fitting humans into nature.

The examples and sketches in this report emphasize the cohesive, integrated, and optimized elements found in nature's genius. Though we have framed these stories to help designers understand the elements involved, we cannot guarantee a successful outcome. After grasping these elements, the next step is to apply them.

life’s principles: design lessons from nature

Life follows common patterns. The fundamental principles underlying these patterns represent nature’s strategies for surviving and thriving on Earth. These principles have been compiled into a list we call Life’s Principles.

Integrating biology into design involves seeking nature’s advice at all stages of design. Discovering nature’s blueprints is the first step, followed by finding the patterns and principles of how nature manages its challenges. Designs guided by these principles will fit into an ecosystem and not be shallow in their mimicry. The final step is to test a design against principles found in nature. Life’s Principles serve as an overarching scoping and evaluation tool—nature’s eco-design checklist.

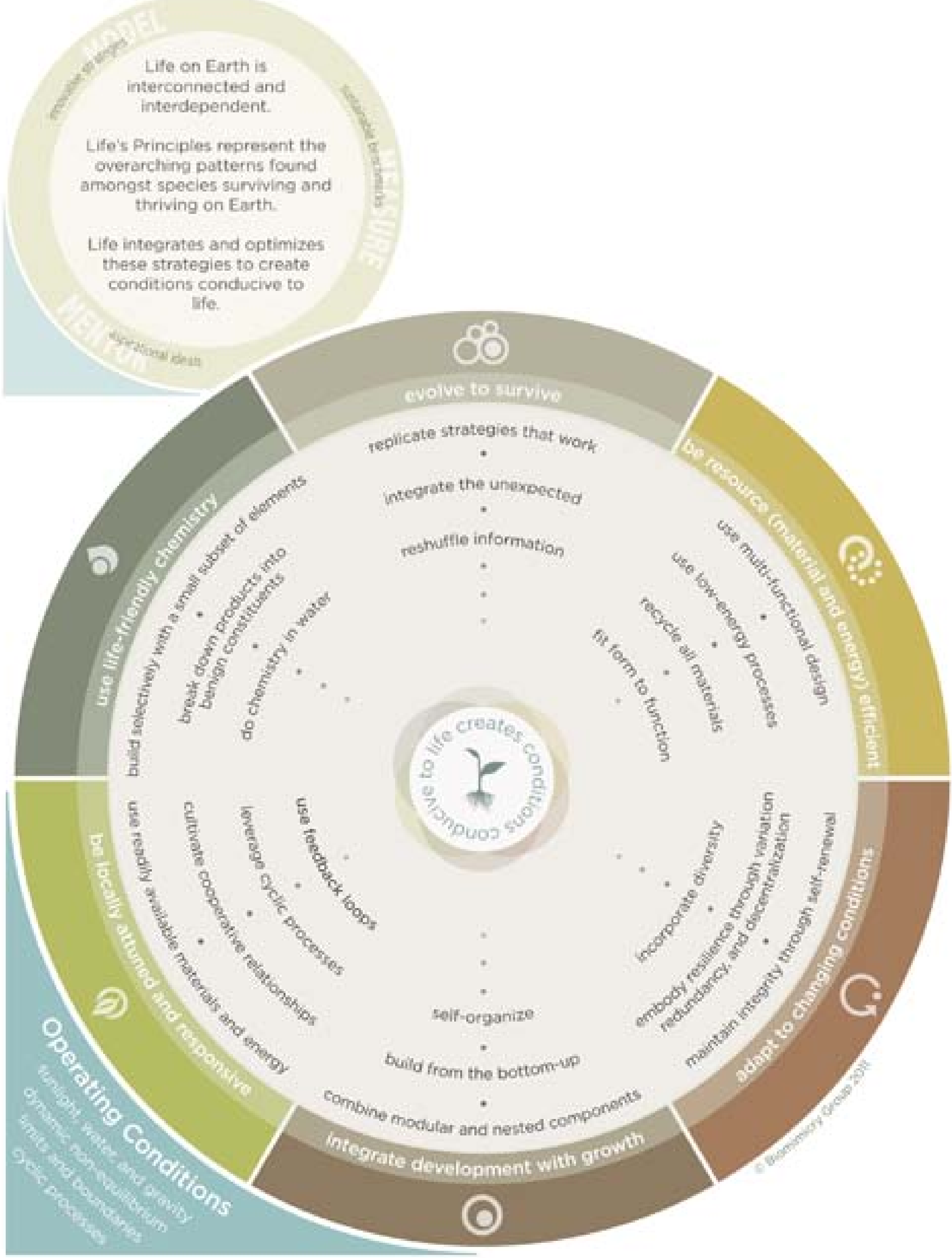
Examples of how Life’s Principles can be applied at the design level are given at the beginning of each challenge section: Water, Energy, Materials, Social, and Economy.

Life’s Principles are presented on the next page as a diagram with a set of definitions.

The small circle in the upper left reminds us to view nature as a mentor, model, and measure.

These principles are the result of and subject to the operating conditions of the planet, found in the blue arrow on the lower left side of the circle. The center of the circle is both the aspirational goal and the emergent property of these principles—creating conditions conducive to life.

Just as no principle stands alone, all principles are interconnected. Use the tool and the diagram as it suits you, remembering that the integration and optimization of the collective, collaborative suite of principles yields life’s successes.


Life on Earth is interconnected and interdependent.
Life's Principles represent the overarching patterns found amongst species surviving and thriving on Earth.
Life integrates and optimizes these strategies to create conditions conducive to life.
MODEL
MEASURE
MENTOR
innovative strategies
sustainable benchmarks
aspirational ideals
evolve to survive
replicate strategies that work
integrate the unexpected
reshuffle information
be resource (material and energy) efficient
use multi-functional design
use low-energy processes
recycle all materials
fit form to function
adapt to changing conditions
incorporate diversity
embody resilience through variation redundancy, and decentralization
maintain integrity through self-renewal
integrate development with growth
self-organize
build from the bottom-up
combine modular and nested components
be locally attuned and responsive
use feedback loops
leverage cyclic processes
cultivate cooperative relationships
use readily available materials and energy
use life-friendly chemistry
build selectively with a small subset of elements
break down products into benign constituents
do chemistry in water
life creates conditions conducive to life
Operating Conditions
sunlight, water and gravity
dynamic non-equilibrium
limits and boundaries
cyclic processes
© Biomimicry Group 2011

LIFE'S PRINCIPLES DEFINITIONS

Evolve to Survive	Be Resource-Efficient (Materials and Energy)	Adapt to Changing Conditions
Continually incorporate information to ensure enduring performance.	Skillfully and conservatively take advantage of resources and opportunities.	Appropriately respond to dynamic contexts.
Replicate Strategies that Work Repeat successful approaches.	**Use Multi-Functional Design** Meet multiple needs with one elegant solution.	**Maintain Integrity Through Self-Renewal** Persist by constantly adding energy and matter to heal and improve the system.
Integrate the Unexpected Incorporate mistakes in ways that can lead to new forms and functions.	**Use Low Energy Processes** Minimize energy consumption by reducing requisite temperatures, pressures, and time for reactions.	**Embody Resilience Through Variation, Redundancy, and Decentralization** Maintain function following disturbance by incorporating a variety of duplicate forms, processes, or systems that are not located exclusively together.
Reshuffle Information Exchange and alter information to create new options.	**Recycle All Materials** Keep all materials in a closed loop.	**Incorporate Diversity** Include multiple forms, processes, or systems to meet a functional need.
	Fit Form to Function Select for shape or pattern based on need.	

Integrate Development with Growth

Invest optimally in strategies that promote both development and growth.

Combine Modular and Nested Components
Fit multiple units within each other progressively, from simple to complex.

Build from the Bottom Up
Assemble components one unit at a time.

Self-Organize
Create conditions to allow components to interact in concert to move toward an enriched system.

Be Locally Attuned and Responsive

Fit into and integrate with the surrounding environment.

Use Readily Available Materials and Energy
Build with abundant, accessible materials while harnessing freely available energy.

Cultivate Cooperative Relationships
Find value through win-win interactions.

Leverage Cyclic Processes
Take advantage of phenomena that repeat themselves.

Use Feedback Loops
Engage in cyclic information flows to modify a reaction appropriately.

Use Life-Friendly Chemistry

Use chemistry that supports life processes.

Build Selectively with a Small Subset of Elements
Assemble relatively few elements in elegant ways.

Break Down Products into Benign Constituents
Use chemistry in which decomposition results in no harmful by-products.

Do Chemistry in Water
Use water as solvent.


1
2
3
ENERGY
4
nature's design
5
design principle
6
leaves
7
BaDT brainstorm
design ideas
8

how to interpret a genius of biome design

1. **Challenges**
   Five challenge areas were identified: Water, Energy, Materials, Social, and Economy. These categories were chosen from the HOK and Biomimicry 3.8 FIT™ Approach.

2. **Biologized Challenge**
   Frames the question in a way that can communicate with biological strategy. “How does nature...?”

3. **Life’s Principles**
   These principles represent the overarching patterns found among species surviving and thriving on Earth.

4. **Nature’s Design Description and Summary**
   The design of an organism or ecological process and how it solves the challenge.

5. **Design Principle Description and Summary**
   The elements and processes fundamental to the nature’s design example.

6. **Other Related Design Principles**
   Designs found in nature are always related or interconnected to other designs that are just as valuable. Because optimal functionality typically occurs when many mechanisms or processes are linked, it is difficult to focus on only one design principle.

7. **Biologist at the Design Table (BaDT) Brainstorm**
   Examples of emulating design principles from nature that can guide design ideas.

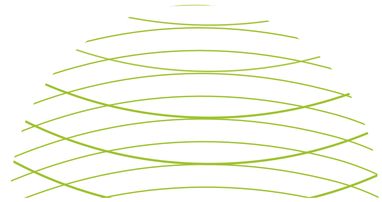
8. **Design Ideas**
   Sketches from HOK designers suggesting a design application based on the design principle. In some cases, these ideas come from outside this specific biome in recognition that some design principles can be applied more universally. These are first-generation ideas intended to inspire others to actively engage the *Genius of Biome*. Not all design principles have sketches of ideas. This is a living document - some ideas have yet to be realized.

TEMPERATE BROADLEAF FOREST

SEARCH CHALLENGES

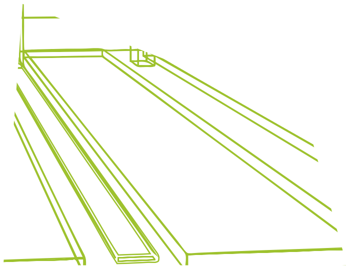
WATER
27

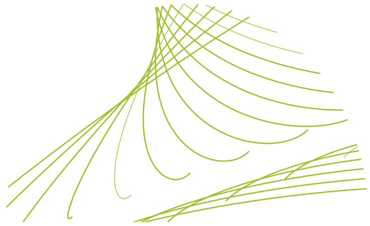
- **minimize erosion** 29
  - beavers 35
  - vegetation 29
- **minimize negative impacts of rain water** 41
  - lichen 41
- **optimize water resources** 47
  - rivers 47
- **dehumidify in summer** 53
  - bryophytes 53



ENERGY
59

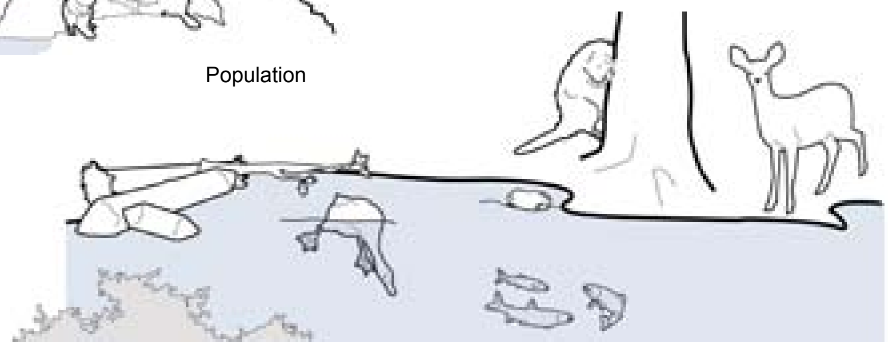
- **adjust to temperature change** 61
  - leaves 61
  - trees 67
- **respond to seasonal change** 73
  - animals 79
  - plants and animals I 73
  - plants and animals II 85
- **optimize light** 91
  - trees 91





Organism

Population



Community

ecosystem realities

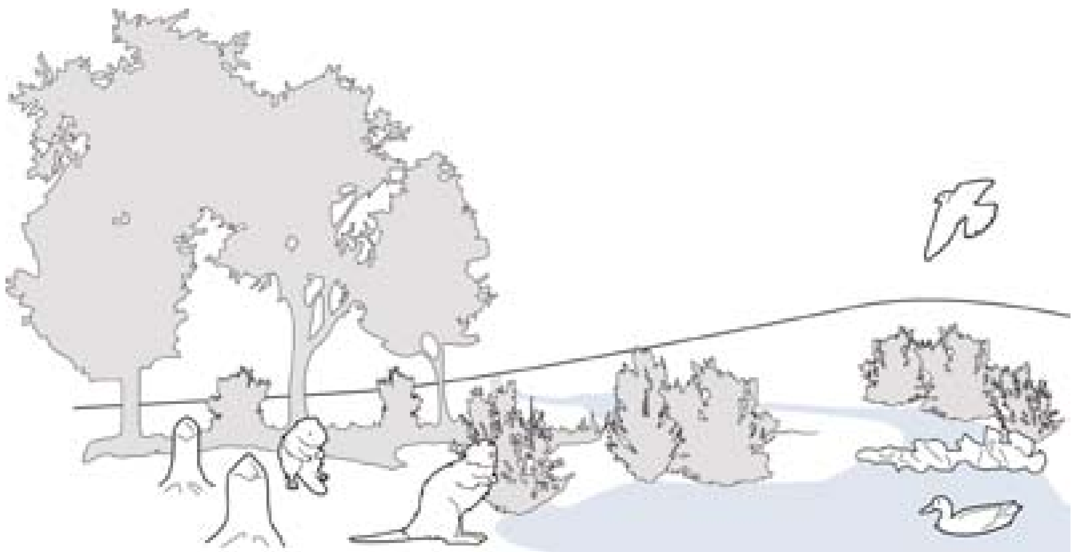
Temperate broadleaf deciduous forests can be found on six of the seven continents, including the eastern half of North America, north-central Europe, southwest Russia, Japan, eastern China, the southern tip of Chile, the east coast of Paraguay, New Zealand, and the east coast of Australia.

The temperate broadleaf forest biome on each continent experiences four distinct seasons: spring, summer, fall, and winter. The average annual temperature of this biome is 50° F (10° C), with 30-60 inches (75-150 cm) of rainfall per year, though this can vary widely from one region to another. Winters are cold and dry, spring is cool and breezy, summers are hot and humid, and fall is warm and breezy. The climate type is generalized as “moist continental.” The climactic dynamics of this biome result from prevailing ocean and wind patterns.

This biome is characterized by broad-leaved trees, evergreen plants such as conifers and holly, and dense shrubs — all of which drop their leaves in the fall and are dormant in the winter. Trees have thick bark to protect from cold weather and ice storms. Vegetative growth is limited to the late spring and summer seasons, an adaptation that allows plants to survive cold winters. Many animals hibernate through the winter. Those that remain active are well-adapted to eating a wide variety of food sources, which are often limited. Others migrate south for the winter because their strategy for dealing with the challenges of the long, cold winter is avoidance.

The extremely fertile soil in this biome supports a wide diversity of life. Forest vegetation, the basis of the **food web**, displays five distinct layers. The first is the ground layer, which is composed of lichen, mosses, bacteria, fungi, and a rich seed bank. The second is the herb layer, including short plants like herbs and grasses. Next is the shrub layer, followed by the small tree and sapling layer. These two layers together are often known as mid-canopy. The fifth layer is the tree canopy, which can reach heights of 60-100 feet (18-30 m) and is generally dominated by oak, beech, maple, and birch trees. Coniferous trees include pine, fir, and spruce, which populate the mid-canopy and canopy. Vines and other climbing plants connect the different layers. The greatest concentration of **biodiversity** occurs on or near the ground level.

The unique microclimates expressed in each vegetative layer create a diverse and dynamic vertical forest structure, which creates ample opportunities for animals to find their own **niches**. This biome is home to a diverse cast of mammals, insects, birds,



Ecosystem

reptiles, amphibians, and fungi, many of which are endemic, found only in this biome. The loss of large, native predators has had many cascading impacts on forest structure and functionality.

This biome is subject to periodic large-scale disturbances such as fire, ice storms, blow down, insect and disease outbreaks, and increasingly more disruptions from human developments, agriculture, and resource exploitation. While the forest has co-evolved with natural disturbances, most of the species that live in this biome are best adapted for late-succession conditions. The increased frequency and extent of human-caused disturbances are threatening the integrity of many habitats.

The largest temperate broadleaf forest ecoregion is found on the eastern coast of the United States. The loss of this temperate broadleaf forest in China has led to seasonal dust storms and disastrous flooding on the Loess Plateau and the North China Plain. Comparing these two ecoregions offers valuable guidance for designers. Nature has built-in mechanisms that adapt to change, but some changes come too fast and are too overwhelming.

nature’s designs

Biomimicry is a design and leadership discipline that seeks sustainable solutions by emulating nature’s time-tested ideas. Flourishing on the planet today are the best ideas — those that perform well in context while economizing on energy and materials. Whatever the design challenge, the odds are good that at least one of the world’s 30 million creatures has not only faced the same challenge, but evolved effective strategies to solve it.

Examples of nature’s designs from the temperate broadleaf forest biome can inspire innovation. The organisms that inhabit this biome, as well as the ecosystem processes formed by both biotic and abiotic conditions, are evidence of the embodied wisdom of successfully living in place. The abstracted design principles and ideas from nature occurring in this biome can tell us more about site conditions than a scientific explanation, and therefore offer inspiration for emulating a well-adapted design.

Living organisms produce designs in nature that can help solve human problems. We know, for example, that the beaver builds dams to create a safe habitat. A beaver will respond to flooding by strengthening a dam or repairing it and will allow water to seep through it. From an engineering perspective, a beaver’s dam holds interesting principles of continual flow, sediment retention, and enhancement of biodiversity by creating more habitat for more living organisms. Nature can be a source of inspiration and innovation.

While a strategy is a behavior or set of behaviors used by an organism to solve a challenge, the *Genius of Biome* also encompasses designs formed by processes in local communities and ecosystems. We have called these nature’s designs. The translation to design principles, and from there an abstraction to design ideas, provides the most direct methodology for design inspiration.

WATER

A common pattern of how water flows in nature is “slow it, sink it, store it.” This means the net effect of rainwater movement in an ecosystem results in water movement slowing as it moves through a system, water sinking into the soil, and water being stored and made available for use as needed. Can designers use these patterns as a template for valuable ideas?

In the following section on water, we see examples of how nature designs mechanisms and processes involving water. We see that beaver dams create habitats that attract more species and thus add more biodiversity. Beaver dams increase water infiltration, reduce downstream flooding, and collect sediment that eventually creates new habitat. In other words, a beaver dam is a closed-loop system that benefits not only the beaver but many other organisms that share the same habitat. How can this design be emulated to solve erosion and flooding?

When it rains, the drops fall first on a forest canopy of leaves and branches, slowing the velocity and force. We see the raindrops pooling and then soaking in or starting to flow down the topography of the land. However, they quickly run into plant litter, fallen logs, soil, and pores in the soil. The roughness of the whole landscape of a temperate forest slows the force of water effortlessly and without energy. The land is protected from erosion by a complex set of structures.

Shifting to a microscopic view, we see that many surfaces in nature, such as lichens, are rough. This roughness affords yet another benefit — hydrophobicity. Such a design enables a breathable, waterproof surface. What design principles can we learn from the temperate broadleaf forest biome? How can these patterns be emulated to solve our human challenges?

- Increase infiltration
- Slow water
- Create air flow
- Purify water
- Moderate humidity

WATER

LIFE'S PRINCIPLES

REFERENCE THE DEFINITIONS

EVOLVE TO SURVIVE

Replicate strategies that work

Incorporate surface roughness at multiple scales to slow water and allow it to infiltrate.

INTEGRATE DEVELOPMENT WITH GROWTH

Self-organize

Design water capture and management systems to allow components to interact with each other and stay flexible to respond to new relationships as opportunities emerge.

BE RESOURCE-EFFICIENT (MATERIALS AND ENERGY)

Use multi-functional design

Manage stormwater using existing structures and create new ones that have additional purposes.

BE LOCALLY ATTUNED AND RESPONSIVE

Use readily available materials and energy

Take advantage of existing structures and local materials, including waste materials, to create surface structures for slowing water.

ADAPT TO CHANGING CONDITIONS

Embody resilience through variation, redundancy, and decentralization

Create many small structures of different shapes, sizes, and locations to slow water and allow it to infiltrate.

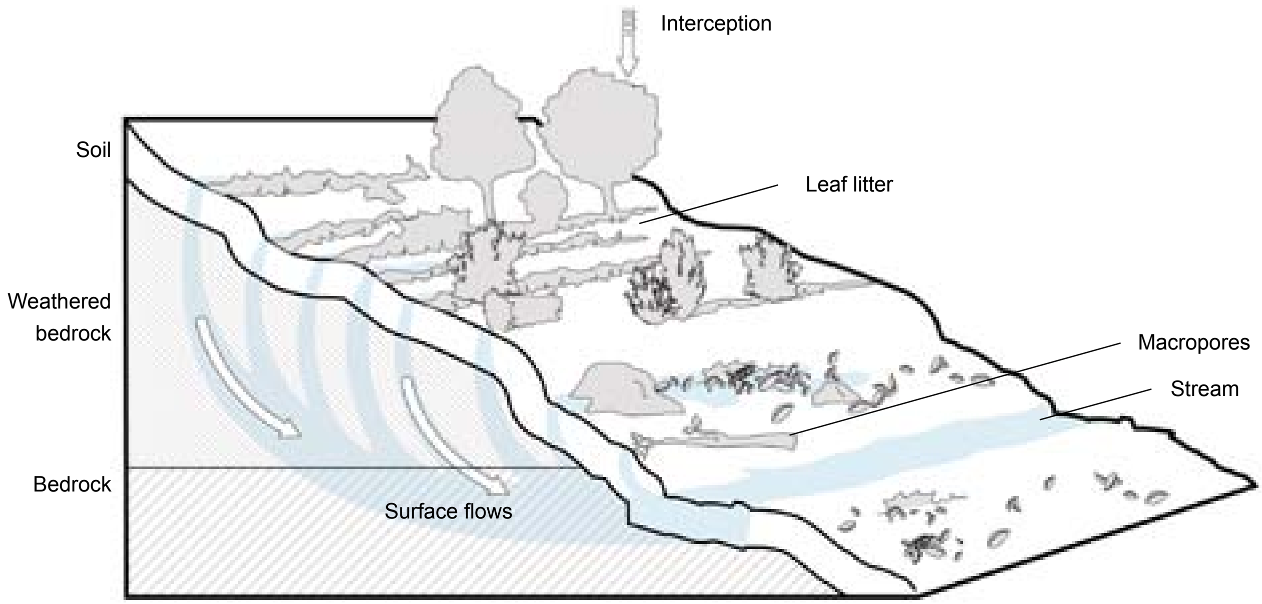
USE LIFE-FRIENDLY CHEMISTRY

Select building materials and processes that do not degrade water quality.

minimize erosion

vegetation

Multiple modes of interception reduce the energy of falling and flowing water, encouraging infiltration rather than erosion of land.



nature's design

surface roughness increases infiltration

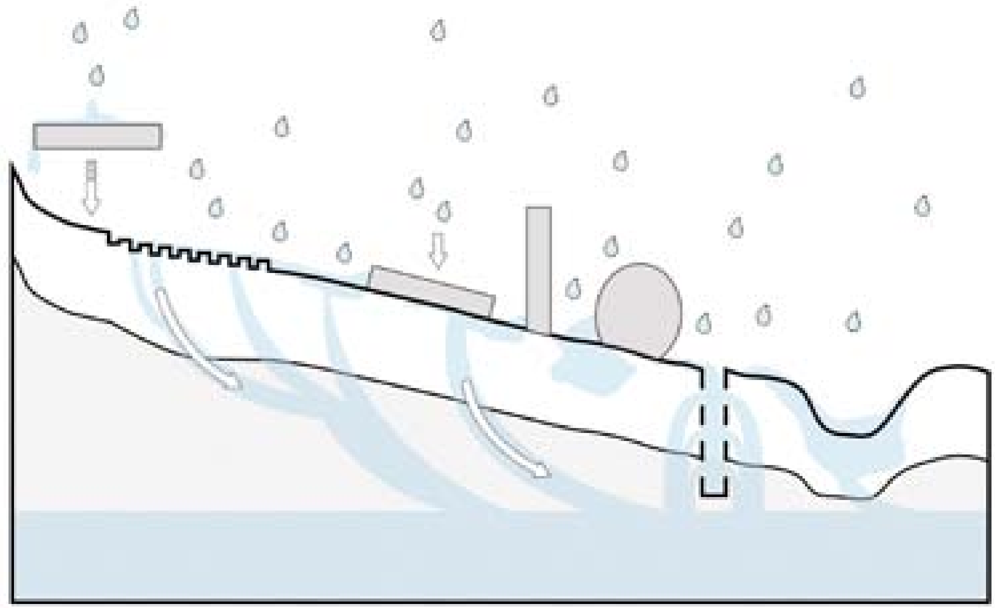
Surface runoff is rare in deciduous forests because of the cumulative effect of thousands of small ways that vegetation slows down water flow, especially if the runoff is first slowed in upper watersheds. During rainfall, forest leaves and branches are first to intercept and absorb the energy of raindrops, causing the water that collects to slow and pool below and partially infiltrate the soil. Plant litter, trunks, stems, and stalks add to the dissipation of raindrop energy due to friction, giving the water time to soak in.

Rainwater infiltration is enhanced by the deep, extensive root systems under forests, soil pores associated with plant roots and animal burrowing, and soil mixtures. Rich, organic matter in the forest soils allows faster infiltration.

Macro roughness on the soil surface also slows water. Downed trees (logs) that fall across a slope and settle into the ground slow water and trap sediments. Decaying logs are highly absorbent, holding water and releasing it slowly during dry periods. Remnants of logs and blown-over trees with up-tipped roots create a pit-and-mound topography that interrupts water flow and traps sediments.

The cumulative effects from burrowing creatures to leaves, branches and trunks, soils and topography are responsible for minimizing erosion and flooding.

- Canopy and litter interception, stemflow, and throughfall assist in preventing erosion.
- Biotic and abiotic forces contribute to soil porosity in forest soils.
- Humic acid, the result of breakdown of organic matter, holds water in soils.
- A diverse micro- and macro-fauna population breaks down organic materials and creates soil pores.
- Most rainfall moves to streams by subsurface flow pathways where nutrient uptake, cycling, and contaminant sorption processes are rapid.



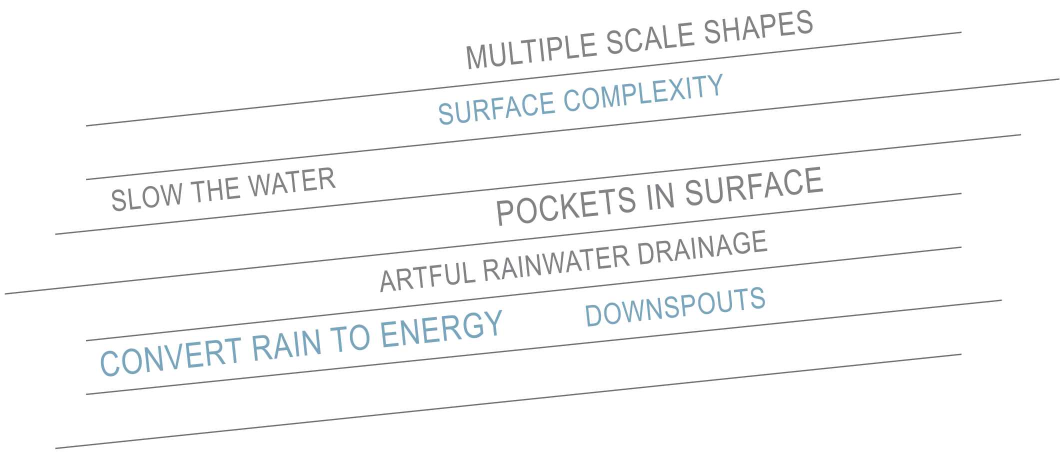
design principle

varied, multiple surface barriers increase infiltration

Varied and multiple structures reduce the velocity and energy of flow. Cumulatively, many structures slow flow long enough for it to infiltrate rather than flow overland and erode surfaces. These include horizontal, above-ground, and ground-surface structures that intercept; vertical structures placed in the path of flow that cause friction, creating turbulence that slows flow; porous structures in the surface that aid in infiltration and retention; and topographic features that increase surface roughness, resulting in temporary pooling.

Related design principles:

- Chemical compounds can increase holding capacity.
- Structures capture solid elements.
- Local materials decrease water flow.

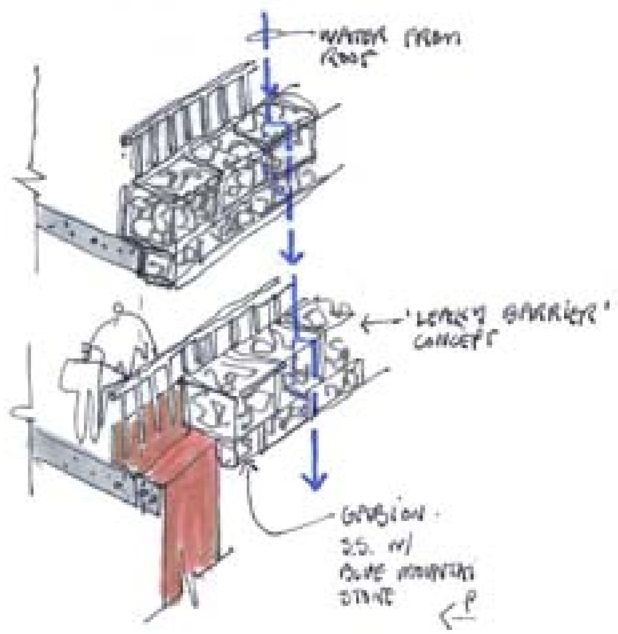


BaDT brainstorm

design ideas

Application Ideas

- Use shape on multiple scales to reduce the flow of water over surfaces. For example, create surface complexity on a roof or building facade.
- Consider vertical and horizontal structures that can slow the movement of water. This could include built elements such as buildings, parking structures, and awnings or natural elements such as landscaping, water features, terracing, and green roofs.
- Create a layered or pocketed system that increases infiltration and slows water velocity. For example, rather than direct down spouts, create an artful rainwater drainage matrix that forces the water to “meander.”
- Convert rainwater descending from roofs and gray water descending through the plumbing of a tall building into energy with micro-hydro technology. In the case of a meandering downspout system, there are even more opportunities to generate energy. Make energy generation information available to building users in real time.



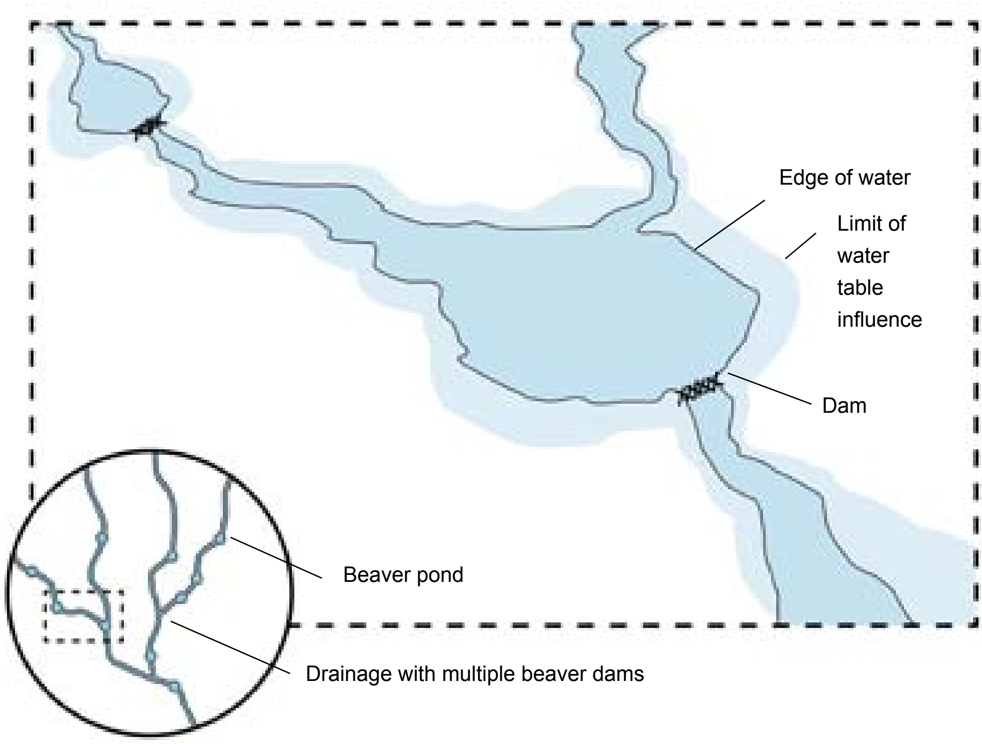
Water from upper regions of site sheet flow across the garage roof, running down a series of outward projecting gabion cages filled with rock.

The slowing water cascades through the porous construction, cooling pathways from the garage to the entrance building. Water is returned to the site and atmosphere.

minimize erosion

beavers

Beaver dams are arranged in a stair-step pattern that descends through drainages reducing the kinetic energy of stream flow and benefiting the ecosystem in many ways.



nature's design

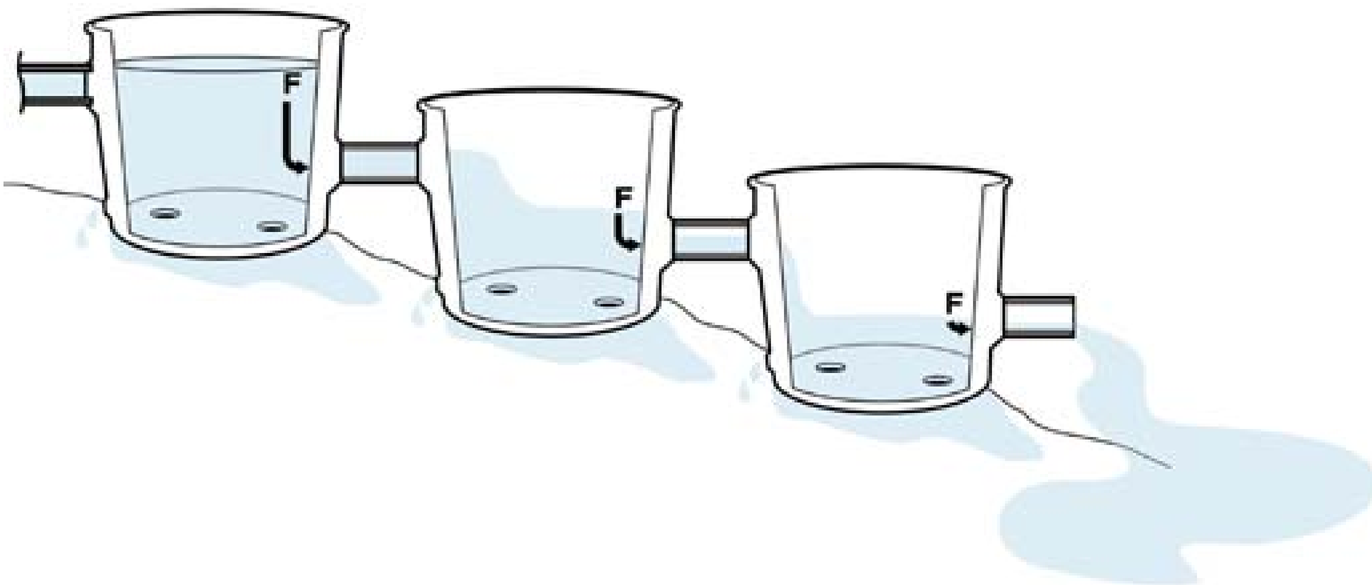
series of upstream barriers slow water

Beavers are ecosystem engineers that alter stream and upland habitats by cutting down trees and building dams across rushing streams, modifying streams into a series of stair-stepped ponds that descend down landscapes and drainages. These dams create a variety of habitats that many other species rely on in these ponds.

The backing up of water into ponds creates wetlands that slow water long enough for much of it to spread out, drop sediment and organic matter, infiltrate into the soil, raise the water table, and return moisture into the atmosphere through evaporation. Ponds in upper drainages reduce flooding in lower drainages. Beaver dams are leaky, slowly releasing water into the stream and reducing the kinetic energy of stream flow, especially farther up in drainages where water gradients are higher.

Beavers are considered an important **keystone** species because they create **shifting mosaic habitats** that are productive and dynamic. Beaver ponds sometimes fail and empty, especially as beavers move to new areas after their food runs out. These ponds may fill with sediment and organic materials, creating new soil for re-sprouting of trees and shrubs and then becoming meadows and forests. The activity of beavers enriches the biodiversity and overall health and resilience of the broader ecosystem.

- Beavers are ecosystem engineers and a keystone species.
- Dams are leaky structures.
- Dams slow and store water, creating wetlands and increasing water filtration and evaporation.
- Dams occur in a stair-step pattern.
- Beaver ponds can reduce flooding downstream.
- Habitats created by beaver enrich biodiversity and health of the ecosystem.



design principle

series of upstream barriers slow water

A series of leaky barriers reduces kinetic energy and increases infiltration but does not completely stop the flow of water. Multiple spillways are produced, leaking at both high and low flow. Storing water allows for infiltration into surrounding areas, further slowing flow. Instead of flowing away, elements are captured and stored temporarily, resulting in a shifting mosaic of conditions that increases diversity and creates a dynamic community.

Related design principles:

- Barrier reduces kinetic energy.
- Slowing water raises water table.
- Slowing water captures sediments.
- Small materials in cross-wise pattern provide leaky barrier.
- Increases biodiversity by diversifying landscape elements.
- Allows flow that increases aquifer recharge.

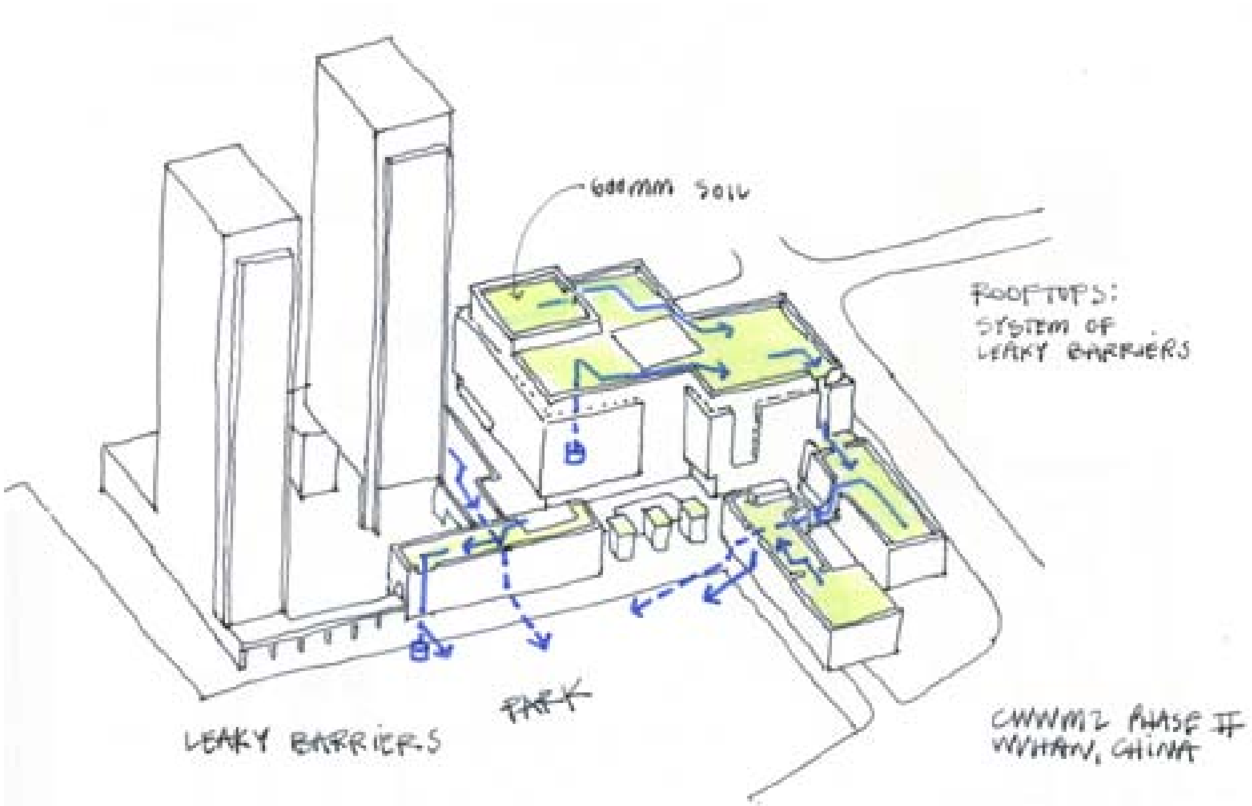
BaDT brainstorm

design ideas

Application Ideas

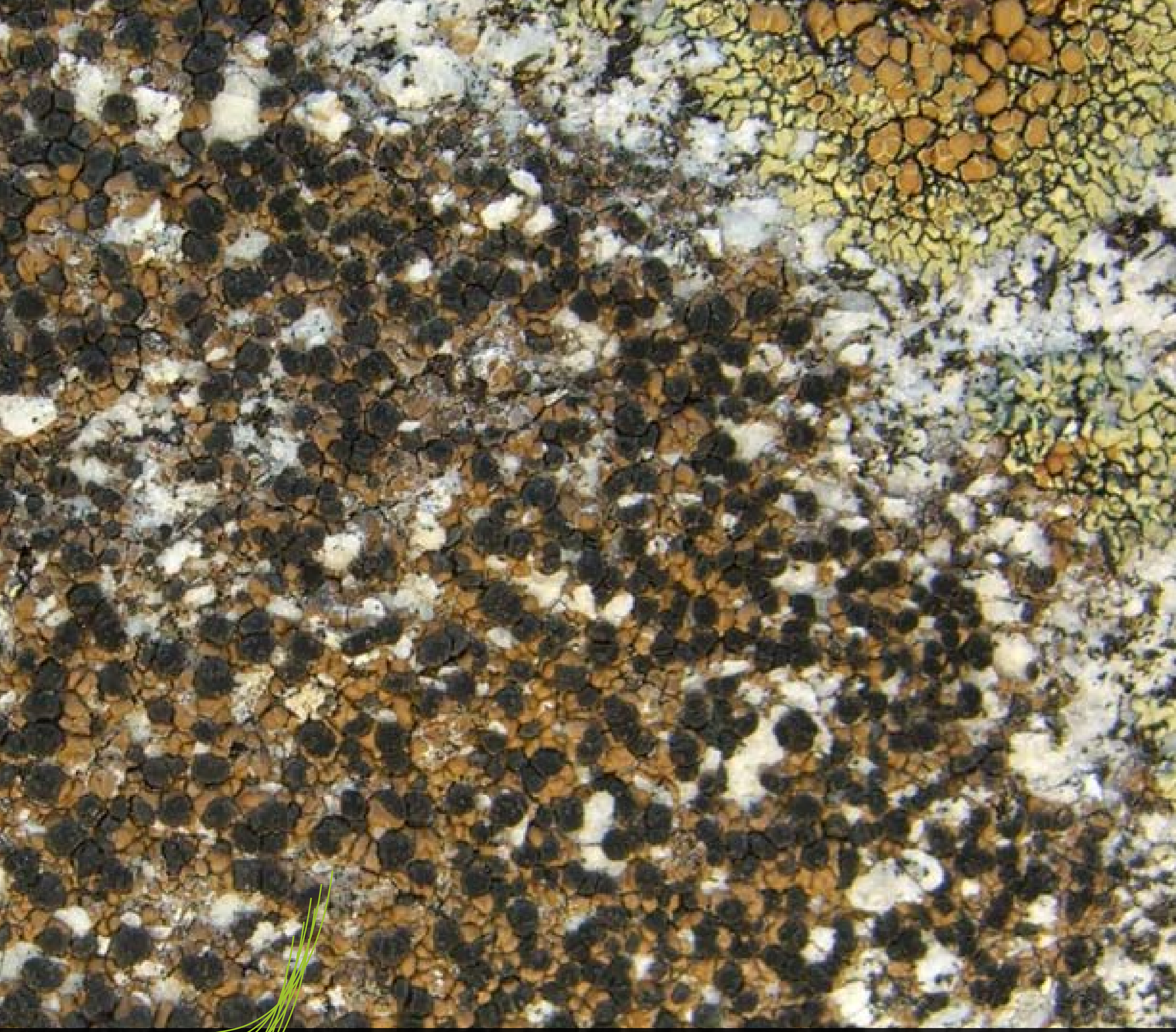
- Consider installing a series of underground or partially buried cisterns that collect rainwater and snowmelt. These cisterns should be leaky and extend away from the building, hydrating the landscape slowly and from the bottom up.
- A network of underground cisterns could connect buildings within a given development. This could serve as the basis of a water guild (see **Social: Foster Social Integration • pollinators**) where landscaping plants use the soil moisture. Humans indirectly benefit by interacting with the landscape (biophilia). A well-hydrated landscape is also important for microclimate regulation, another indirect benefit to humans. This creates many benefits and opportunities for a diversity of life.
- Construct water barriers as far up in a drainage area as feasible to decrease downstream effects of too much water.

LEAKY BARRIERS ROOFTOPS



A series of green roofs could be connected as a series of leaky barriers. Lower roofs with shorter spans have more capacity and function as water gardens in wet periods.

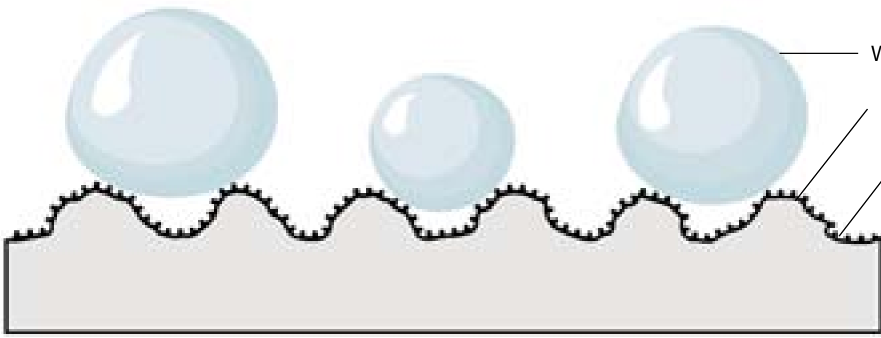
Excess water is given over to the park. The overall system reduces combined storm sewer overflow events.



minimize negative impacts of rain water

lichen

A lichen that grows on tree trunks acts like a waterproof, yet breathable, barrier due to a rough surface and hydrophobic compounds that cause water droplets to perch while allowing airflow.



nature's design

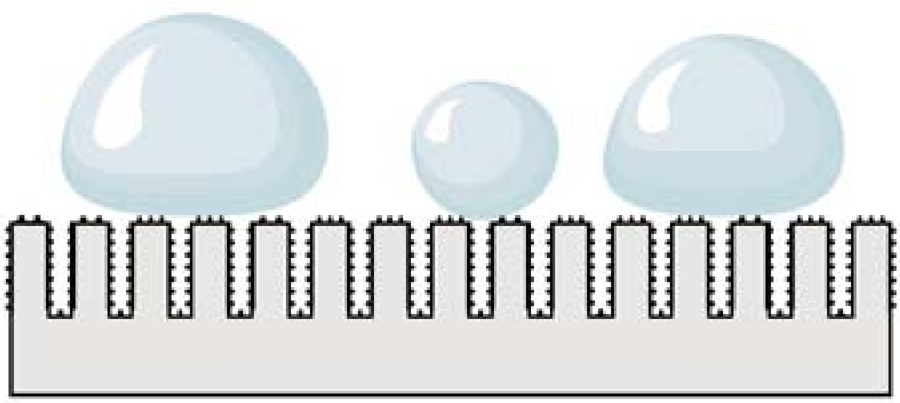
rough surface, hydrophobic spaces create air flow

The lichen *Lecanora conizaeoides* grows on tree trunks, using the tree for support and access to light and water. It does so without harming the tree.

Lichens are compound organisms, meaning they consist of **symbiotic partners** — algae embedded in a fungal matrix. The algae and the fungi live together as one organism, mutually supporting each other with the algae photosynthesizing sugars and the fungi providing a protective home for the algae. The rough surface of the fungus, with structures of different sizes layered on one another, keeps water droplets perched on top rather than coming in contact with the whole surface. Channels between the structures are coated with hydrophobic compounds called hydrophobins, so that the channels remain dry, allowing air to reach the algae. This combination of rough structure and hydrophobic compounds produces a biological analogue of a waterproof, breathable garment.

Lichens play an important role in ecosystems, thriving in places where plants can't grow, thus adding to the total energy-gathering, carbon-fixing ability of the ecosystem without competing with other plants. They are also a food source for insects and mites and provide shelter either directly as structures or by being incorporated onto insects' bodies as a form of camouflage.

- Lichens are compound organisms made up of symbiotic partners.
- Lichens grow on trees without drawing nutrients from them or causing harm.
- Lichens photosynthesize even during rain.
- The fungal partner in *Lecanora* sheds water due to a rough surface combined with a hydrophobic compound.
- The algae partner retains access to air for gas exchange.
- Lichens are important components of the forest ecosystem.



design principle

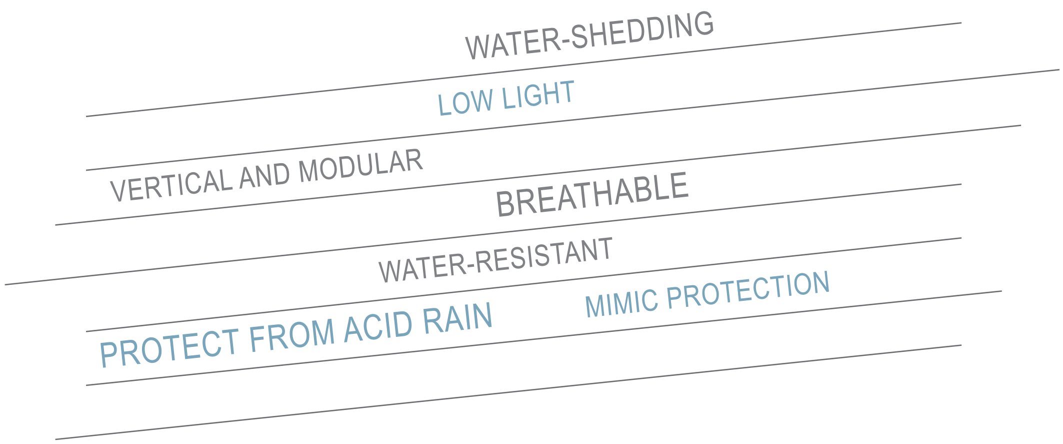
rough surface, hydrophobic spaces allow air flow

Breathable, water-shedding surface made of hydrophobic compounds combined with multi-layered roughness.

A water droplet is made up of highly polar molecules. If put in a situation where its molecules are more attracted to each other than to a surface, it will form a sphere. A series of peaks with hydrophobic valleys will keep a sphere of water molecules perched on top, rather than seeping into the spaces between the peaks. This facilitates water rolling off a surface. At the same time, the spaces between the peaks stay dry and air can flow through them. This creates a breathable, yet waterproof, surface.

Related design principles:

- Symbiosis provides opportunities to find mutual benefits through relationships.
- Symbiosis provides opportunities for one organism to gain from another without harming the host.
- Empty spaces can provide sites for compatible uses.
- Solar energy is captured during rain.



BaDT brainstorm

design ideas

Application Ideas

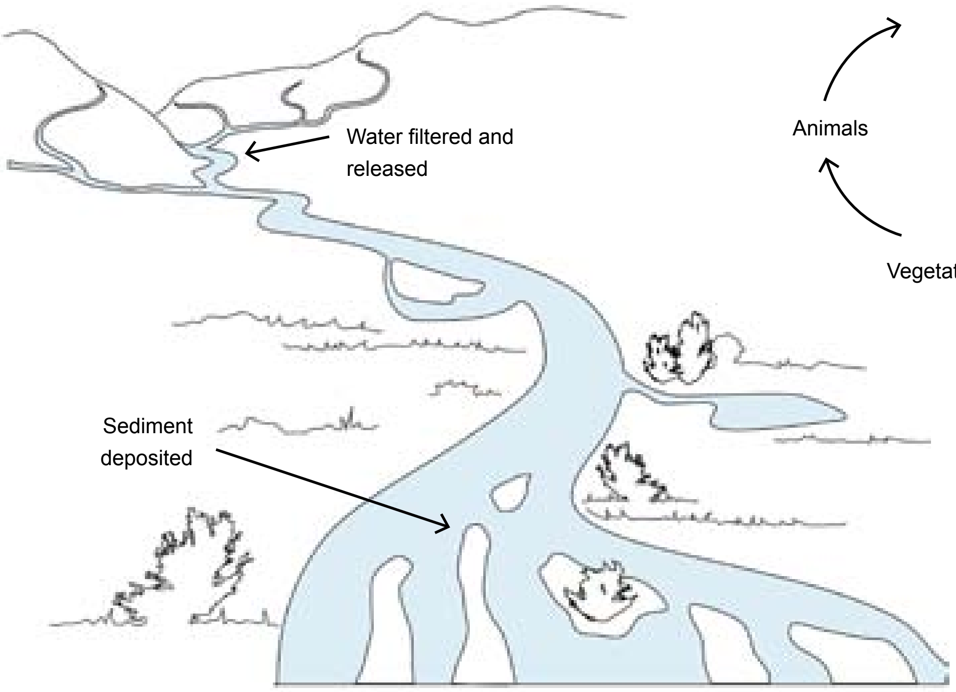
- Lichens can photosynthesize during a rainstorm. Developing a water-shedding surface treatment for solar panels may allow them to be more effective during low-light, stormy conditions common in the temperate broadleaf biome.
- If the building is thought of as an analogue to the tree a lichen grows on, a conceptual application could be installing a micro-solar system on a building's vertical surface. This discrete micro-solar system could be modular and interconnected so that if one section failed, the overall system would continue to operate.
- Lichens work like a breathable, water-resistant fabric. In a humid climate, a building skin that is both waterproof and breathable can provide a more comfortable interior.
- Lichens shed water effectively, which protects from acid rain. A building surface or structure applied to the building surface that mimics the lichen may protect from the damages of acid rain.
- The way that lichens shed water could be incorporated into structures used to capture water, resulting in less adherence and therefore more complete capture and fewer opportunities for buildup of algae and biofilms.

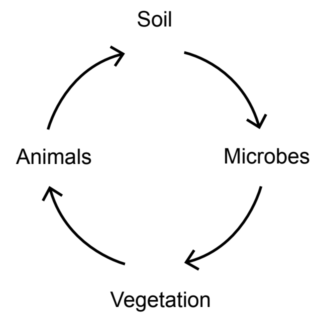
future design ideas

optimize water resources

rivers

Rivers bring life to the landscape, distributing water that is used and reused in a constant cycle.





nature's design

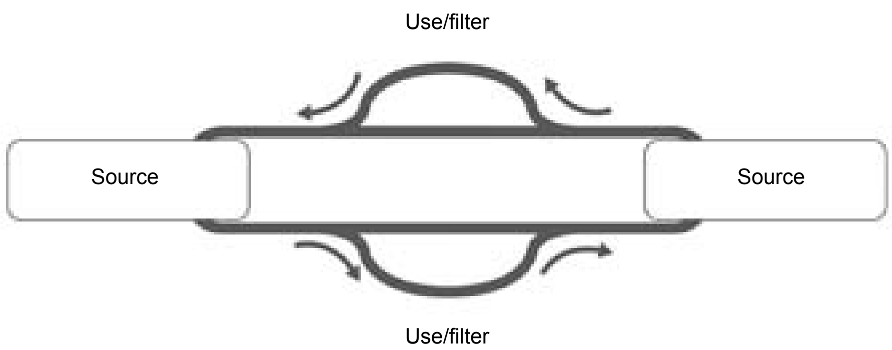
velocity, torturous path and filters purify water

The hydrological cycle involves not just the flow of water but also exchange of heat through condensation, and cooling through evapotranspiration. Climate affects the kind of vegetation that stabilizes the landscape, as well as what kind of river, channel pattern, and sediment sequences develop. Water flows through lakes, streams, rivers, ponds, wetlands, groundwater, and deep aquifers. Water moves from one reservoir to another by evaporation, condensation, precipitation, infiltration, runoff, and subsurface flow.

Rivers are complex systems that vary with their position in the landscape. Three zones -- the upper, middle, and lower reaches of a river course -- make up a river system. The upper reach is characterized by valleys, hills, or mountains, which are gradually leveled by erosion. The middle reach is largely a zone of sediment transport that usually forms meandering or braided channels. The lower reach has a prolonged net sediment accumulation in a basin area.

A river contains **detritus**, dust particles, sediment, and minerals that flow with the water through the system. Water is cleaned throughout the system by turbidity and velocity caused by moving over landscape forms, through soils, sediment, and filtered though the bodies of living organisms. There is no wastewater in nature because living organisms treat water and its constituents as food.

- In nature, water transforms into vapor, condensation, snow, ice, and rain water.
- Rain water collects into bodies of water such as streams, rivers, lakes, ponds, and oceans.
- River water flows in a predictable, dynamic cycle through the seasons.
- Channel patterns are formed by local or regional conditions.
- Water found in nature is not sterile.
- Redundant food webs clean and maintain ecosystem function and health.



design principle

flow, filter, and purify water

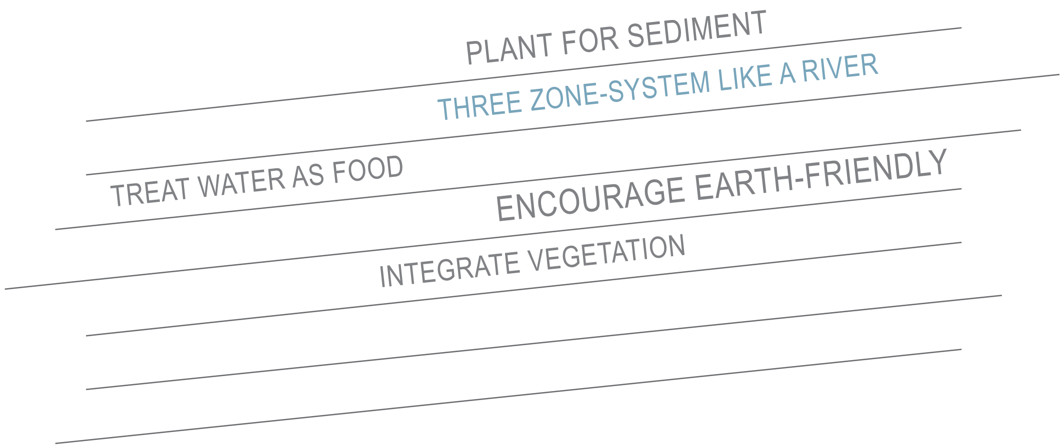
A flow is made up of elements that aggregate into a larger mass. Flows can be managed by planning how to direct the flow. The main variables in a drainage network that control a water system are gradient, discharge, and sediment.

Collected water, especially water with a high velocity, can produce strong forces against objects, causing displacement and erosion. It is costly to try to control the flow of water because of forces such as gravity and fluid dynamics. Water wants to move.

Filtering of a flow can occur through turbidity and velocity. Physical filters can pull out and consume unwanted materials.

Related design principles:

- Water flows serve more than one purpose.
- Healthy flows are not static.
- Water moves materials with its flow.
- Water wants to branch and channelize.
- Plants and living organisms help purify water.
- Sediment provides resources and a filter.



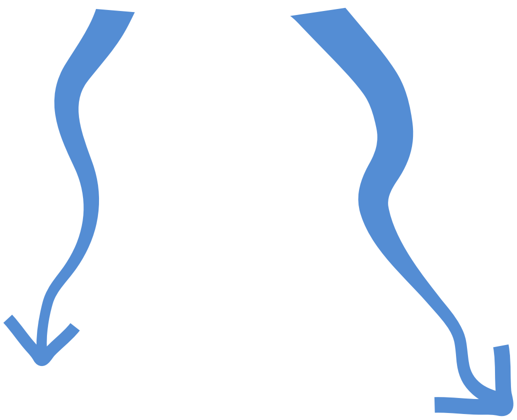
BaDT brainstorm

design ideas

Application Ideas

- Plan for drastic changes in water flow amount over short periods of time.
- Plan for not just filtering, but consumption of the gathered elements.
- Identify where vegetation can help purify water in a water flow system.
- Integrate vegetation that is best suited to purifying water.
- Plan for accumulation of sediment and minerals and use water flow to flush accumulation.
- Design a gray water system with three zones like a river.
- Design a water system that encourages the use of non-toxic cleaning materials and proper disposal of pollutants.
- Metaphorically, treat water as valuable food.

Building as a landform that forms a river

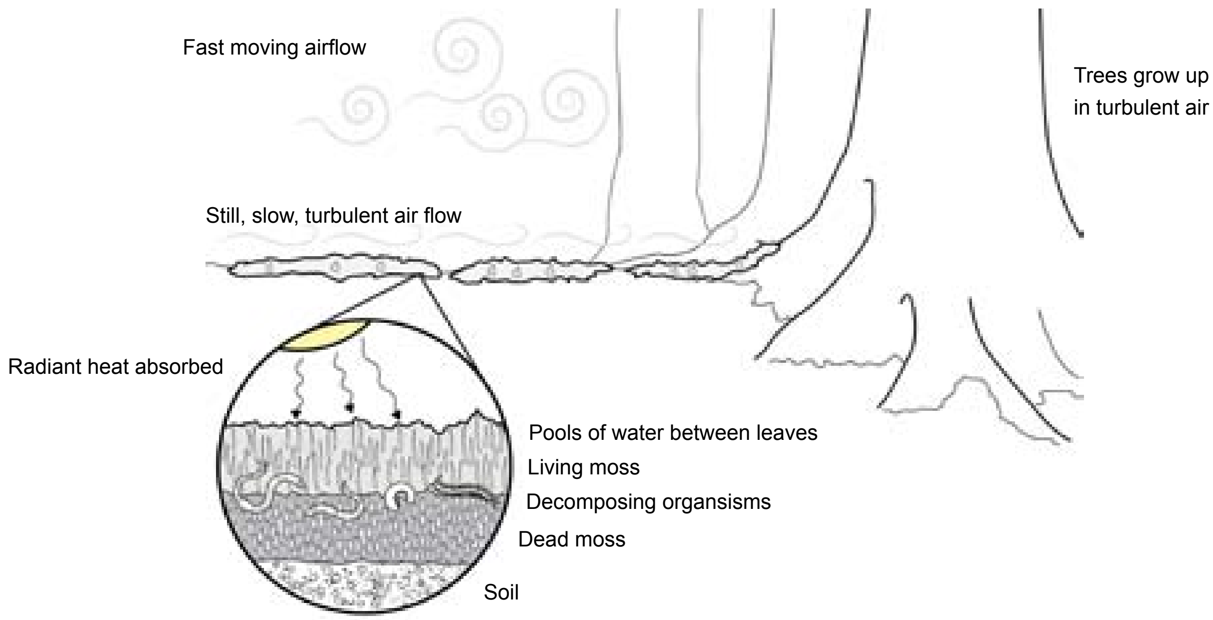


Buildings surfaces can be the first step in the overall slowing, sinking, and storing regime

dehumidify in summer

bryophytes

Mosses, liverworts, and hornworts form a thin layer of green growth on top of a layer of dead tissue at the still air boundary layer of the forest.



nature's design

absorbable, water-holding material moderates humidity

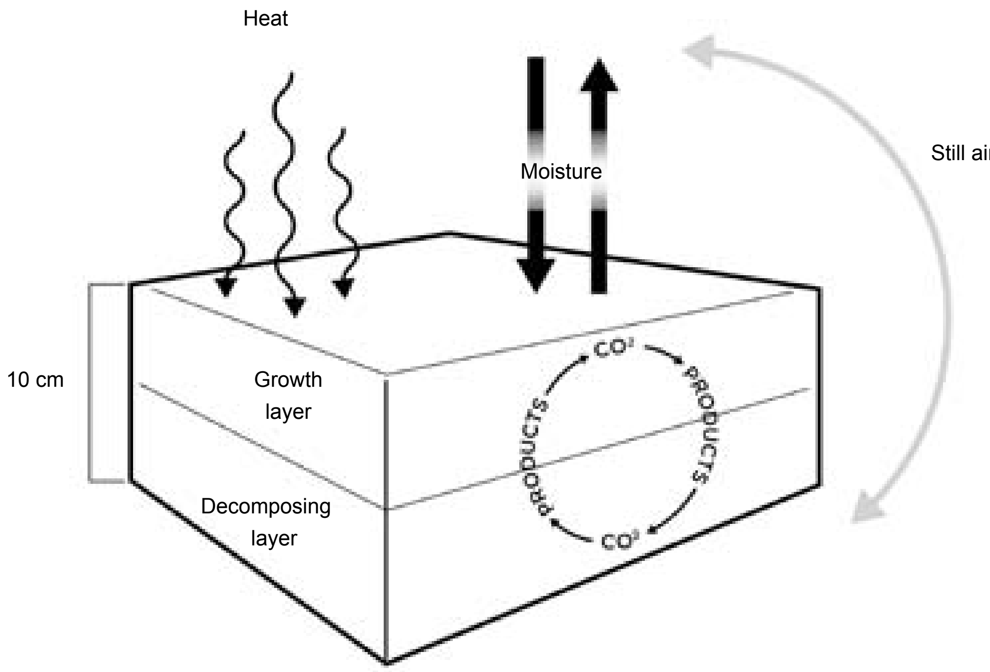
Nature responds to humidity as a resource, not as a problem to be managed. Nature allows flow of materials instead of resisting or constricting flow.

Bryophytes do not have a waxy outer cuticle, a vascular system, or roots like most other green plants. Therefore, bryophyte tissue absorbs water immediately. The bryophyte layer under the deciduous forest canopy forms a vertical structure with a living "green" zone atop a "brown" zone of dying tissue and decaying detritus. A dense, double-layer structure, combined with a still air layer that protects against evaporation, allows the bryophyte layer to hold on to moisture. When evaporation does occur, bryophytes desiccate and die, adding to the underlying dead layer. Decomposing organisms living in these layers and the bryophyte plants resurrect when moisture returns, re-forming an upper living layer.

Decomposing organisms (nematodes, tardigrades, bacteria, fungi) produce carbon dioxide that supports bryophyte growth. Larger organisms such as tree seedlings, worms, insects, salamanders, and frogs thrive in the upper layer.

The bryophyte layer creates a predictable microclimate in the shade of a forest. Other bryophytes are adapted to living on rocks and trees or form peatlands in wetter, sunny areas. Bryophytes can be found in almost every ecosystem on the planet, from the tundra to the rainforest to deserts.

- Living and dead layer provides habitat for a diverse community of organisms (fungi, bacteria, tardigrades, nematodes, mites, springtails) and invertebrates that contribute to production of biomass and materials recycling.
- Layers capture leaf canopy nutrients washed down by rain, adding to soil nitrogen.
- Bryosphere regulates local temperature, soil and vegetation hydrology, soil chemistry, and nutrition.
- Bryosphere prevents soil erosion.



design principle

absorbable, water-holding material moderates humidity

To modify humidity, small, simple structures in a dense, double layer absorb and release moisture in a still-air environment.

A dense layer of small structures with tissues that can absorb moisture creates conditions for interaction and cooperation with other elements. This develops into a manufacturing cycle of energy inputs, product outputs, breakdown, and recycling.

Related design principles:

- Energy produced locally decreases costs.
- Layers of active and inactive material interact.
- Systems occur within systems.
- Recycling of waste creates a closed loop system.
- An interconnected manufacturing web maintains materials within the system.

WATER VAPOR-ABSORBING FACADE
MICRO-PROCESS POLLUTANTS
VERTICAL APPLICATION
TEXTURED, SHADED SURFACES
MODERATE SURROUNDINGS

BaDT brainstorm

design ideas

Application Ideas

- Develop or find a building facade material that can absorb water from the air and either hold it for later use or drain it into a reservoir. Use in combination with a water-impermeable layer to prevent deeper saturation into more sensitive building materials/layers.
- This water-absorbing/holding/draining material could also conduct micro-processing of environmental wastes, either physical (debris) or chemical (pollutants). The Biolytix technology is an example of how this works in a horizontal system. Could a similar system be designed for vertical applications?
- A literal application would be to design textured, shaded surfaces adjacent to walkways, parking lots, and buildings to encourage moss and bryophyte growth that will absorb rainwater and moderate micro-climate conditions in the immediate surroundings.

future design ideas

ENERGY

Life has had 3.8 billion years to test ideas for capturing, storing, and efficiently using energy. One energy challenge in this biome is the seasonality of energy availability and usage.

A common summer condition in the temperate broadleaf forest is high heat combined with high humidity. Plants have an elegant cooling system that is coupled to production of energy and the passive processes of evaporation, water adhesion, and cohesion. The resulting design also uses something else in ample supply in this biome — water. Humidity is a resource that is used to help cool every leaf, and in turn, the whole forest. This is an example of two patterns repeatedly seen in nature. One is that nature rarely spends energy on resistance and makes use of locally available resources. The other pattern can be described as the principle of “lots of littles.” That is, many small, seemingly weak elements combine to create a powerful, problem-solving process.

Another pattern in this biome related to energy is a diversity of designs. During the seasonal change of winter, organisms must adapt to long months of cold temperatures and a drastic change in available nutrients. Trees drop their leaves, move nutrients to their roots, and store them while reducing their metabolism in the long wait for spring and warmer weather. Animals reduce their energy expenditure, hibernate, find cover, and store energy as fat or store food in caches. The many designs evidenced in these adaptations suggest that nature doesn’t rely on a single solution. Solutions vary because nature thrives on diversity and novel ideas.

- Cool structures
- Move moisture passively
- Reduce energy expenditure
- Create thermal cover
- Store energy
- Optimize energy sources

ENERGY

LIFE'S PRINCIPLES

REFERENCE THE DEFINITIONS

EVOLVE TO SURVIVE

Replicate strategies that work

Replicate successful methods to meet similar functions.

INTEGRATE DEVELOPMENT WITH GROWTH

Invest in strategies that promote development and growth in relationship to life conditions.

BE RESOURCE-EFFICIENT (MATERIALS AND ENERGY)

Use multi-functional design

Use one design to perform more than one function.

BE LOCALLY ATTUNED AND RESPONSIVE

Design heating and cooling systems to be responsive to ambient conditions and needs of people within a space.

ADAPT TO CHANGING CONDITIONS

Embody resilience through variation, redundancy, and decentralization

Decentralize solar collectors and vary their design, placement, and type based on exposure to light and shade.

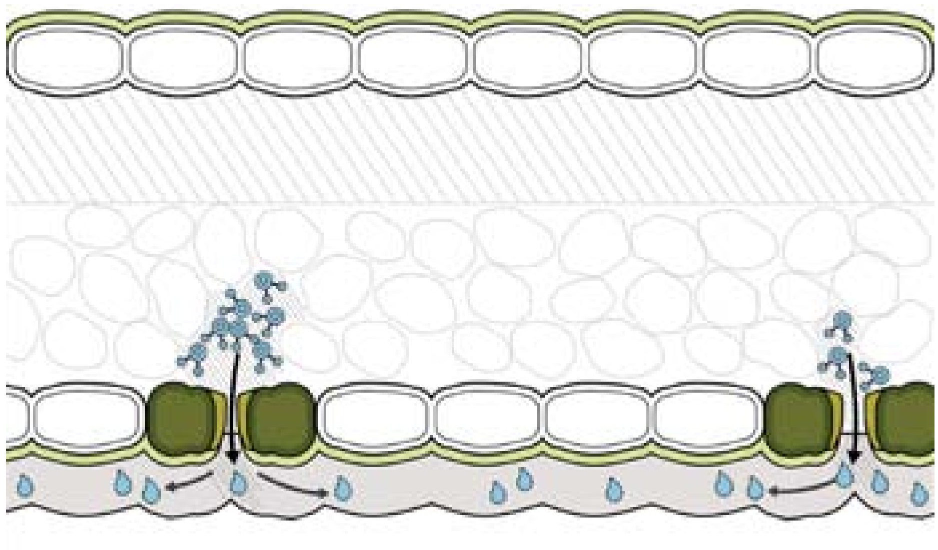
USE LIFE-FRIENDLY CHEMISTRY

Transport water to cool without using polluting energies.

adjust to temperature change

leaves

Leaves are cooled by drawing soil moisture up through the tree and into leaf stomata that release water vapor to the surrounding leaf and to the atmosphere.



nature's design

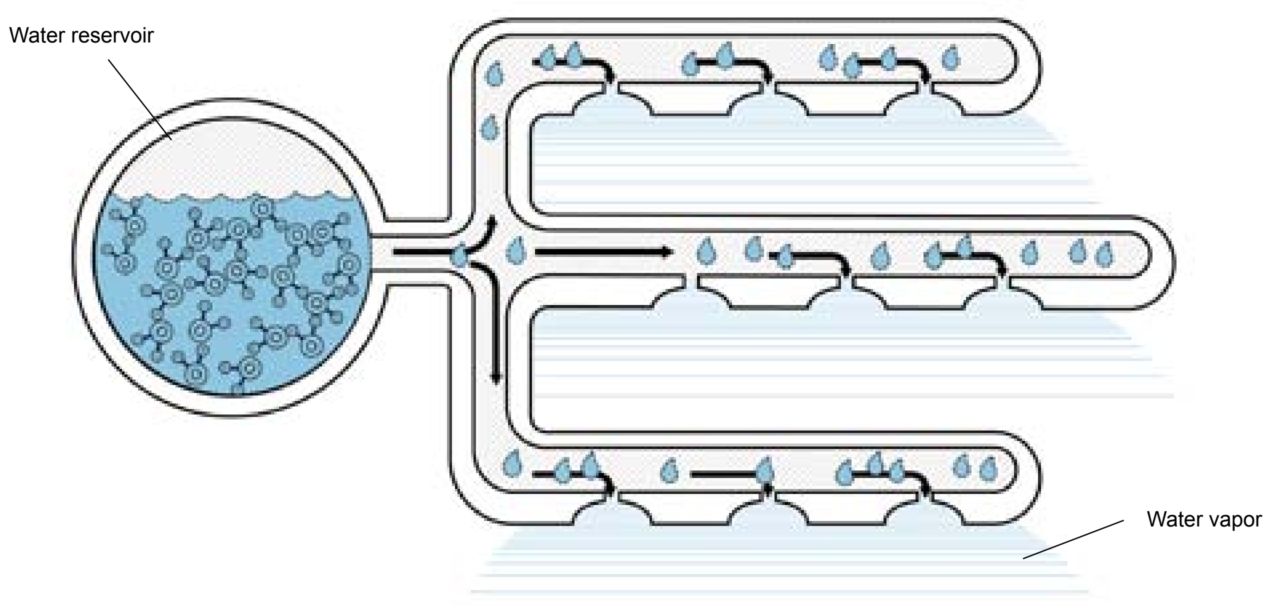
passive valve cools with moisture

A leaf's primary job is to conduct photosynthesis, capturing the energy provided by the sun to convert carbon dioxide into organic compounds. Enzymes play an important role in this conversion, but they can't work at high temperatures.

A leaf cools itself through transpiration, in which soil moisture is drawn upward from the roots of the tree through stems, branches, and veins to leaf stomata. Leaf surfaces can cool by as much as 20-30° F (11.1 to 16.7° C). Special "guard cells" regulate the opening and closing of the stomata.

All trees transpire and thus cool the forest temperature. Within the temperate broadleaf and mixed forest biome, the average temperature in urban areas is 14° F (8° C) warmer in the summer than in the dense, tall forested vegetation surrounding them. This cooling effect comes from evaporation of moisture from the soil and transpiration of moisture from millions of leaf surfaces. At the largest scale, this results in a cooling of temperatures throughout the ecosystem.

- Transpiration pulls a string of water molecules from the roots up through the plant via cohesion and adhesion forces.
- Water is drawn to the guard cells of the stomata by osmosis (potassium pump system).
- Guard cells swell by inflow of water and contract by loss of water; this opens and closes the pore.
- Stoma closed → water uptake → increased pressure → stoma open.
- The outer surface of the top of the leaf is tightly sealed by wax-coated, interlocking pavement cells.
- Stomata are found in greater numbers on the underside of the leaf.



design principle

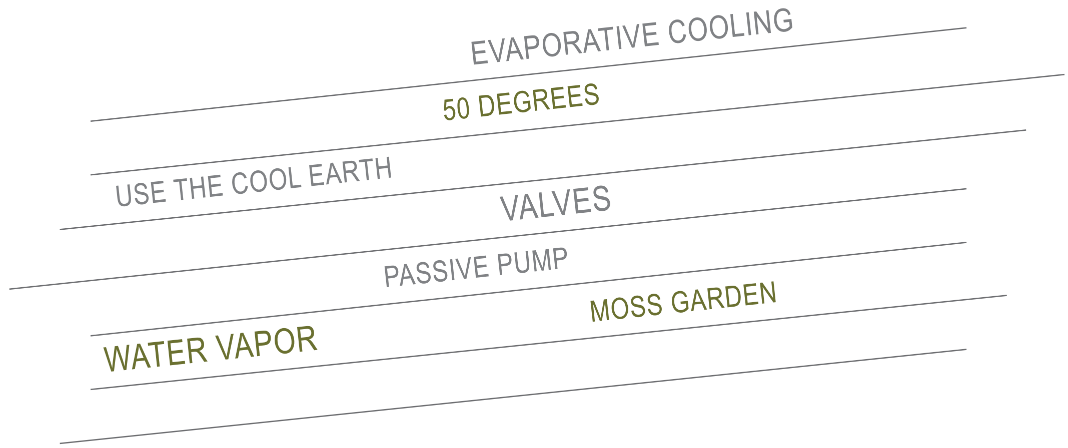
passive energy pump with valve transports water

Design an evaporative cooling system that draws moisture from a source and delivers to a sink site where valve-like pores are triggered to open and close based on humidity and heat levels.

A passive energy pump draws water from a lower source through a structure to the outside of that structure to create a water vapor layer that cools the whole structure. Several systems, including sensory valves, are coupled and triggered in response to changes in temperature and humidity. Many units of evaporation produce an additive effect to create a greater result.

Related design principles:

- Moisture flow responds to varying requirements.
- Repeated structures create an additive effect.
- Systems are coupled to reinforce effect.
- Valve opens and closes in response to humidity and heat fluctuations.
- Different forms of water (vapor and liquid) allow cooling effect.
- Valve positioned away from heat source to protect from desiccation.



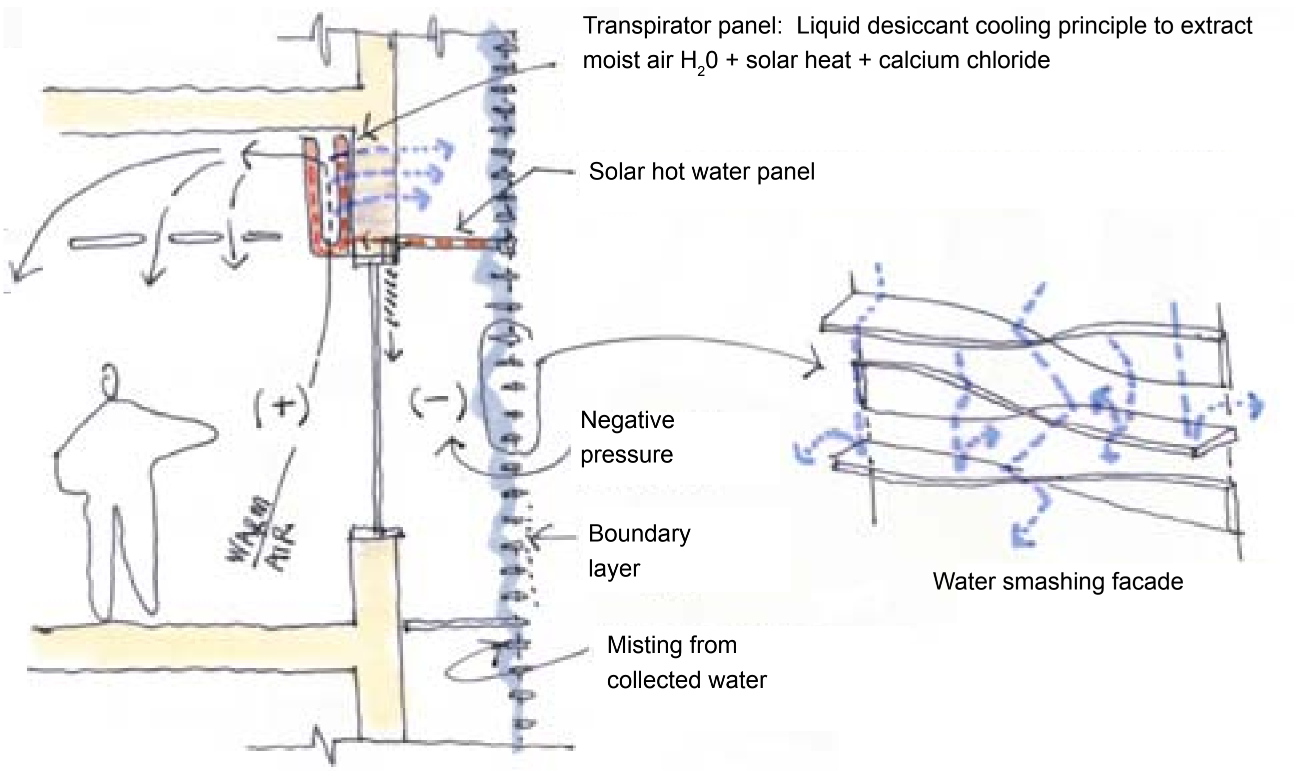
BaDT brainstorm

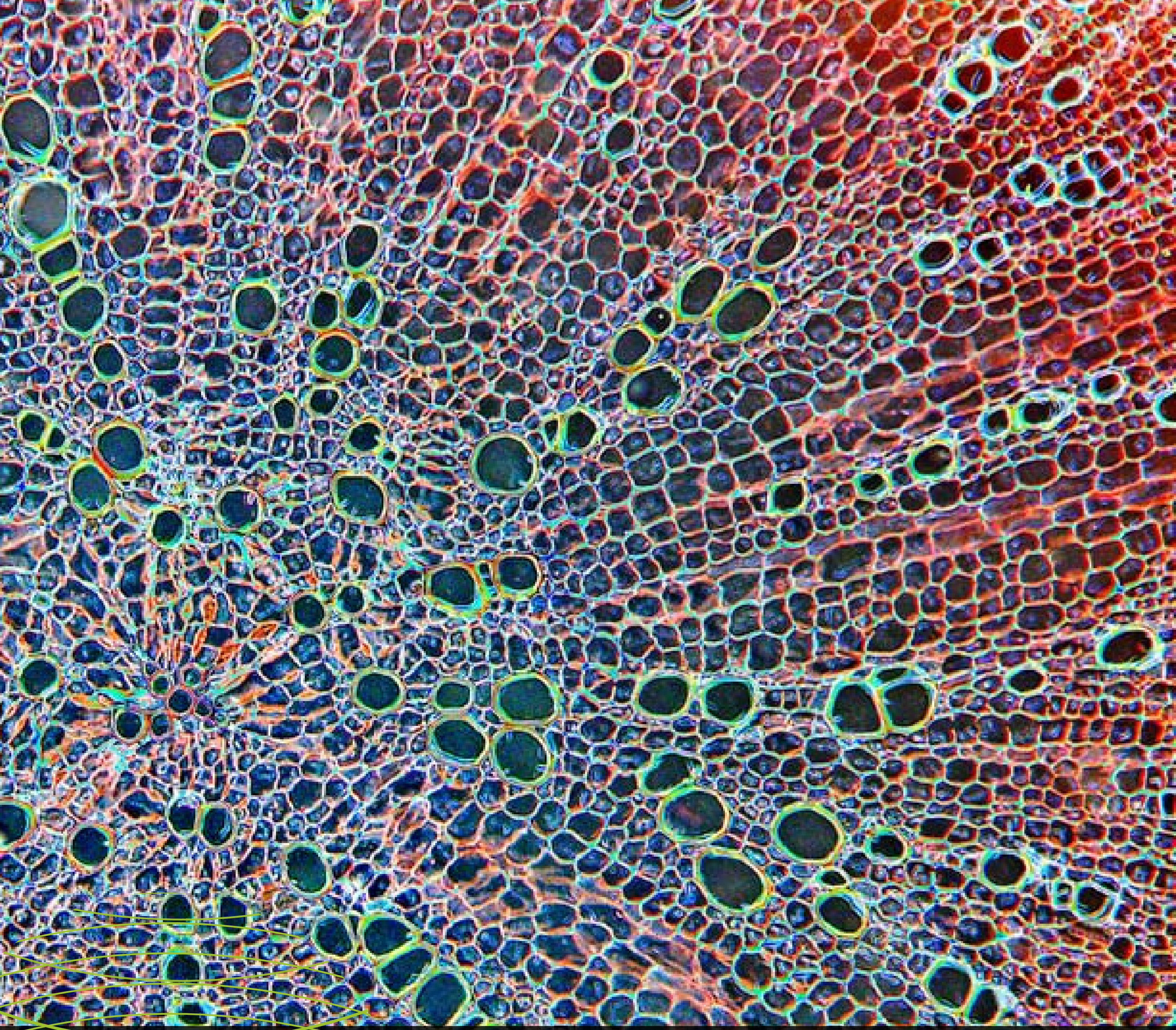
design ideas

Application Ideas

- Evaporative cooling technology (swamp cooler) is not considered effective in humid climates such as the temperate broadleaf biome. Yet this is the cooling method of choice for all vegetation in this habitat and it has important implications for macroscale climate patterns.
- The water moving through the plant is cool — the earth keeps it around 50° F (10° C). Is there a way to use the earth rather than an electrical refrigerant system to cool the water that runs through the evaporation system? Perhaps this strategy can be combined with the beaver dam strategy of underground cisterns.
- Valves that control the rate of this artificial transpiration could be tuned to respond to ambient temperature and humidity levels. The pump would move cool water when the room was too warm or dry and would shut off when the room had cooled or reached a maximum humidity level.
- A literal application could involve water vapor being released onto a bed surface for a moss garden. This method could be used in an indoor or outdoor garden area.

BIO-ADAPTIVE FACADE

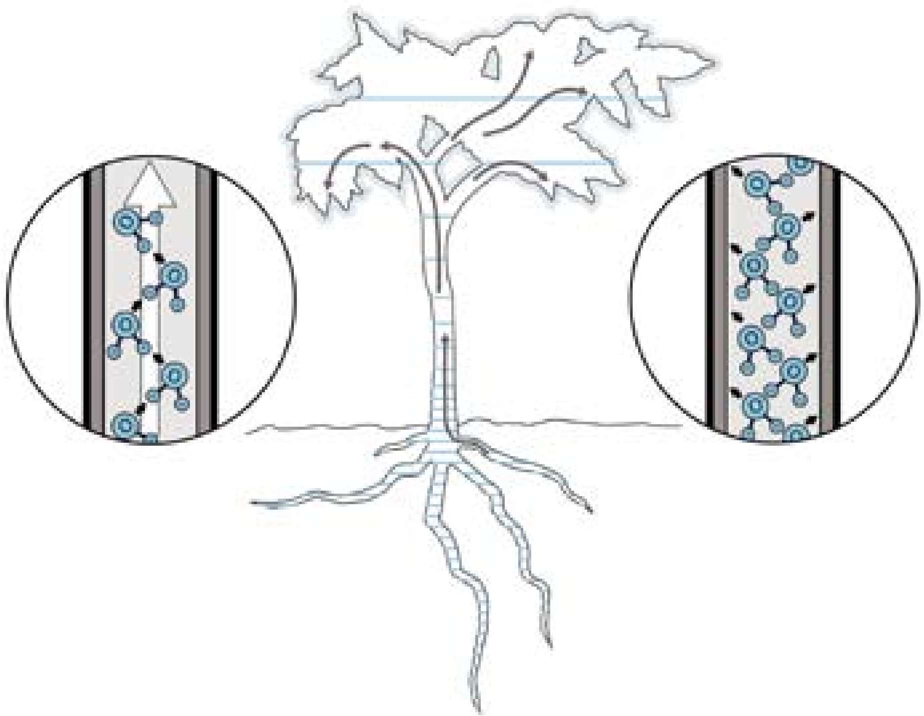




adjust to temperature change

trees

Water is drawn up from roots through stems, branches, and veins to the stomata in leaves using passive forces of cohesion and adhesion.



nature's design

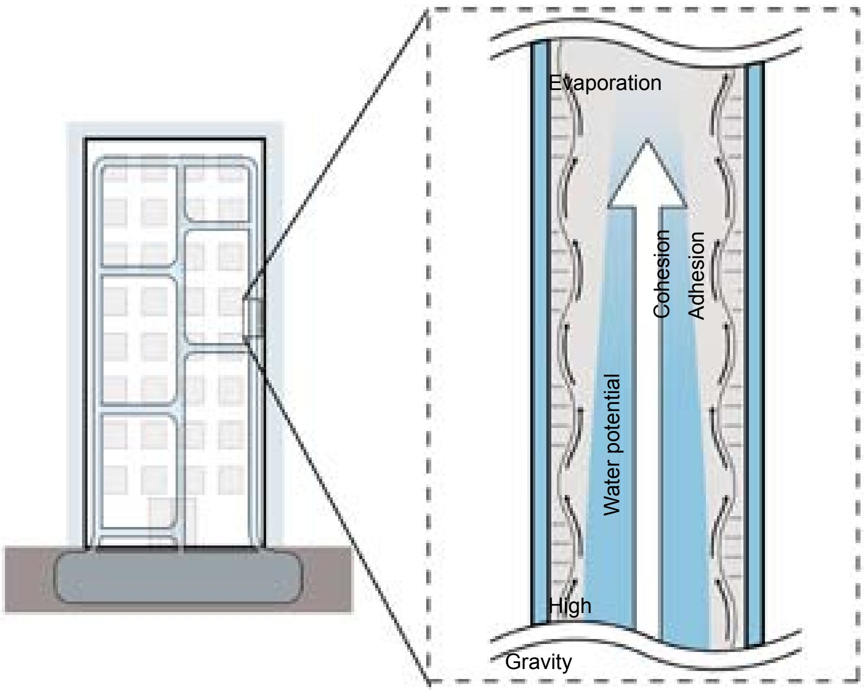
transpiration moves water

Trees are protected from hot temperatures and water loss by pulling soil moisture from the soil through the roots and then up the vasculature of the trunk, branches, and veins to the leaves. There, the moisture is released as water vapor through leaf stomata and into the surrounding atmosphere. Wind causes evaporation and a cooling effect around the tree canopy.

Moisture is pulled up through the vasculature of the tree by two chemical forces — cohesion and adhesion — acting on the water molecules. Water movement is additionally driven by a pressure gradient created by the pulling force of evaporation. Evaporation of water from the leaves of a tree causes water in the conduits to move from the soil, a source of moisture that has higher water potential, up a conduit with decreasing water potential along its length, to the sink (leaf evaporation).

At the tree scale, moisture is brought to leaves to produce cooling evaporation to protect the leaves. At the forest scale, all trees transpire together and cool the temperature of the forest. At the ecosystem scale, soil moisture also evaporates, contributing water vapor to the surrounding atmosphere and resulting in a cooling of temperatures throughout the ecosystem.

- Cohesion is formed between the hydrogen bonds in water molecules.
- Adhesion causes water molecules to be attracted to the tree vessel walls and to overcome gravity.
- Transpiration pulls a string of water molecules from the roots up through the trunk and into the leaves.
- Water provides structural support for the architecture of young branches, stems, and leaves.



design principle

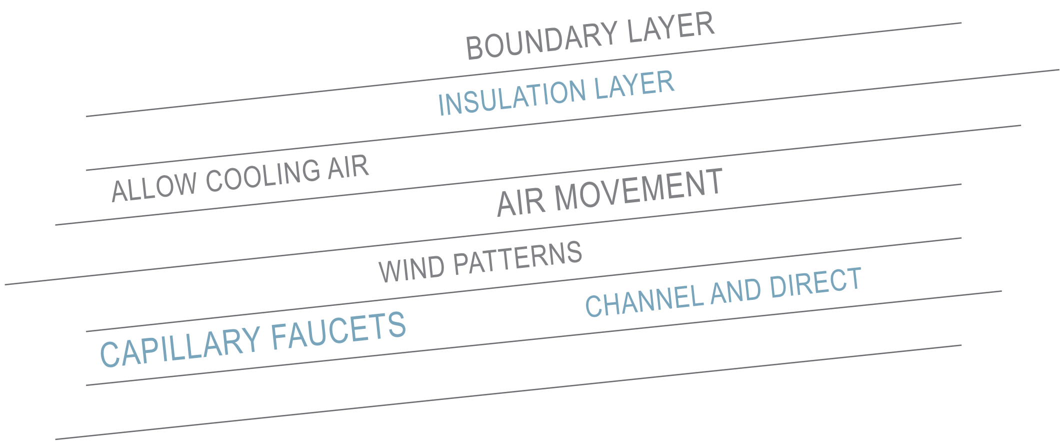
water pulled against gravity by adhesion and cohesion

Moisture is drawn upward from a lower source through a series of vertical tubes inside a structure. The moisture is released to the outer surface to create a water vapor layer that cools the whole structure. The process pulls water from a lower source with higher water potential up to a higher sink with lower water potential.

A passive energy pump is created, pulling water against the force of gravity by the combined forces of evaporation and the attraction of water to the sides of a series of vertical, microscopic tubes via cohesion and adhesion.

Related design principles:

- Cohesion-tension theory of intermolecular attraction of water moves water upward, against the force of gravity.
- When one water molecule is lost to evaporation or transpiration, another is pulled along by the processes of cohesion and adhesion.
- Source and sink move water.
- Suction moves water.



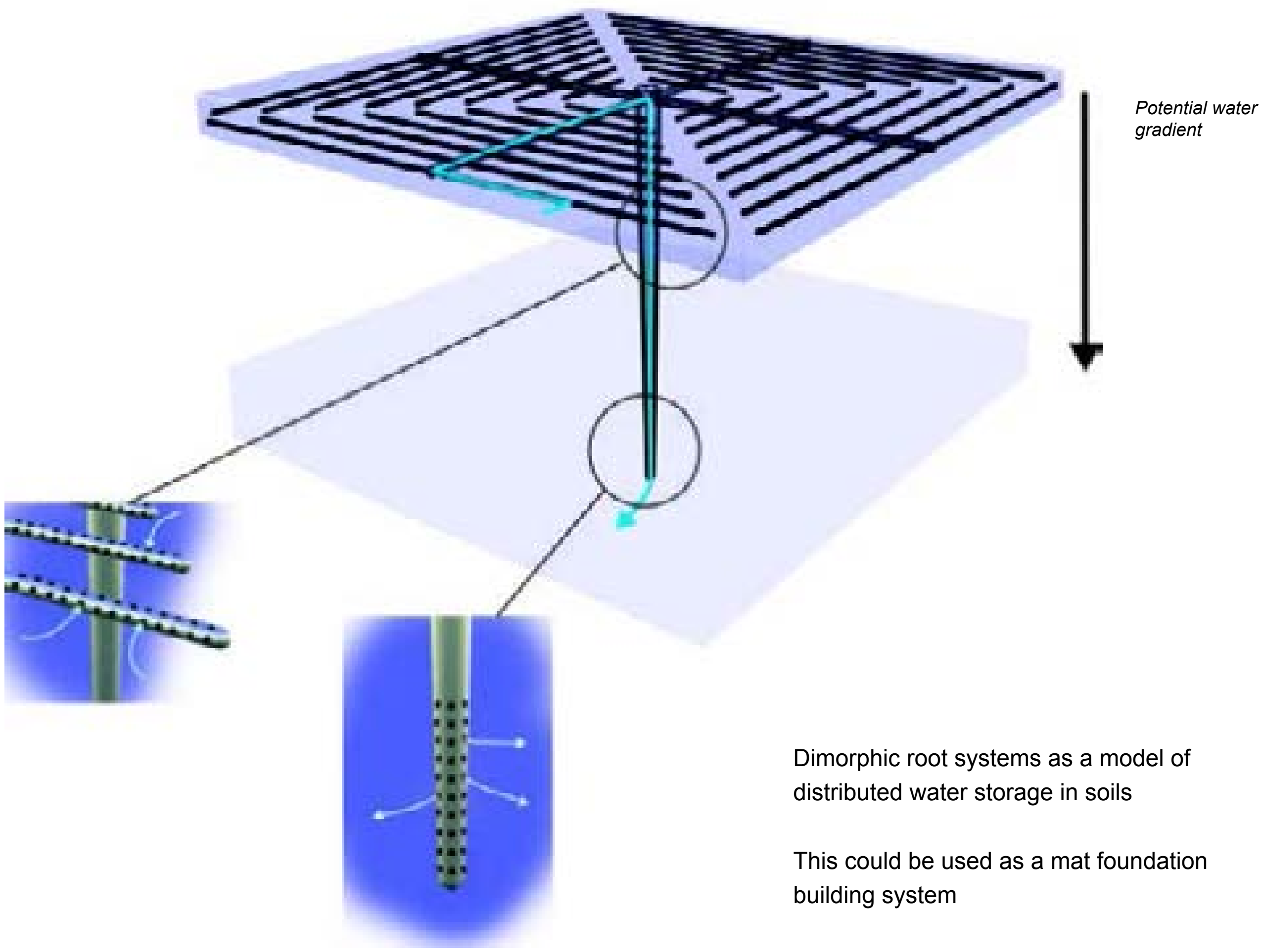
BaDT brainstorm

design ideas

Application Ideas

- Create a boundary layer on roof surfaces that can be opened and closed to create an additional layer of insulation in the winter or allow cooling air to move over the surface of the building in the summer. This boundary layer can be especially useful to moderate the temperature near functional/mechanical components on exposed surfaces.
- Utilize air movement on the site to increase evaporative cooling. This can involve taking advantage of prevailing wind patterns, or it could be contrived by arranging buildings or landscaping in a way that channels and directs small air movements across building surfaces.
- Design capillary faucets to pull water up through a building (cooling as it goes), then as the water flows down use that movement to generate energy (see “Energy Machine” at AskNature.org).
- Water from reservoir is drawn up through conduits using cohesion and adhesion forces into a garden that is evaporating.

HYDRAULIC REDISTRIBUTION



Dimorphic root systems as a model of distributed water storage in soils

This could be used as a mat foundation building system

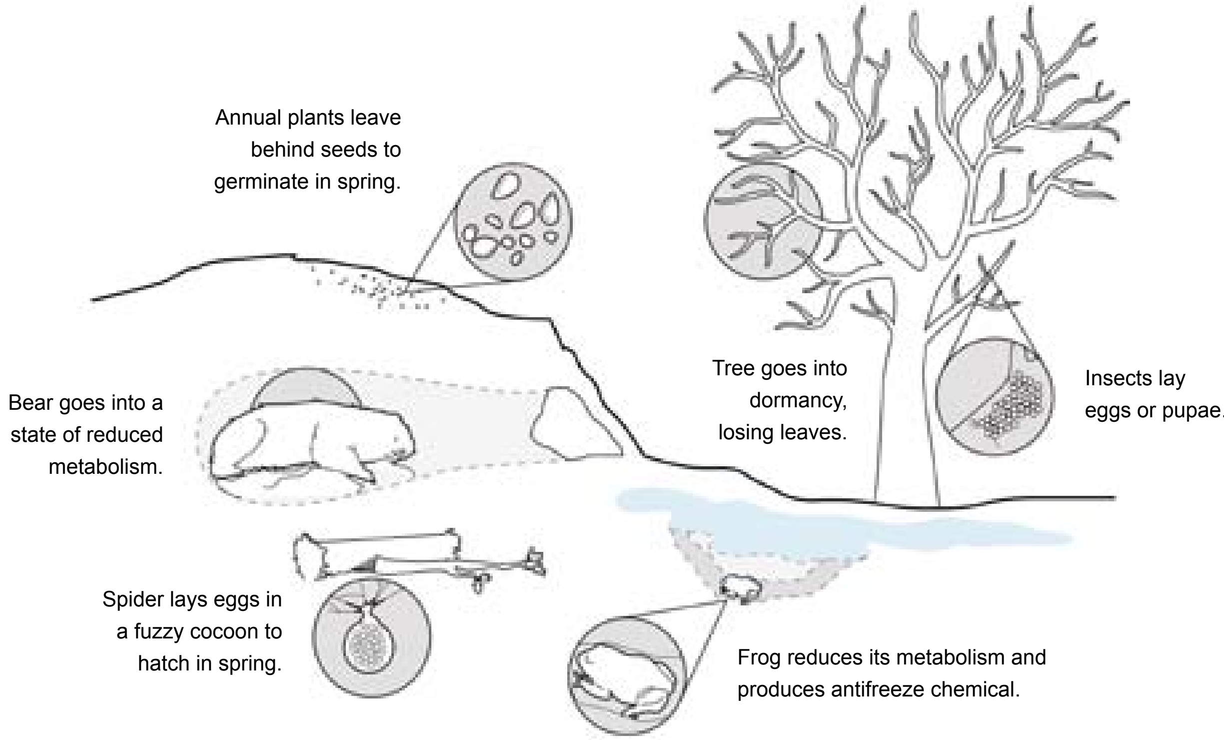
mechanism

Lateral roots absorb excess moisture from surface layer soil and the tap root sends the collected moisture downward to recharge groundwater. During the dry season, the reverse happens.

respond to seasonal change

plants and animals I

Organisms survive winter's challenges by reducing activity to minimize required activity input.



nature's design

energy-saving methods reduce energy expenditure

In winter, there is less energy input to the system due to less photosynthesis. Staying warm and searching for food during cold weather is costly. One strategy for coping with this challenge is to reduce the energy expended.

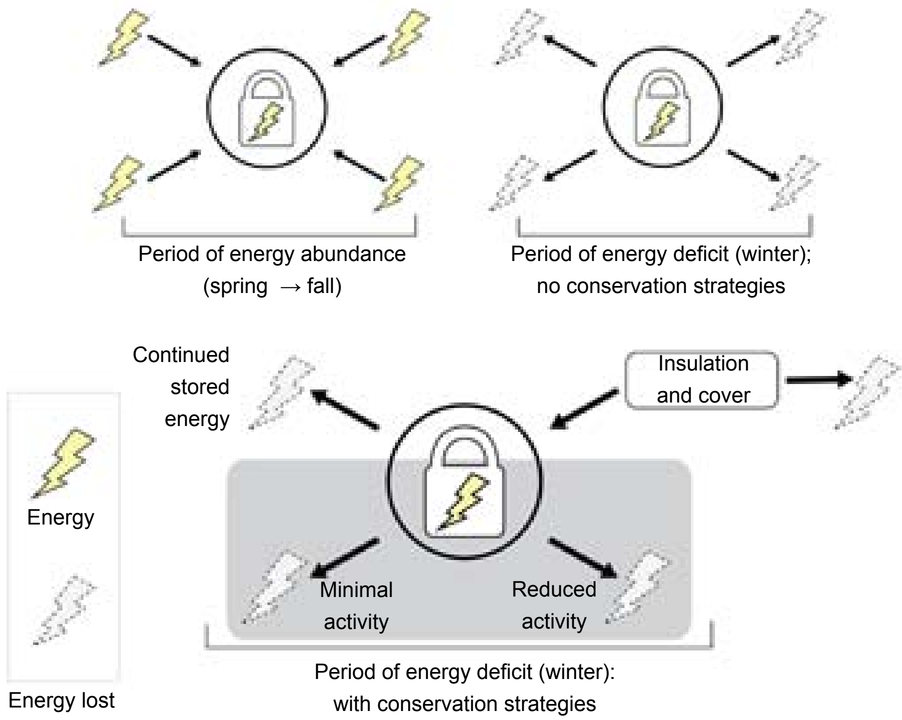
Some animals reduce their metabolism during extremely cold periods. For example, bats, European hedgehogs, and some ground squirrels drastically reduce their metabolism during the winter, expending stored fat slowly. Breathing and heart rate slows and body temperatures are reduced. Trees and shrubs lose their leaves and become dormant.

Frogs and insects use a combination of lowered metabolism and production of antifreeze chemicals to survive the winter. Antifreeze chemicals prevent formation of ice crystals, which can damage sensitive cell membranes.

An extreme form of reducing metabolism is dying while concurrently leaving offspring behind in a protected state. While this is not beneficial for the individual, it ensures the continuation of the population and species. Examples include insects that leave their young in the form of eggs or pupae, annual plants that leave behind seeds, and spiders that leave eggs in fuzzy casings.

Deep snow creates problems for deer, causing them to expend extra energy to move around and avoid predators. Deer spend winters in sheltered areas with lower snow depth.

- Winter is a time of reduced energy availability.
- Excessive energy expenditure is a challenge in winter.
- Seasonal adaptation of activity levels saves energy.
- Multiple strategies for coping with winter's challenges increase survival.



design principle

behavior adjustments reduce energy usage

Reducing the amount of energy used helps reduce energy costs. Where energy requirements change on a seasonal or daily basis, adjusting activity levels can reduce or even out usage. One option is to decrease the rate of energy usage throughout the system. Another is to completely stop the use of energy by some users on a daily or seasonal basis. When the costs of obtaining energy change on a daily or seasonal basis, finding ways to reduce usage during those peak periods can reduce costs.

Related design principles:

- Chemicals protect from damage due to cold.
- Combine strategies such as storing energy and reducing usage to increase effectiveness.
- Sacrifice unneeded energy usage to focus on those most needed to decrease costs.

INCORPORATE SOCIAL NETWORK
PROMOTE ENERGY EFFICIENCY
EXPLOIT COLD TEMPERATURES
COLD CONVECTION
WINTER ENERGY BUDGET
TARGET RATE
TARGET AMOUNT

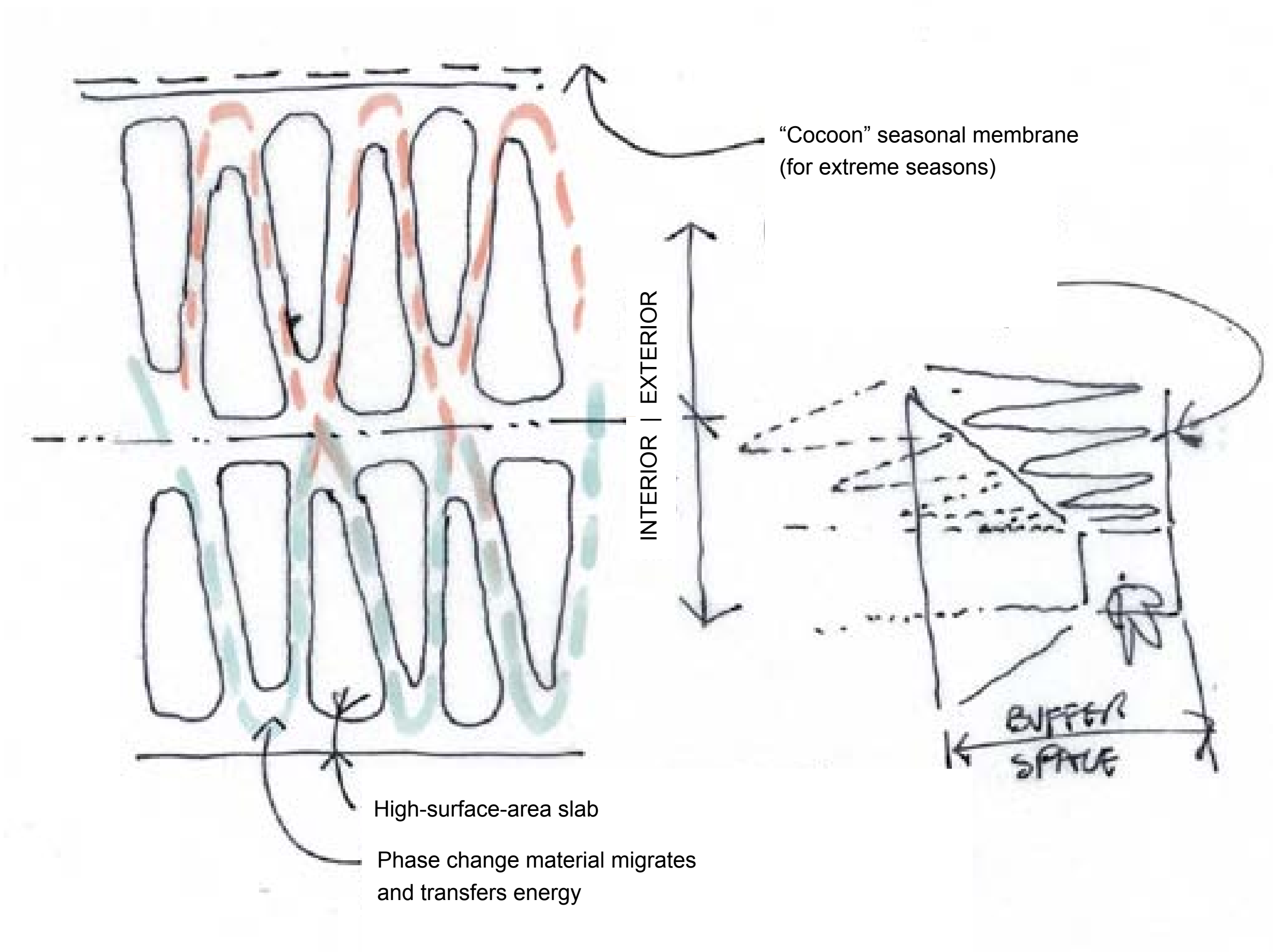
BaDT brainstorm

design ideas

Application Ideas

- Incorporate a social network-type system that promotes building energy efficiency through behavioral nudges that track individual usage and compare with other users.
- Rather than using energy to create refrigeration in the winter, exploit external cold temperatures to lower energy consumption. Use cold convection through metal rods to produce refrigeration.
- Develop a summer energy budget and a winter energy budget for a building. This reflects seasonal variations in available energy (based on daylight and sun strength) and gives users a target amount and rate to function within.
- Implement a system that anticipates future power usage by collecting usage data from “buzz” social networks, weather, and news reports.

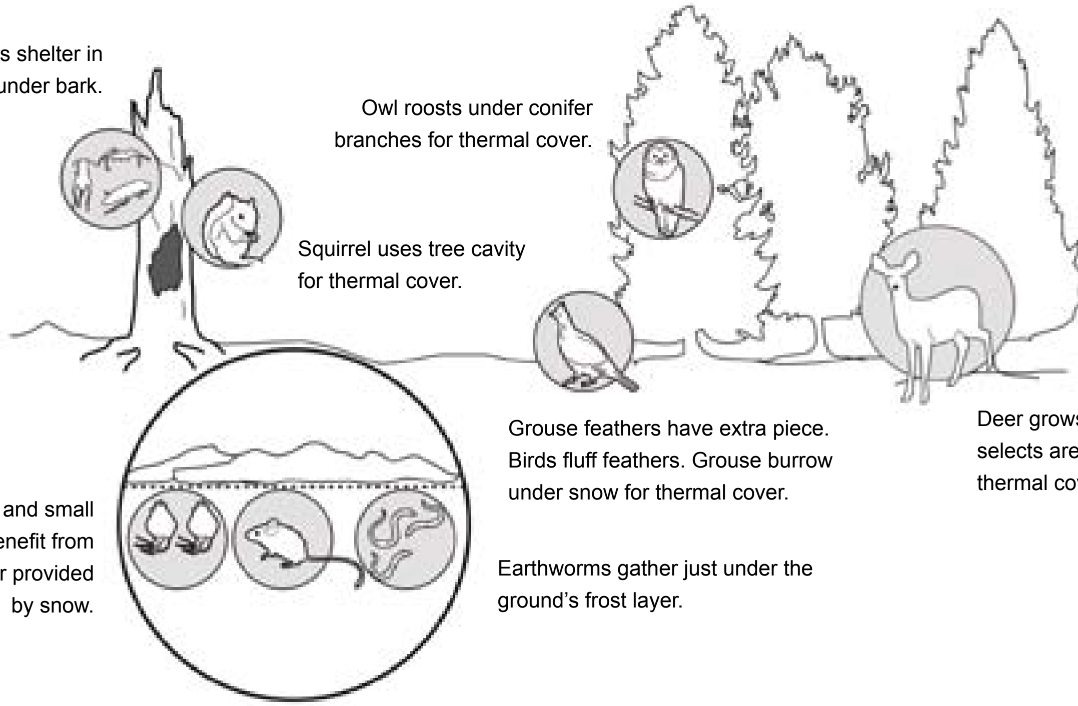
ACTIVE THERMAL BRIDGING SYSTEM



respond to seasonal change

animals

Organisms survive winter’s challenges by adjusting microhabitats to reduce energy loss.



nature's design

thermal cover protects from cold

Winter is a period of combined challenges: cold temperatures, deep snow, and less food. Organisms employ a variety of methods to reduce the amount of energy lost to heat.

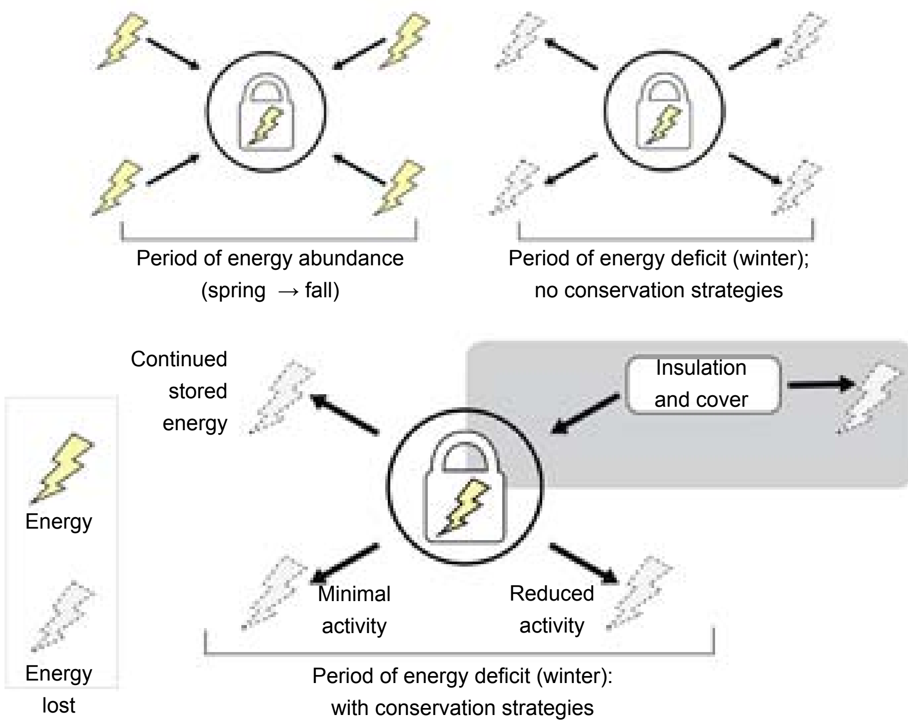
Some seek thermal cover above ground. Deer move to deeryards, areas of less snow with overhead cover to reduce heat loss. Hedgehogs build thick nests of leaves. Owls and grouse spend cold winter periods among branches of dense conifers to reduce heat loss from above. Squirrels and nuthatches use tree cavities as thermal cover. Some insects spend the winter tucked under pieces of bark, in logs, or under leaf litter.

Other organisms seek thermal cover underground. Earthworms move deep into the ground into the frost-free layer. Snakes gather in underground dens in rocky areas. Bears winter in underground dens.

Deep snow also offers thermal cover. Small mammals burrow under snow for thermal cover, access to food, and protection from predators. Perennial plants, grouse, and voles rely on snow cover for thermal insulation.

Another way to reduce heat loss is to increase the insulation value of fur or feathers. Mammals grow thicker underfur in the winter, covered by waterproof guard hairs. Birds adjust to cold temperatures by fluffing their feathers, capturing warm air within the structures.

- Major challenges are food availability, cold temperatures, and snow cover.
- Waterfowl and upland game birds have special feathers that add insulation.
- Combining heat by communal roosting decreases heat loss.
- Timing of activities for warmer periods prevents excess heat loss.



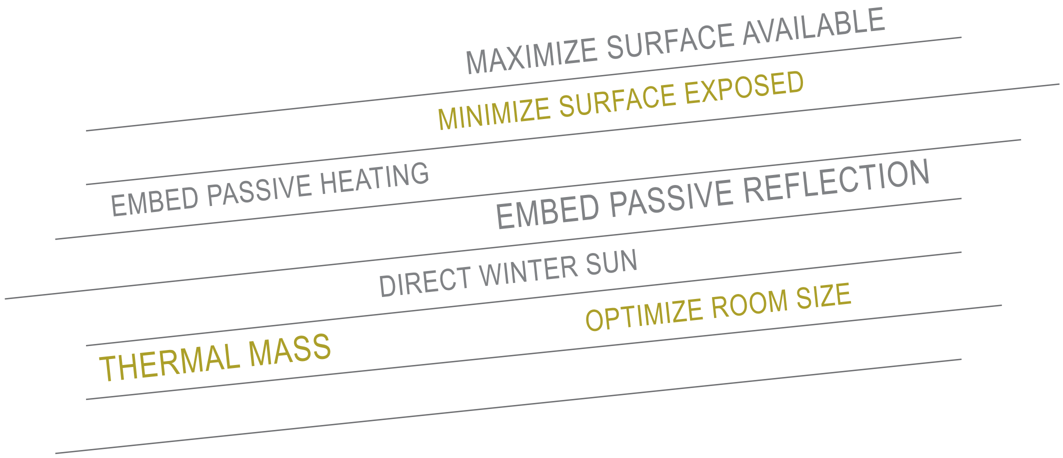
design principle

insulation changes adjust to seasonal changes in temperature

Thermal loss is a major source of energy usage in the winter. Because heat rises, protecting heat loss from overhead is a key technique for saving energy. Insulating structures trap warm air within a closed space, capturing lost body heat or other released heat and using it to maintain a comfortable temperature. Insulating structures can adjust to temperature and humidity by opening to create more air space and insulation, and then closing to decrease insulation. This provides the ability to adjust to daily and seasonal temperature changes. Wind moving across a surface increases thermal heat loss, so protecting the insulating structures from air movement increases heat retention. The structure of the insulation itself is also key to heat retention and breathability.

Related design principles:

- Capture group heat to increase value of thermal cover.
- Capture waste heat to reuse as an energy source.
- Time activities to avoid excessive waste of energy through heat loss.



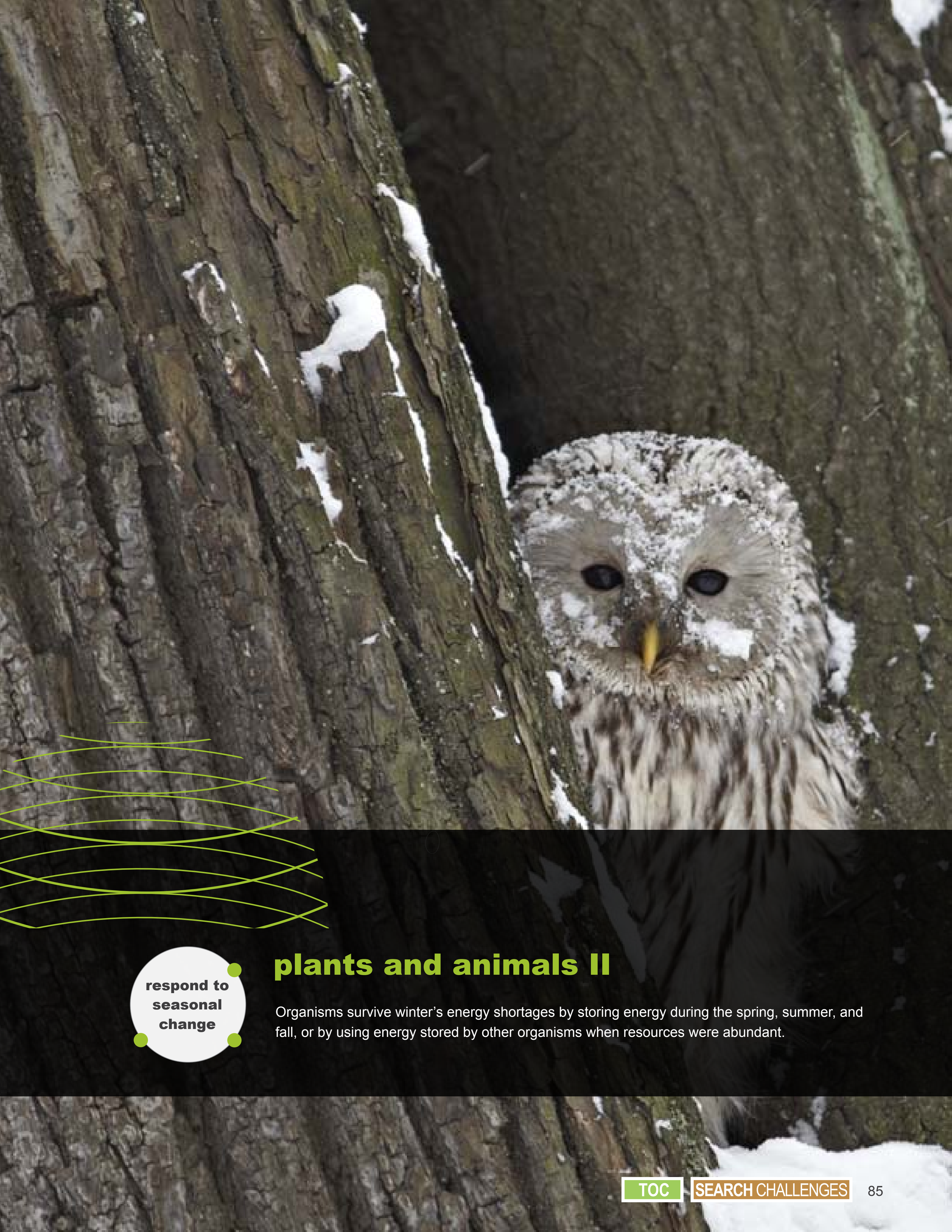
BaDT brainstorm

design ideas

Application Ideas

- Maximize the surface available for energy production but minimize the surface area exposed to desiccating wind. The right balance will result in optimization.
- Embed passive or reflective heating elements in the building facade to prevent snow accumulation or direct winter sunlight to create warm air.
- Look for sources of waste heat that could be recovered and reused. This could be from friction, vibration, or radiation via thermal mass or from hot water from boilers or plumbing.
- Optimize room sizes to capture and potentially store heat from occupants. This will be most effective in areas where people consistently gather.

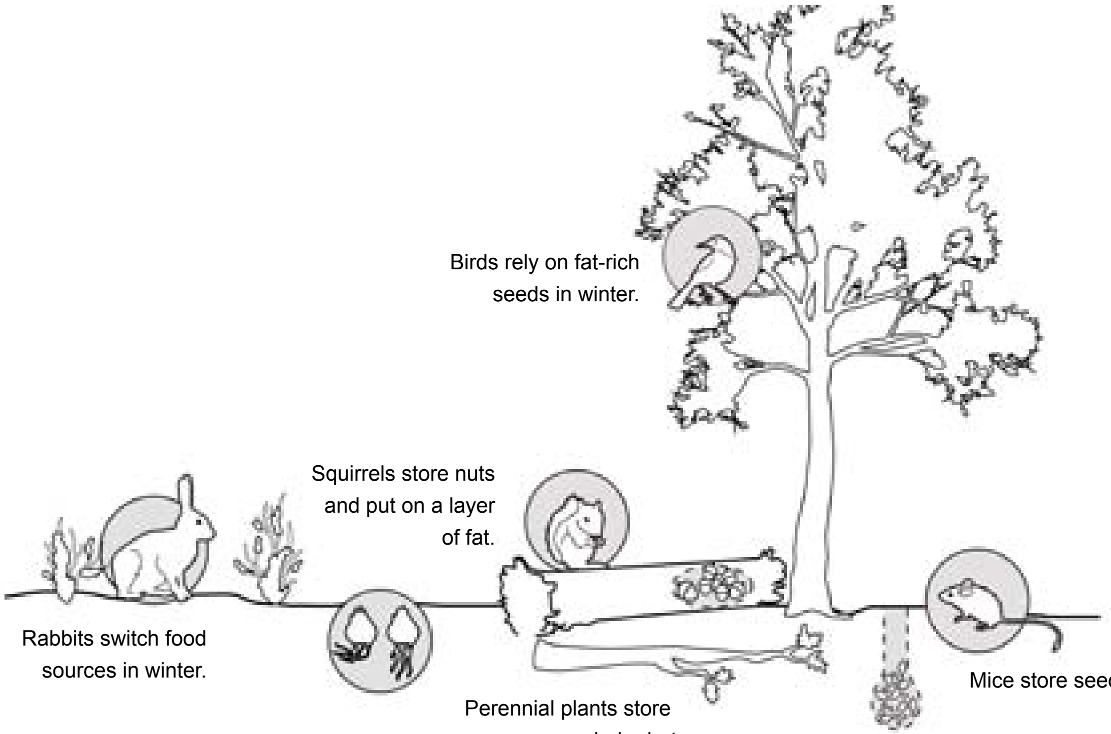
future design ideas



respond to seasonal change

plants and animals II

Organisms survive winter's energy shortages by storing energy during the spring, summer, and fall, or by using energy stored by other organisms when resources were abundant.



nature's design

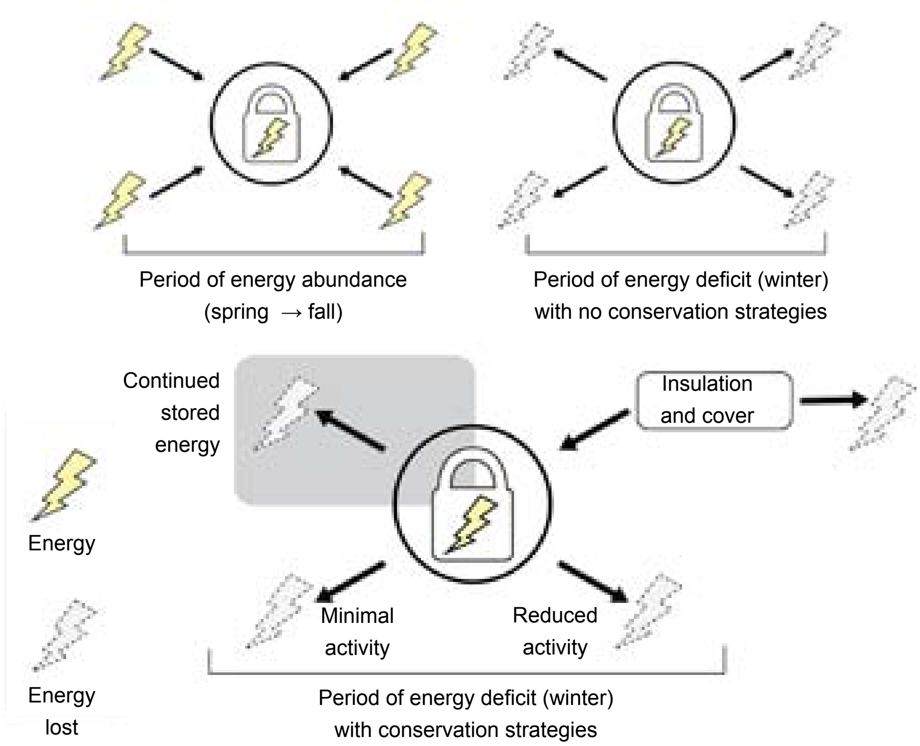
energy storage and alternative sources

The period between spring and fall is a time of great energy input in the temperate broadleaf forest biome, ultimately due to photosynthesis. This is when food is plentiful, young are produced, and energy from the sun is stored as carbohydrates and fats.

Winter is a time of lower energy inputs. Some animals store food items for consumption in the winter. These include squirrels, mice, beaver, and some species of birds. Some, such as bears, deer, and birds, store energy as fat. Perennial plants, which grow every year rather than from seed, store energy for the next year's growth in the form of carbohydrates in underground bulbs or tubers.

A different way of dealing with decreased food resources is to change the types of food consumed. Deer and rabbits, for example, forage for three seasons on soft foods like leaves and flowers. In the winter, they change to chewing the woody branches and bark that are all that remains of deciduous trees and shrubs after they lose their leaves. Sometimes, switching food types requires a change in intestinal microflora, the bacteria that help digest complex molecules like cellulose. Birds that stay around for the winter switch from a nutrient-rich diet of insects and fruit to an energy-rich diet of seeds.

- A major challenge in winter is food availability.
- Coping mechanisms include leaving the area entirely (migration), staying active and exposed, and reducing metabolism.
- Organisms still require energy for each of those coping mechanisms.
- Combinations of coping mechanisms are employed so that no one organism uses just one mechanism.
- Seeds and nuts "want" to be stored by squirrels and other animals because this is how they get dispersed and planted.



design principle

energy storage and variety of sources adapt to seasonal changes

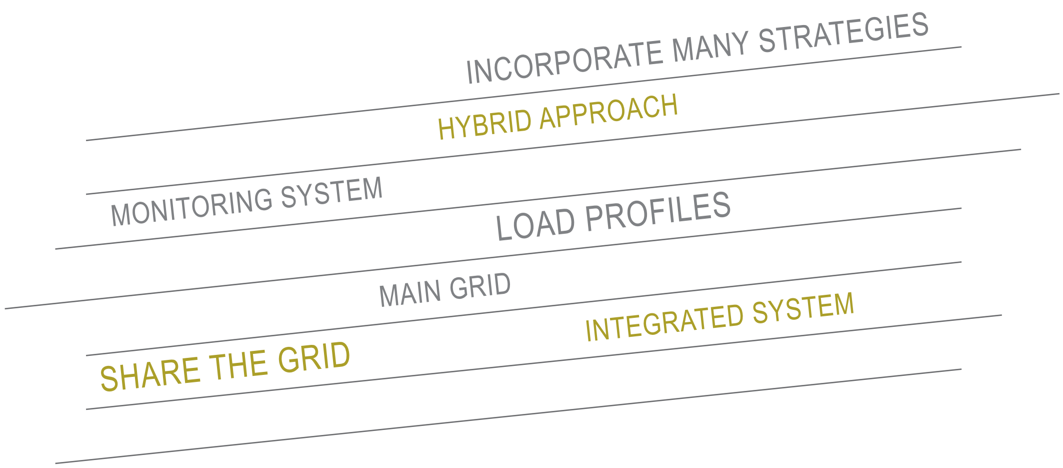
During periods of abundance, energy or resources can be stored for times of scarcity. This is easier to plan for in a predictable environment than one that is unpredictable. Scarcity can be the result of reduced energy input into a system, such as lower amounts of sunlight or lower food production due to cold weather. Both of these are predictable. Scarcity can also be caused by access to energy or other resources being cut off due to disruption of delivery, such as transportation difficulties due to storms or damage to power sources. Another unpredictable cause of scarcity would be the length of time or the severity of the period of low energy input, such as an extremely cold or long winter.

Having a variety of mechanisms to cope with energy or resource abundance and scarcity increases the chances of surviving them. Relying on just one mechanism may work in predictable cycles, but could be disastrous when faced with unexpected shortages or disruptions.

Ensuring that energy or resources are sufficient to last throughout the season by planning for both predictable and unpredictable scarcity maintains functions in a system throughout the year.

Related design principles:

- Take advantage of existing distribution networks to move other resources.
- Have ability to change types of energy sources to increase resilience to disruption.



BaDT brainstorm

design ideas

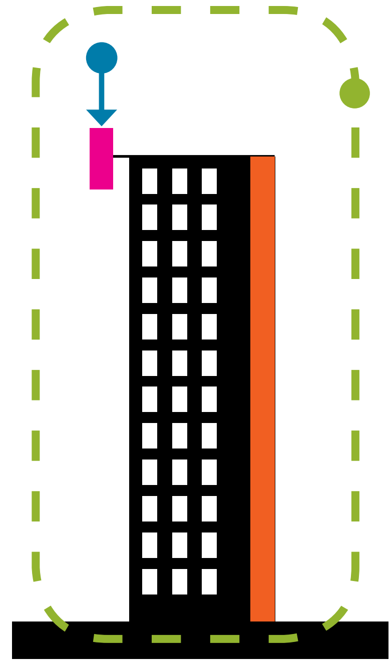
Application Ideas

- Rather than focusing on just one “alternative energy” source, incorporate as many strategies as possible in combinations that reduce the need for energy and supply renewable energy when it is needed. A hybrid approach of passive solar, geo-thermal, geo-cooling, solar, wind, micro-hydro, and heat recovery mechanisms creates modularity and redundancy. In a robust integrated system like this, it could be appropriate to use small amounts of coal or gas energy in some applications.
- Incorporate a monitoring system that suggests best energy usage behaviors based on load profiles of building users/occupants and supply condition of the grid.
- Feed extra energy gained from individual buildings into the main grid or feed extra energy to a neighboring building.

GRAVITATIONAL POTENTIAL ENERGY (GPE) STORAGE SYSTEM

Ecosystems make use of various means of energy storage for later use during times of scarcity or emergency. If humans are to mimic this macrobiotic idea, they must create efficient means of storing energy across multiple scales and media for use not only to mitigate against seasonal scarcities but also to round out the diurnal peaks and valleys of energy as driven by supply and demand.

This design idea focuses on storing energy at the building scale, thereby decentralizing energy stores, by exploiting simple Newtonian physics. Within the built envrionment, we already make use of a variety of energy storage systems, be they **chemical** as in the case of batteries or biofuels, **thermodynamic** as in the case of thermal reservoirs, motlen salt systems, or nighttime ice production, **electrical** as in the case of capacitors, and **mechanical** as in the case of compressed fluids, springs, or flywheels. However, we fall short when it comes to making use of gravity's potential to do work on an object, which is the basis of a potential energy system. We do use this type of system to generate electricy and even to store it at larger scales as in the case of hydroelectric dams, but we are missing out on the opportunity to use it en mass at the scale of individual buildings.



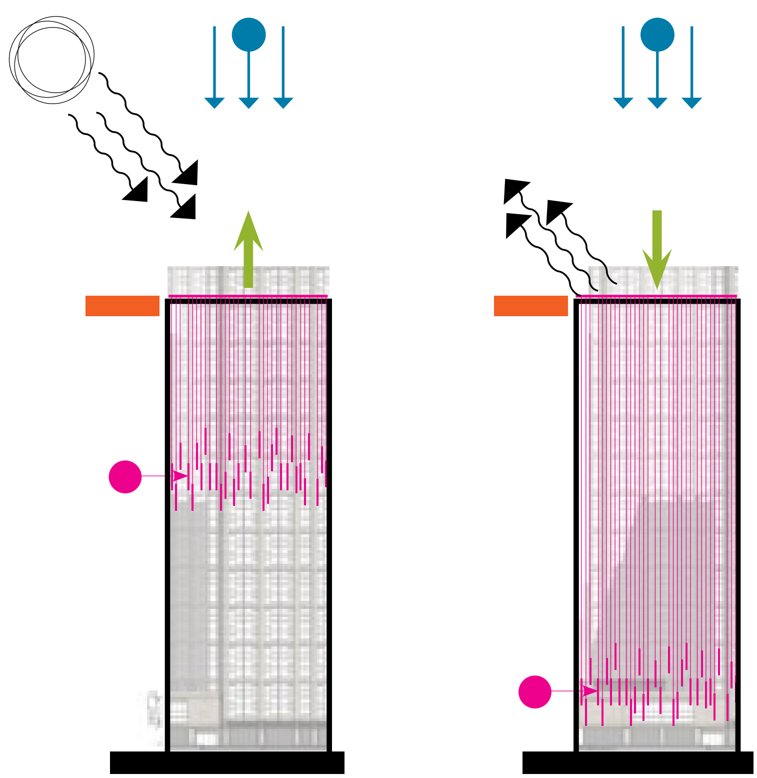
A MASS (m) SUSPENDED AT A HEIGHT (h) HAS A STORED ENERGY POTENTIAL (PE) DUE TO THE ABILITY OF GRAVITY (g) TO DO WORK ON THE MASS.

such that,

$$PE = m \times g \times h$$

* PE measured in Joules, J

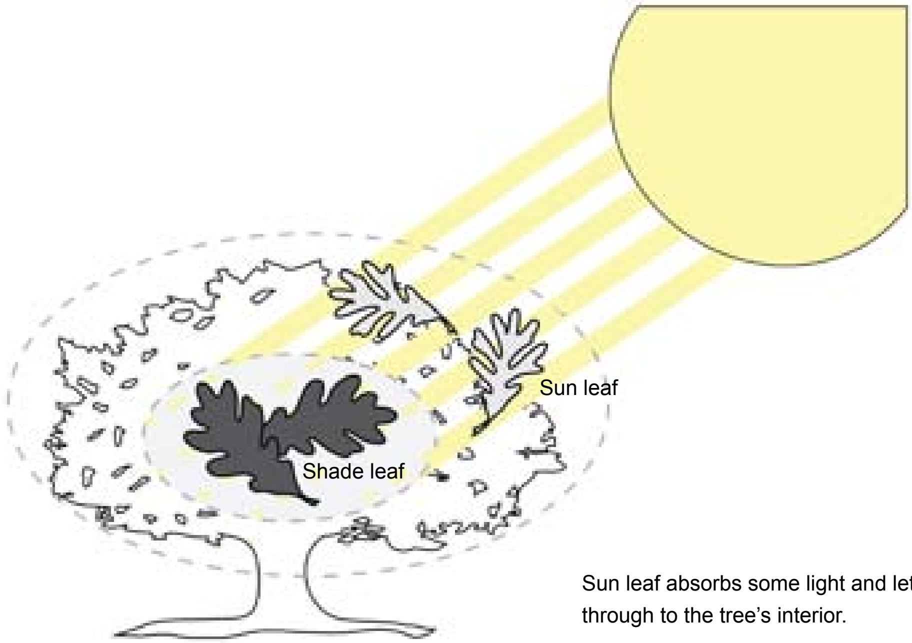
an example of a 200 kWh GPE storage system (700 MJ of potential energy per cycle)



optimize light

trees

Trees have varying leaf shapes and sizes depending on the sunlight exposure levels, allowing even shaded leaves to contribute to photosynthesis for the tree.



Sun leaf absorbs some light and lets light through to the tree's interior.

nature's design

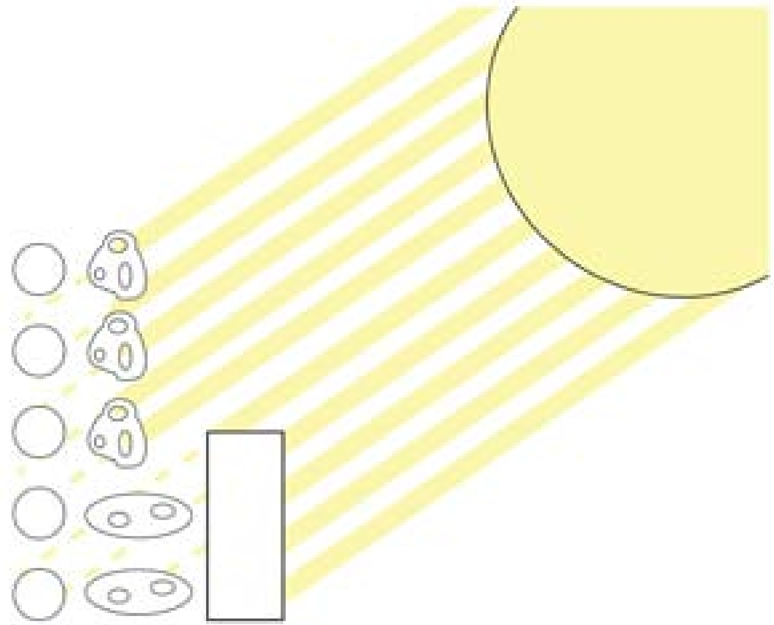
sun and shade leaves optimize energy source

Trees have adapted over millions of years to optimize light collection. Leaves display a range of sizes and shapes in response to the light levels present within a tree. This is called intracanopy plasticity.

Trees in the temperate deciduous forest have sun and shade leaves. In oaks, sun leaves grow near the top and on the more sun-exposed sides of trees, while shade leaves grow within the crown and on the shady sides of the trees. Sun leaves are smaller, thicker, have deeper sinuses between narrower lobes, and have more stomata per unit area. Shade leaves are the opposite in each respect. The shade leaf spreads its mass more thinly over a wider area to capture more diffuse irradiance and is rich in photosynthetic cells, which scatter irradiance internally. The shape of sun leaves allows light to enter the canopy and reach the shade leaves.

Irradiance-driven plasticity may arise from both internal cues and environmental responses. The differences among leaves begin at the time the leaf is in the bud, and the leaves are even more sensitive to irradiance quantity and quality as they emerge and expand. This plasticity means that as conditions change, the tree can respond.

- In one study of the temperate forest, at canopy tops, the area of individual leaves was on average 0.5-0.6 times that at basal-interior, and leaf mass per area was 1.5-2.2 times higher.
- The shape of the tree crown varies depending on the amount of light and the angle at which it strikes.
- Overstory trees tend to be tall and have wide crowns to capture sunlight. Understory species tend to have round crowns to capture more diffuse light.



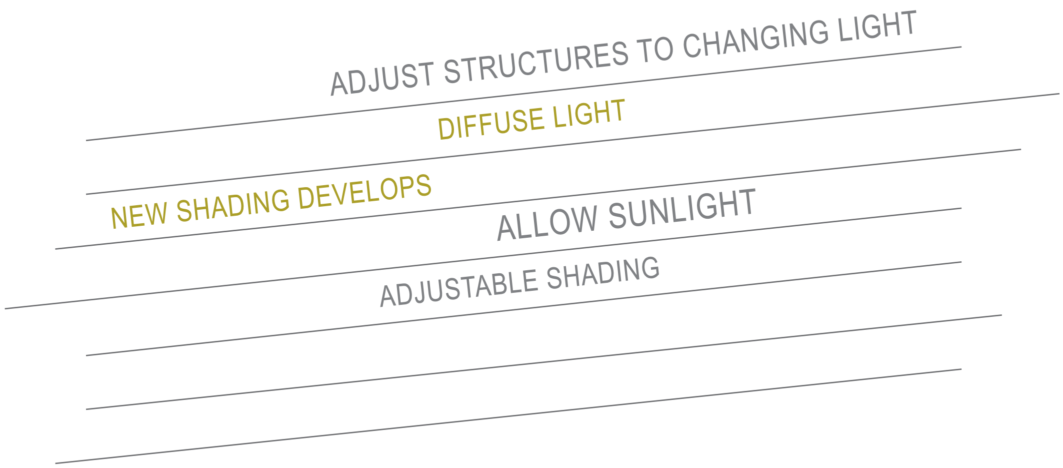
design principle

flexibility optimizes light availability

Related design principles:

- Shape influences ability to absorb light.
- Internal structures scatter light.

Availability of light and shade changes over the course of the season, from season to season, and over the course of years as the local conditions change. Maintaining flexibility over space and time allows for adjustments to changing light availability and intensity. Wide, thin structures absorb more light than narrow, thin structures. Narrow, thin structures allow more light through to areas below. Structures in the shade take advantage of more diffuse light than those in direct sunlight.

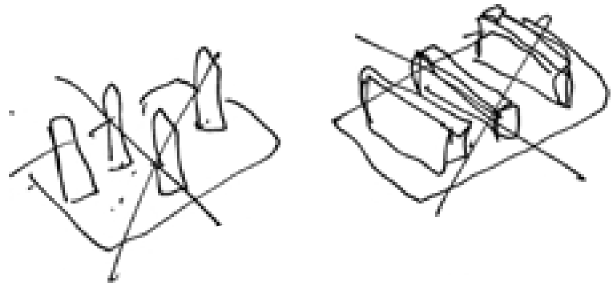


BaDT brainstorm

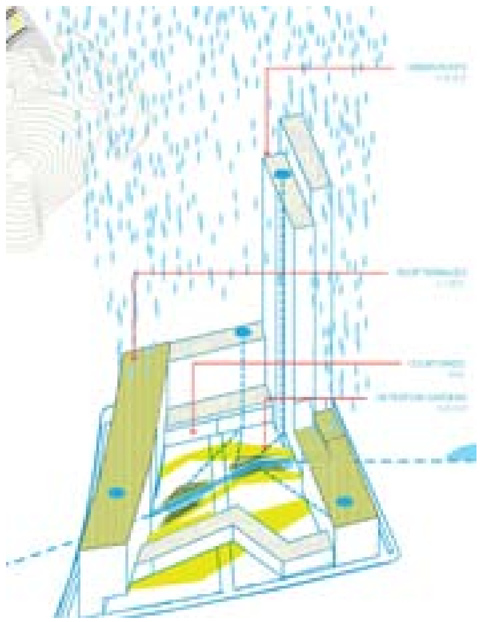
design ideas

Application Ideas

- Maintain flexibility by adjusting structures and groups of structures to changing light availability and light intensity.
- Use optimized solar cell systems in areas receiving diffuse sunlight.
- Allow for adjustment of solar systems, windows, and window shades to respond to new shading from growing trees and new buildings.
- Allow sunlight to enter buildings by designing adjustable shading structures.



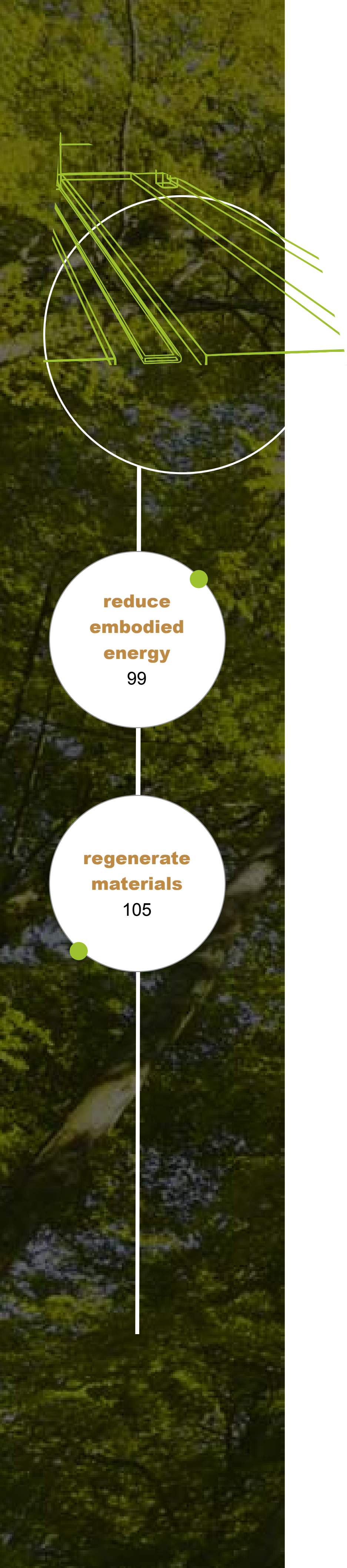
Monocultures



Meixi Lake challenge: Achieve two hours of daylight to each dwelling unit on the "Great Cold Day." Provide a diversity of form, space and arrangement while meeting overall floor area ratio (FAR) of 4.6.

Diversity of Form

Diversity works with low flow multi-path channels to create secondary pedestrian and water movement systems at the block level. All roads lead to the canal.



MATERIALS

The temperate broadleaf forest biome is one of the most human-populated biomes on Earth. Hundreds of thousands of years of exploitation have robbed this biome of its former richness.

One pattern in this biome is the use of locally available materials. Organisms don't spend valuable energy searching far from home. Paper wasps, for example, use locally available wood and chew it, mixing in their own saliva to form a paste that they use to build a nest. This material is water-repellent and easy to manipulate into a multichambered structure that fits their needs. Abandoned nests eventually degrade into material broken down by other local organisms, forming a closed-loop system.

The harbinger of the end of winter is the brief flowering of herbs that take advantage of a leafless tree canopy, finding a niche in the seasonal cycle to capture as much sunlight power as possible. Braving the cold and sending up shoots in melting snow, these millions of plants capture nutrients that would otherwise wash away before the trees can awaken. Again, we see the principle of "lots of littles" at work.

Expending the least amount of energy to procure materials, forming closed-loop systems, and capturing materials at an opportune time are three noteworthy patterns. The ability to interact with one's neighbors cooperatively along with the configuration of the complexity of life is what governs the stability and structure of an ecological network. Networks in nature tend to be modular and nested. This may be why they are both complex and stable.

The metabolic cost to produce materials can be better understood by comparing the relationships among consumers and resources across networks in an ecosystem. This is why material design emphasizes a focus on systems thinking.

- Use local materials
- Capture and release nutrients
- Nest made of local materials
- Nutrient capture and release fills a niche in nutrient cycling

MATERIALS

LIFE'S PRINCIPLES

REFERENCE THE DEFINITIONS

EVOLVE TO SURVIVE
Time capture of resources to local climate and human productivity.

INTEGRATE DEVELOPMENT WITH GROWTH
Combine modular and nested components
Use modular designs to add structures as funding, materials, and needs grow.

BE RESOURCE-EFFICIENT (MATERIALS AND ENERGY)
Recycle all materials
Maintain a closed loop by capturing and intercepting intermittent resources to survive for long periods of few resources.

BE LOCALLY ATTUNED AND RESPONSIVE
Leverage cyclic processes
Time projects to take advantage of the most opportune conditions and availability of needed resources.

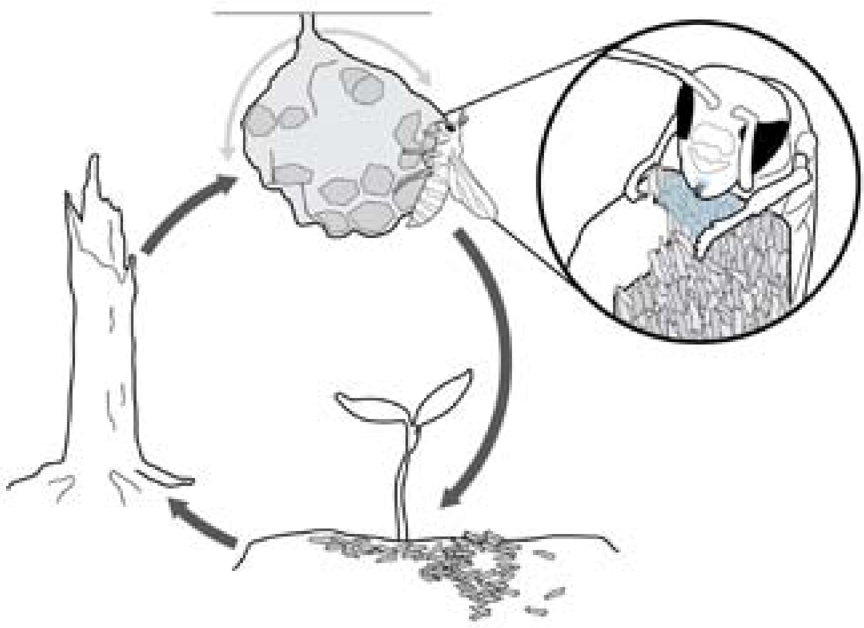
ADAPT TO CHANGING CONDITIONS
Customize the amount of materials and chemicals needed depending on local conditions.

USE LIFE-FRIENDLY CHEMISTRY
Use life-friendly chemistry to capture and store resources.

reduce embodied energy

paper wasps

Paper wasps make nests by combining their protein-based oral fluid with wood fibers.



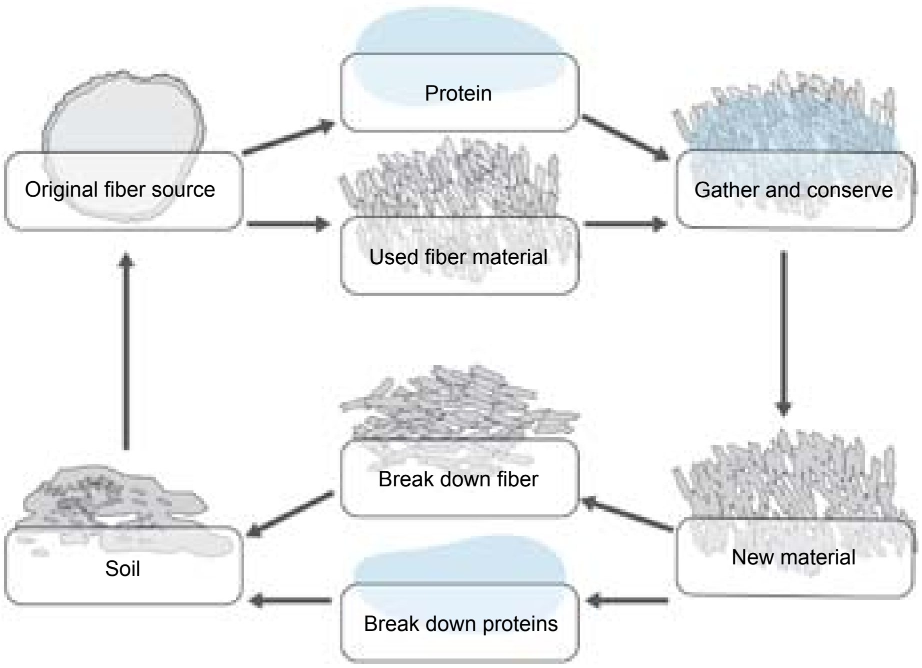
nature’s design

locally available materials optimize resources

Paper wasps scrape wood fibers from dead wood, then chew the material and add saliva to make an adhesive to construct a dome-shaped comb of up to several hundred cells suspended from a central stalk. This composite material dries into a strong, water-insoluble, water-repellent structure. The wasps maintain the water-repellent properties of the nest by continuing to add saliva, but only where it is most needed, such as on top of the comb. Once helpers are born, they start adding cells to the nest. This modular approach to construction matches size and effort to the available work force and resources.

Paper wasp nests make efficient use of limited resources by forming each cell wall to be shared with another. All materials are gathered locally. All materials eventually decompose back into their constituent parts, becoming part of the food web with fungal breakdown of the tougher molecules — cellulose and lignin — to return nature’s building blocks to the soil.

- Paper wasps use wood fiber and protein-rich saliva to create nests.
- Saliva acts as an adhesive, strengthening agent, and water-repellent coating.
- Domed shape sheds water.
- Nests are built in a modular fashion as resources become available.
- Shared walls reduce material usage.
- Materials come from waste and decompose back into the soil.



design principle

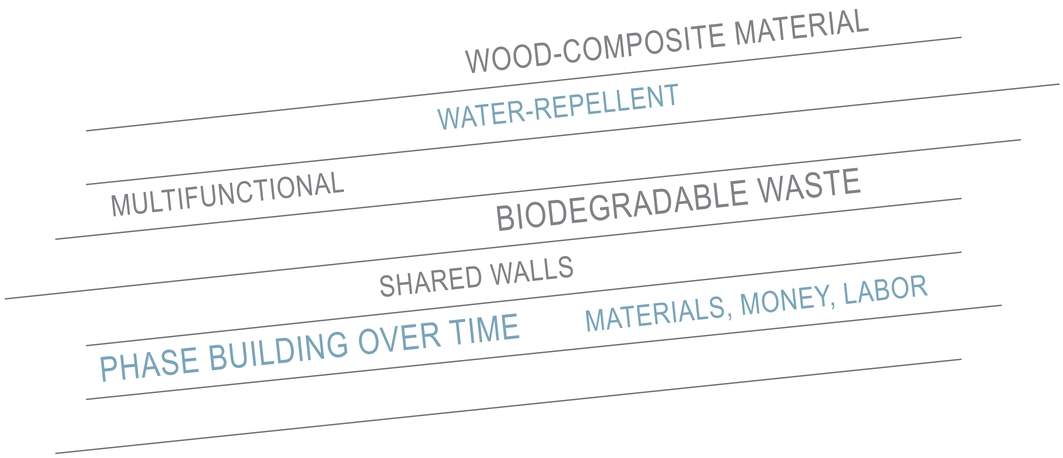
mixing local materials reduces embodied energy

Value-added materials are produced by combining locally obtained fibers with a protein-rich fluid to make an adhesive that is used to construct a structure.

Protein-rich fluid can serve three functions when combined with wood fibers — adhesiveness, strength, and water-repellency. In this example, both fibers and natural chemicals are obtained locally, balancing the cost of effort expended with the benefits provided by the materials. If selected carefully, the chemicals used should decompose into their harmless constituents and be easily taken up by organisms or reused for another purpose.

Related design principles:

- Domed shape sheds water.
- Targeted use and shared walls reduces materials.
- Modular construction allows growth.
- Matching size and effort with available resources minimizes waste.
- Minimizing travel distance to materials conserves energy.
- Collective intelligence coordinates activities.
- The structure causes work behavior to occur.

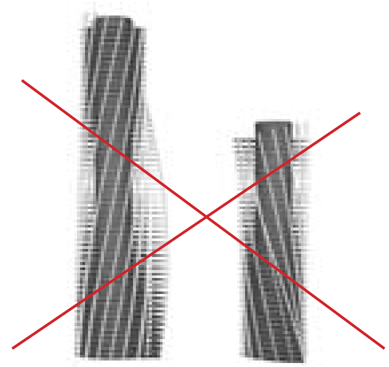


BaDT brainstorm

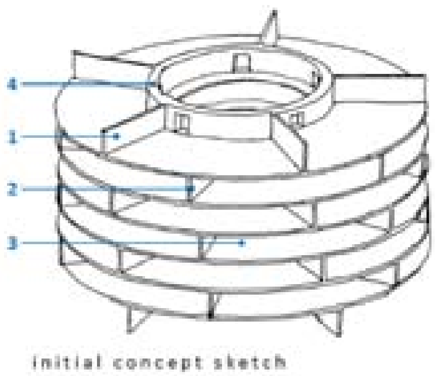
design ideas

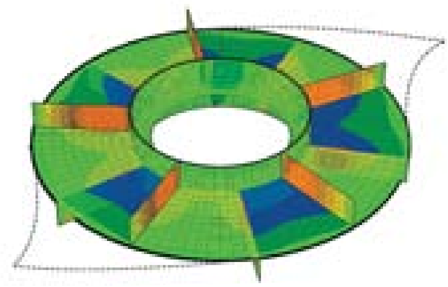
Application Ideas

- Develop a wood-composite material that incorporates water-repellent multi-functional proteins (wasp saliva is particularly high in the amino acid proline). Source the wood locally, perhaps combining it with other local biodegradable “waste” materials. Reclaim and reprocess these materials locally at the end of their life cycle.
- Optimize material use by capitalizing on shared walls.
- As a project phasing strategy, design a multi-level building to be built a few floors at a time, as materials, money, and labor are available. This may be a particularly useful approach during times of economic uncertainty or recession, labor strikes, or material shortages.



Columns on a twisting tower are inefficient.





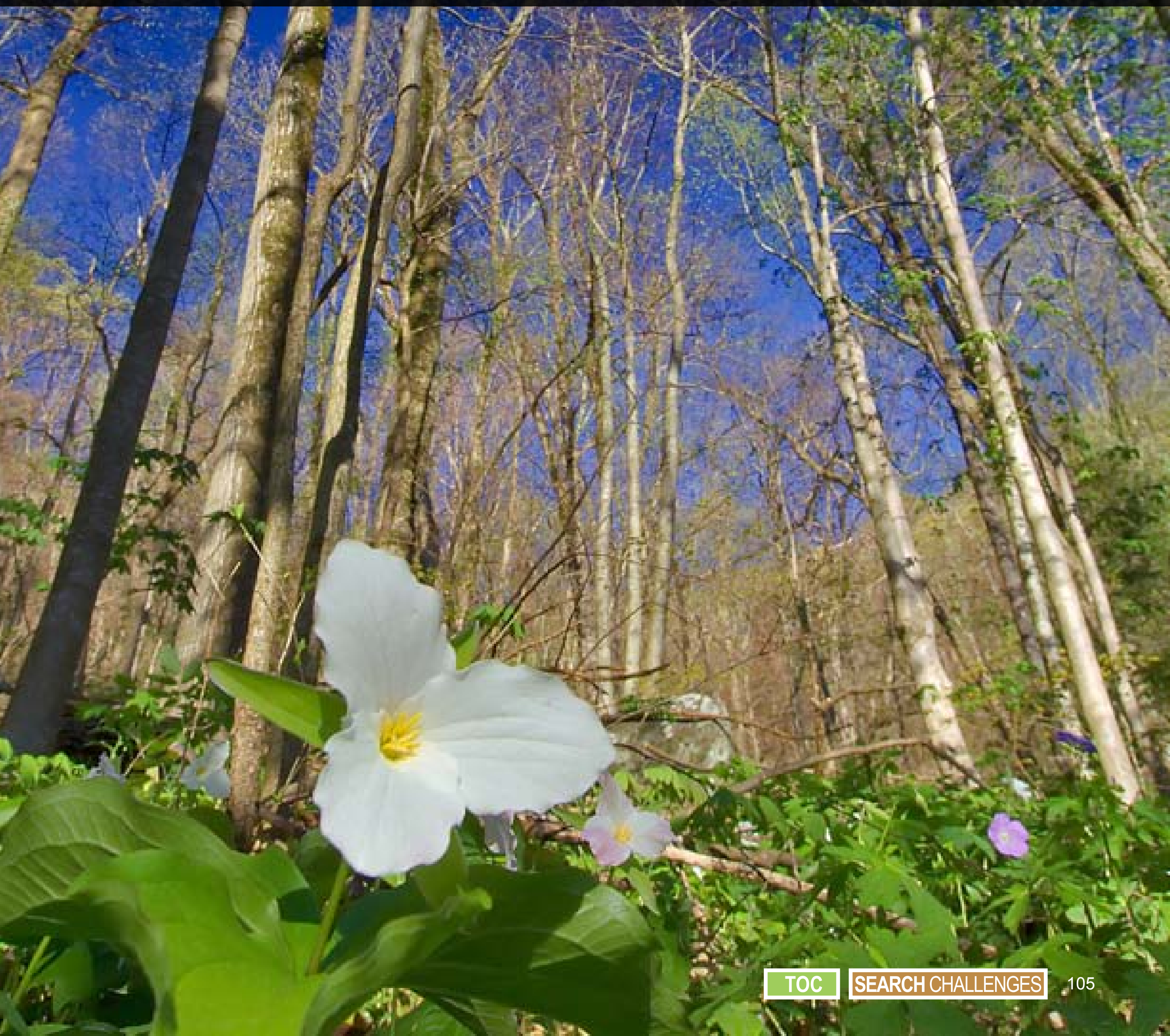
Eliminate all columns: all loads transfer back to the core.

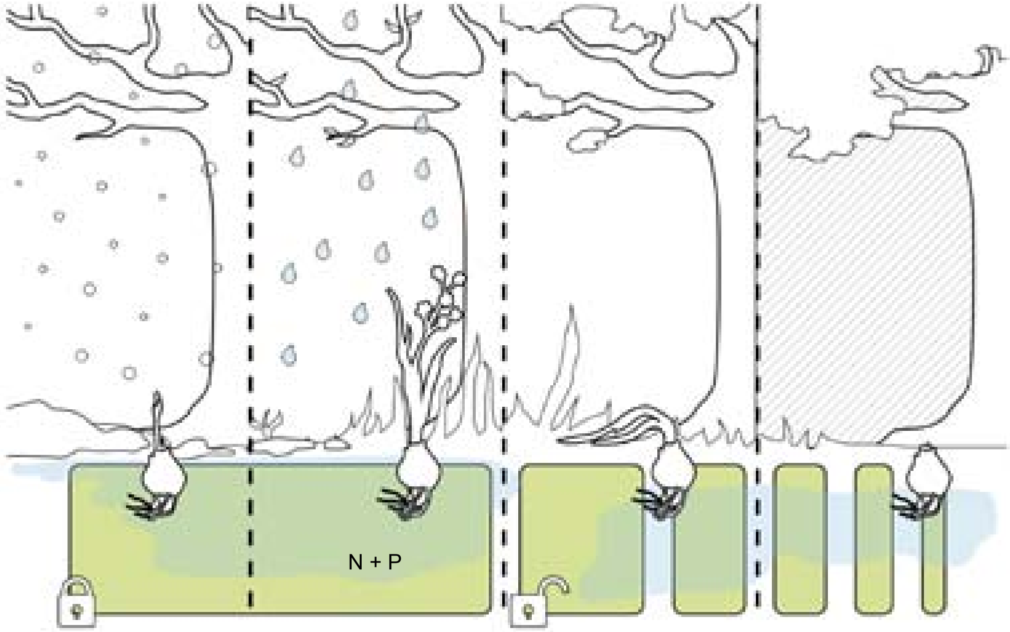
With 20 percent less material, form triumphs over material.

regenerate materials

ephemeral herbs

Ephemeral spring-flowering herbs capture nutrients early in the season, providing a temporary “dam” that slowly releases nutrients back into the soil, making them available in the future for the forest community.





Bulbs (herbs) trap and store nitrogen (N) and phosphorus (P), die back, and then release nutrients slowly back to the soil.

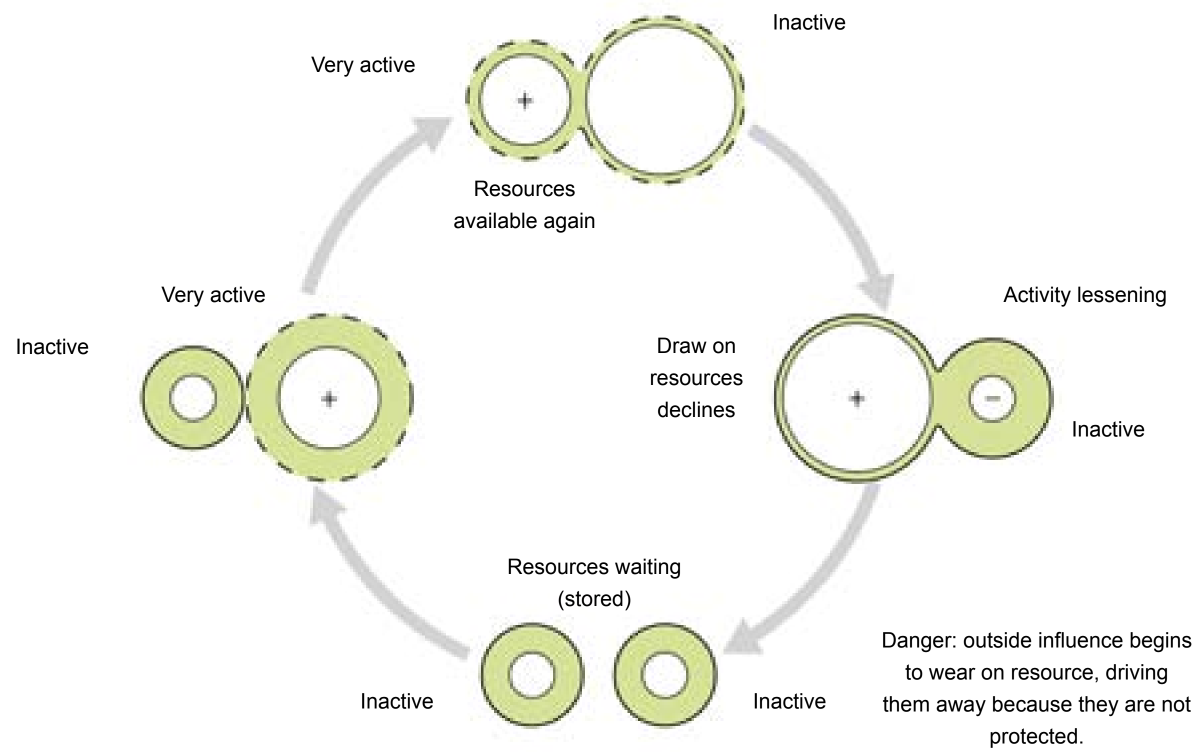
nature's design

temporary dam cycles nutrients

Hundreds of thousands of ephemeral herbs in the understory of the forest canopy are the first to flower in the early spring, capturing available sunlight and nutrients that would otherwise wash away with snowmelt and rain. These early-flowering herbs complete their reproductive cycle in a matter of weeks. As the leaf canopy emerges and sunlight is reduced, these herbs go to seed, die back, and become inactive until the following spring. The nutrients these herbs capture in their above-ground material degrade and are re-released into the soil when trees and other plants need access to them.

The principle of "lots of littles" adds up to perform a large service to the forest community.

- Lower forest layer of spring flowers takes advantage of the high sunlight conditions for brief period.
- Spring flowers absorb nutrients and use them to produce leaves, flowers, and seeds.
- Spring flowers are acclimated to low light availability.
- Spring flower lifespan occurs under high illumination conditions early in the season to capture nutrients.
- Maximizing carbon gain and storage during high to low light transitions is achieved by producing new leaves physiologically suited for spring conditions.



design principle

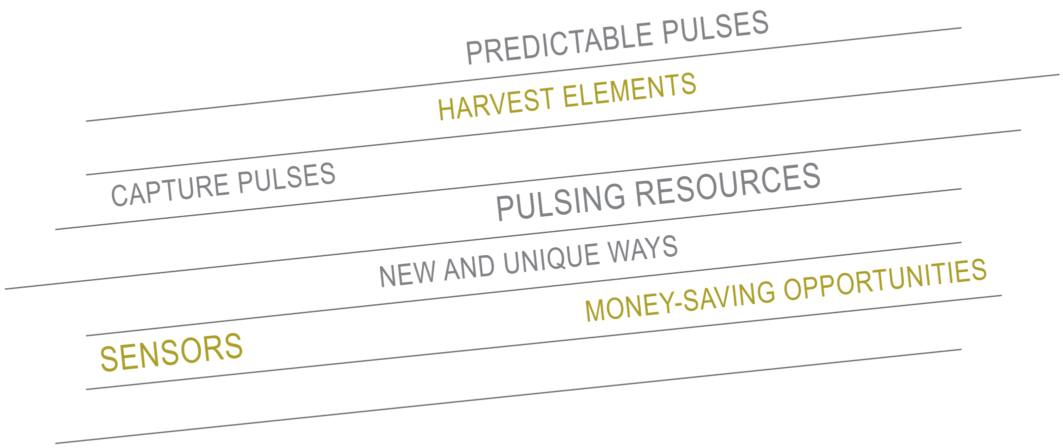
materials in danger of being lost are held within the system, then released

Certain elements become very active once conditions are conducive and before conditions deteriorate. These elements are temporary, low cost, and briefly collect a resource that is ephemeral in nature and at risk of vanishing. The elements take up unprotected resources and use them for growth and replication. Receding at the end of the growth period, the elements release the captured resources slowly, allowing these resources to become available to other elements as they are ready to use them.

Local systems are attuned and adapted to resource flows, capturing resources at opportune times, using a variety of methods, and some short-term damming of resources.

Related design principles:

- Elements respond to local resource availability.
- Systems are linked to capitalize on temporal opportunities.
- Systems are attuned to respond to pulse and cycling of resources.
- Systems integrate short-lived elements.
- Systems synchronize production to resource availability.
- Elements intercept resources at opportune times to prevent resource waste.
- Systems capture resources and store for later use to maximize and reduce resource waste.



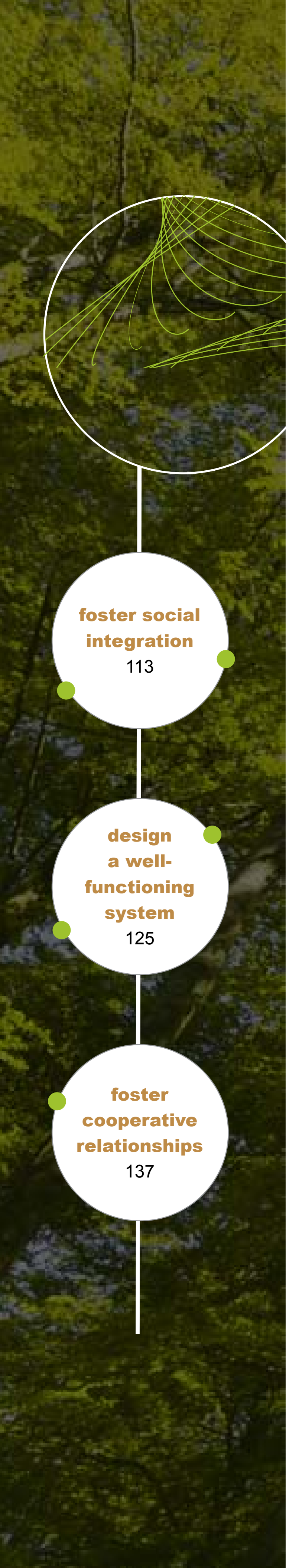
BaDT brainstorm

design ideas

Application Ideas

- Evaluate which resources, energies, or flows (water, energy, occupants, attitudes/moods, traffic patterns) occur in predictable pulses. Do you want to harvest, channel, redirect, or block any of these elements? Develop infrastructure or programmatic elements that can capture these pulses in ways that create long-term benefits for the system.
- Which of these pulsing resources, energies, or flows represent a lost opportunity to capture valuable reserves for later use? Capturing and storing these flows helps slow the movement of resources through a system, creating more potential for them to be used in new and unique ways.
- Install sensors in buildings that transmit information about inefficiencies, problems, and risks. This information can be used to cut off problems before they get bad and also highlight money-saving opportunities.

future design ideas



SOCIAL

Working together, communicating, sharing resources — these are not uniquely human needs. All living organisms must figure out how to engage with each other in ways that create short- and long-term benefits so they can survive and thrive.

Our language and "civilization" tend to separate humans from living systems in nature. Yet human society is a living system in nature. Many of the emergent properties of society and social interaction have risen out of seemingly random interactions. Structure is an important factor that determines what kind of interactions, and thus what kind of behaviors, emerge. Structure, which can include physical structures, rules, or goals, determines behavior by creating context. This is the same for all living, dynamic systems, whether human or non-human. The way we design these structures determines the behaviors that result.

Though human social systems and ways of communicating are different from those of other species, we can examine high-level patterns expressed by other species. These patterns can show us unique nuances that help us design the structures that foster social interaction among diverse groups, encourage cooperation, and promote efficient and fair use of shared resources. Taken together, this can create a well-functioning, resilient system.

- Integrate unlike elements
- Share resources
- Create redundant functional groups

SOCIAL

LIFE'S PRINCIPLES

REFERENCE THE DEFINITIONS

EVOLVE TO SURVIVE

Integrate the unexpected

Maintain flexibility in use of common resources such as meeting rooms, so that if one user alters its use patterns, there is a seamless transition to a new user.

INTEGRATE DEVELOPMENT WITH GROWTH

Self-organize

Create conditions that support self-organization of social systems, rather than try to force them from a top-down approach.

BE RESOURCE-EFFICIENT (MATERIALS AND ENERGY)

Fit form to function

Design transition zones between types of use or types of structures to enhance interactions and sharing of information.

BE LOCALLY ATTUNED AND RESPONSIVE

Cultivate cooperative relationships

Seek opportunities to create, encourage, and support mutual relationships to increase interactions among individuals and groups in a community.

ADAPT TO CHANGING CONDITIONS

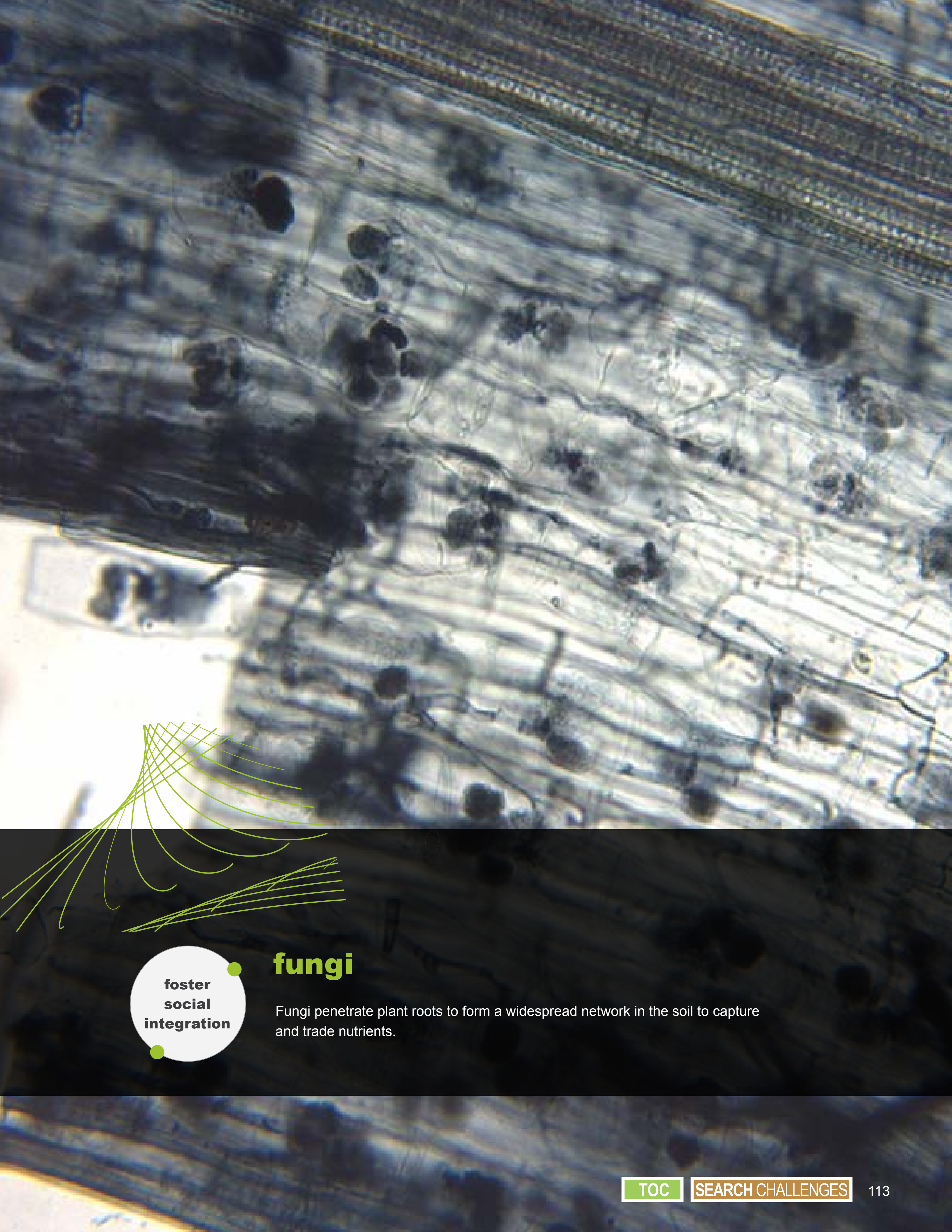
Embody resilience through variation, redundancy, and decentralization

Plan for disturbance or disruption of social systems by maintaining adequate representation of people and organizations that serve similar functions.

USE LIFE-FRIENDLY CHEMISTRY

Build selectively with a small subset of elements

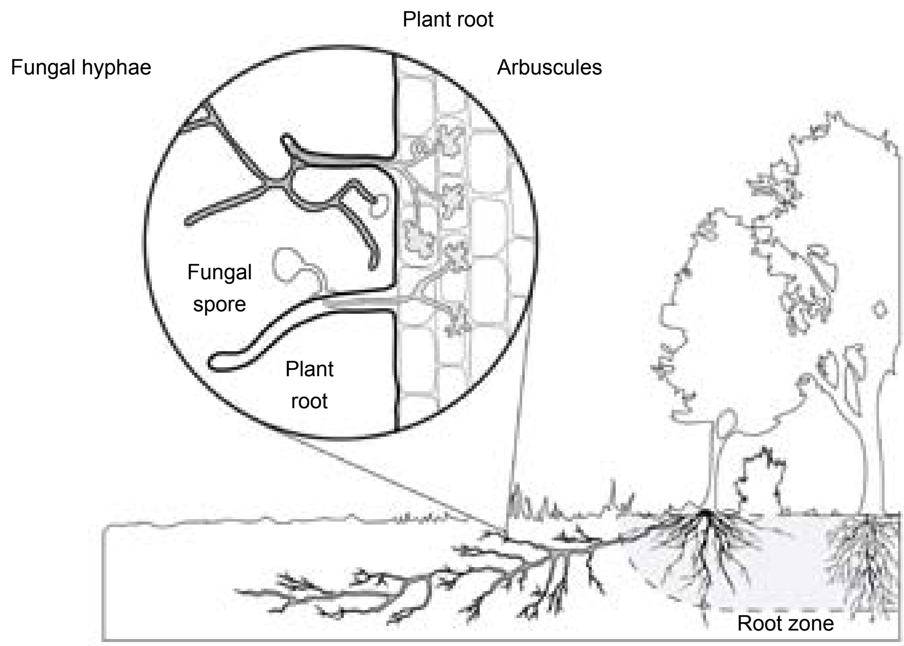
Maintain a healthy community by selecting construction and maintenance materials that minimize use of harmful chemicals.



foster social integration

fungi

Fungi penetrate plant roots to form a widespread network in the soil to capture and trade nutrients.



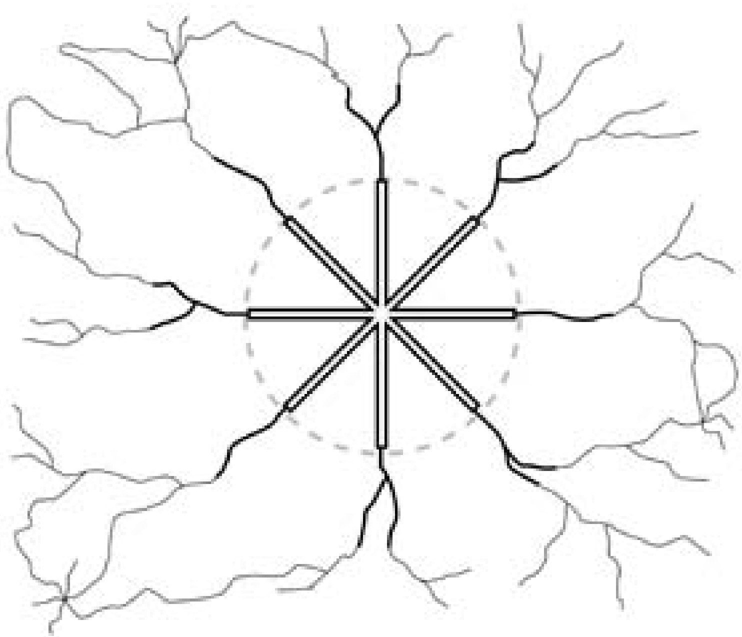
nature’s design

fungi penetrate plant roots to form a widespread network in the soil to capture and trade nutrients

Arbuscular mycorrhizae (AM) are fungi that penetrate cells in plant roots using **arbuscules**, a unique structure to trade phosphates and nitrogen for plant sugars. About 90 percent of plants use this symbiotic and mutualistic trading system in which the fungus must “pay in advance,” making it difficult for the fungus to cheat the plant. The AM fungi form widespread networks of mycelia and hyphae in the soil to travel beyond the plant roots into areas rich in resources and to transport these nutrients back to the plant. AM fungi penetrate plant root hairs and use them to travel into the roots and form a glove-like arbuscule inside of plant cells. No real cell penetration occurs because the fungal arbuscules remain in a compartment of the plant cell, surrounded by an interfacial matrix and a peri-arbuscular membrane that protrudes into the plant cell. The fungus absorbs sugars from the host root and the plant saves the expense of growing roots to gain access to faraway resources by forming this mutual arrangement.

The presence of microscopic structures connected to a widespread network of multi-branched hyphae at the local scale of one plant root is multiplied by the tens of millions of connections in all plants in an area to deliver nutrients and some protection in return for sugar.

- AM fungi colonize roots.
- Roots respond by allowing fungi penetration and proliferate more roots and root hairs.
- AM fungi transfers phosphates and nitrogen across arbuscule membranes.
- Plants allow sugars to transfer to the fungi in response.



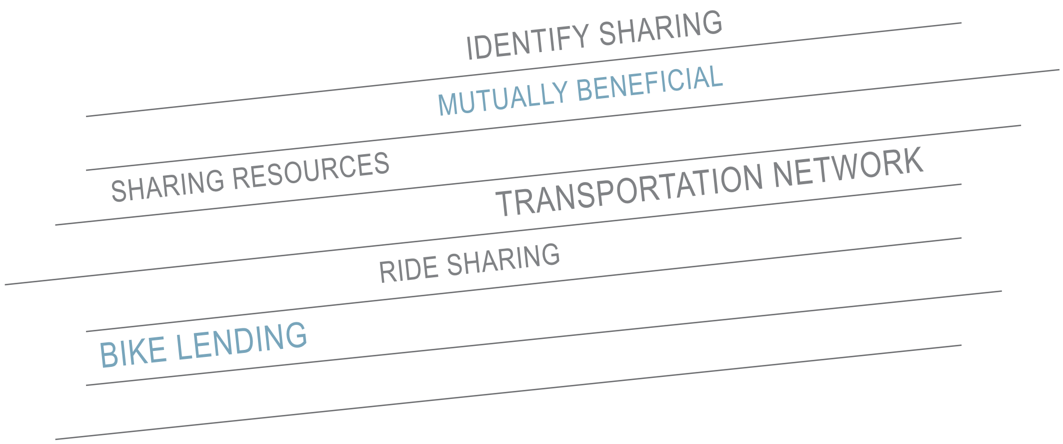
design principle

cooperation among partners increases resources

It is not cost effective to capture distant resources by building more infrastructure. Instead, such resources can be gained through a mutual association with partners. Trading extra resources in exchange for hard-to-access resources also helps reduce the cost. Several elements delivering small amounts of resources add up when multiplied into a large, complex network. Many duplicate connections allow for a stable economy.

Related design principles:

- Easy exchange across borders facilitates sharing of resources.
- Use of empty space within communities provides room to share resources.
- Colonization with permission enhances mutually beneficial relationships.
- Resources beyond a border encourage working together.
- Reciprocal recognition and regulation facilitates sharing of resources.
- Sharing of resources helps others to tolerate stress conditions.
- Interdependence benefits all partners.
- Networking supports community health.



BaDT brainstorm

design ideas

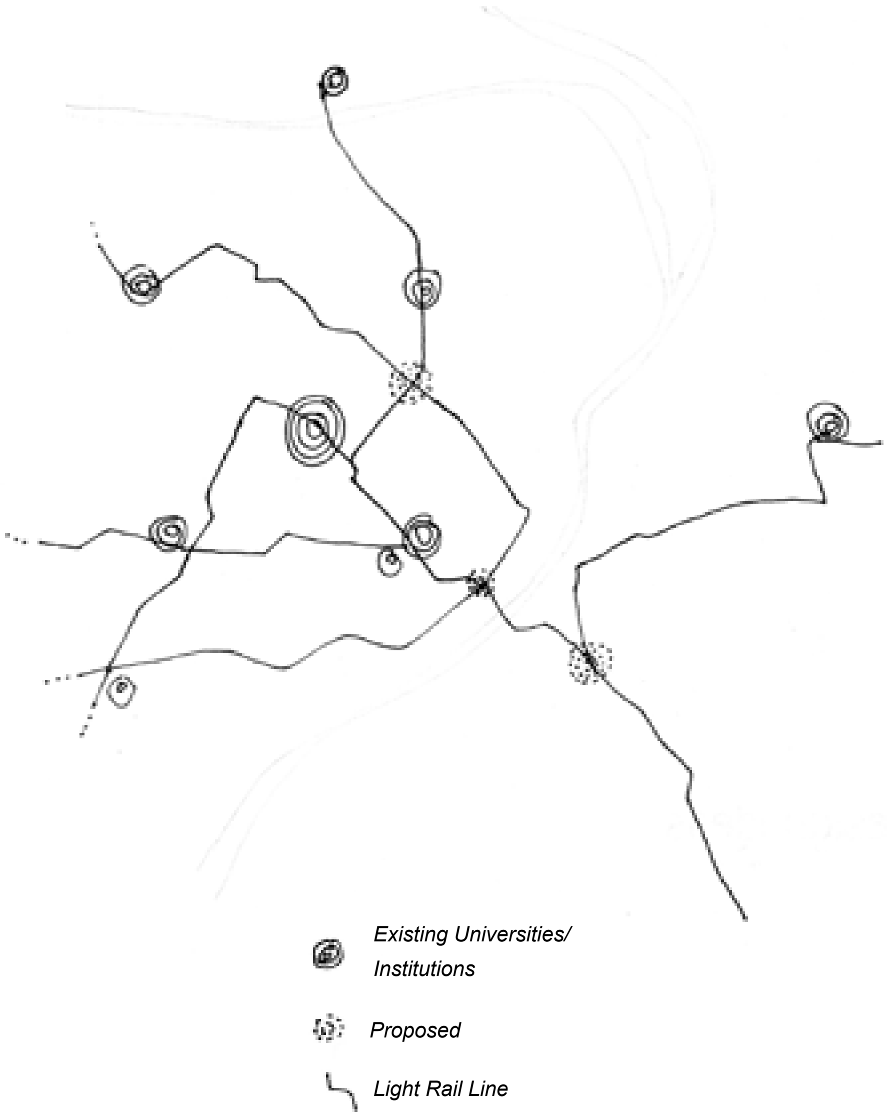
Application Ideas

- Identify other buildings or nearby industrial operations that could share mutually beneficial resources (the resources shared will likely be different).
- Encourage a transportation network among building users/occupants for ride sharing, car lending, or bike lending.

UNIVERSITY NETWORK

Mutual association with partner universities conserves resources

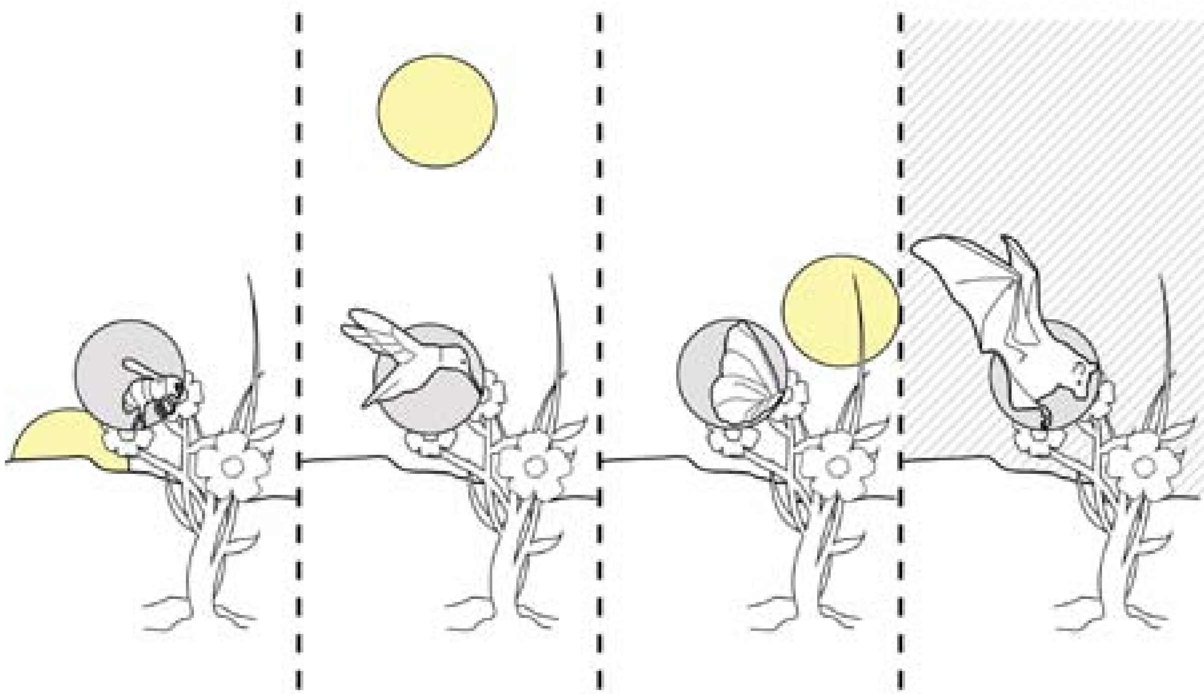
- Network of universities as a large/complex system made up of smaller units delivering fewer, more specific resources
- Cooperation of universities along metro network
- Potential new collaborations along underdeveloped/ underserved areas where systems come together
- Routing new lines to connect to existing universities' resources
- Could pair with transit-oriented development (TOD)
- Mutual association with partners conserves resources
- Trading extra resources reduces cost



foster social integration

pollinators

Resource-sharing guilds allow multiple species to use the same resource without competing.



nature's design

resource sharing guilds allow multiple species to use the same resources without competing

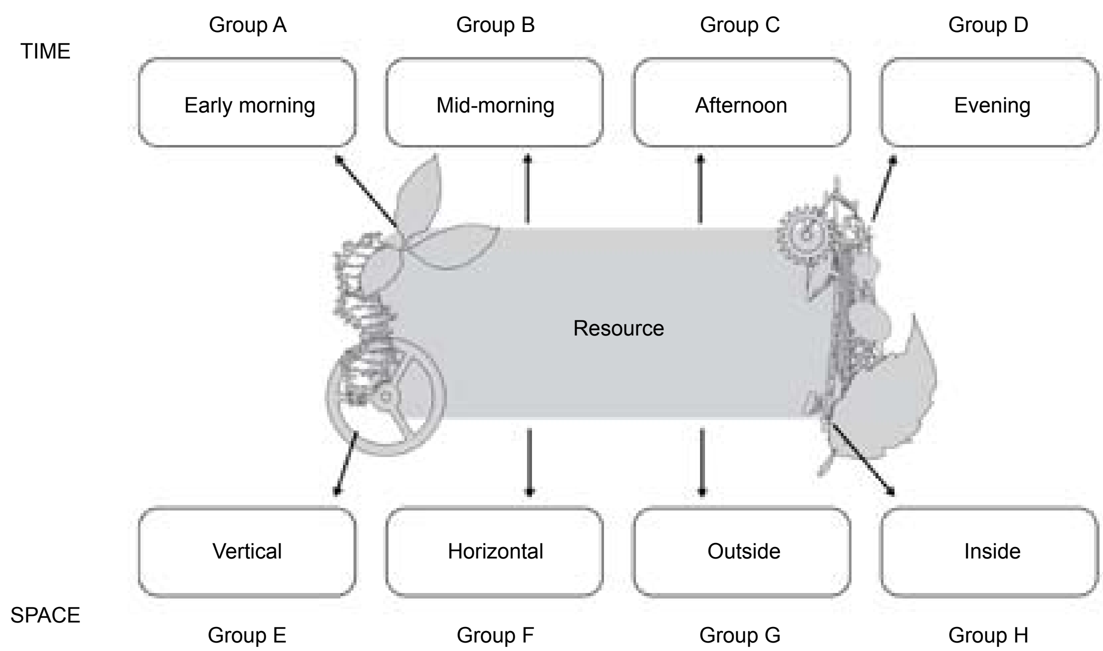
In ecology, guilds represent a basic framework of social structure. A guild is an assembly of species clustered around a central resource that improve its health, avoid competition with each other, and buffer adverse environmental effects.

A resource-partitioning guild consists of species that use the same resource in the same community in a similar way. For example, nectar-feeding animals like bees, birds, some bats, and other insects depend on flowers for food. These organisms avoid competing with each other for a limited resource by feeding at different times, foraging at different locations, eating faster or slower than others, or migrating to another area. This results in effective partitioning of the resource.

Because the flowers are also benefiting from the many nectar feeders, they have co-evolved to flower at different times of the year and even different times of the day. This helps support the diversity of animals dependent on them.

If one species of the guild were to drop out, others could expand their activities or range to fill the gap. This confers stability and resilience because of redundancies in community function and overall flexibility.

- Resource-partitioning guilds are the mechanism organisms use to share a specific resource while avoiding competition with each other.
- Organisms share a resource but vary how and when the resource is used.
- The resource, if it is also a living organism, will respond favorably if it is also benefiting from the exchange.



design principle

partitioning of resources discourages competition and encourages resource-sharing

Sharing a valuable resource is accomplished by partitioning its use in space and time. If the partitioning is designed effectively, the resource will be consumed at an optimum rate and will ideally be regenerated. If one user group left the guild or changed priorities, the resource would simply be re-partitioned.

Related design principles:

- Cooperation fosters social interaction.
- Avoidance of competition fosters social collaboration.
- Multiple consumers of same resource can create resource resilience.
- Maintain resources for long-term use.

BaDT brainstorm

design ideas

Application Ideas

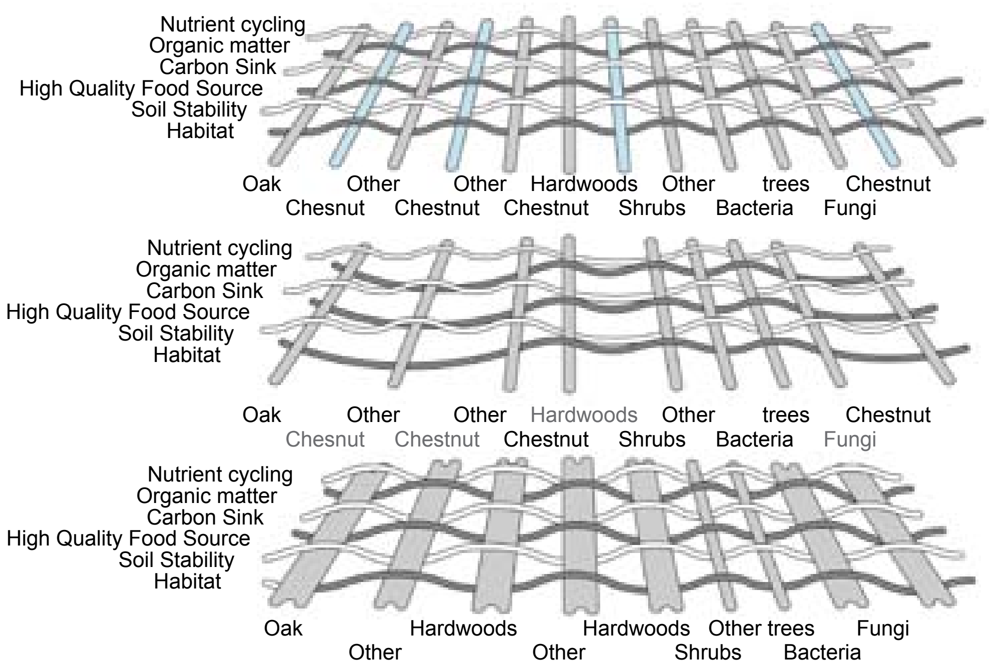
- Use common resources shared by building users to purposely design guilds. This could include water, energy, material flows, or food. Determine the different ways individuals or businesses use the resource and co-develop a shared usage policy/procedure. Create “resource budgets” for any given resource so that people can see and respond to what is available at specific times.
- Create opportunities for users/occupants to find unique ways to access and use the resource—encourage creativity.
- Use the design of programmatic elements to reinforce appropriate use of the resource. Making the resource highly visible often helps people see the impact of their behavior and creates accountability among peers.

future design ideas

design a well-functioning system

tree community

Tree species in a community with redundant roles restored the food web of the broadleaf forest after the widespread devastation of a keystone tree, the American chestnut.



nature's design

redundant functional groups create resilience

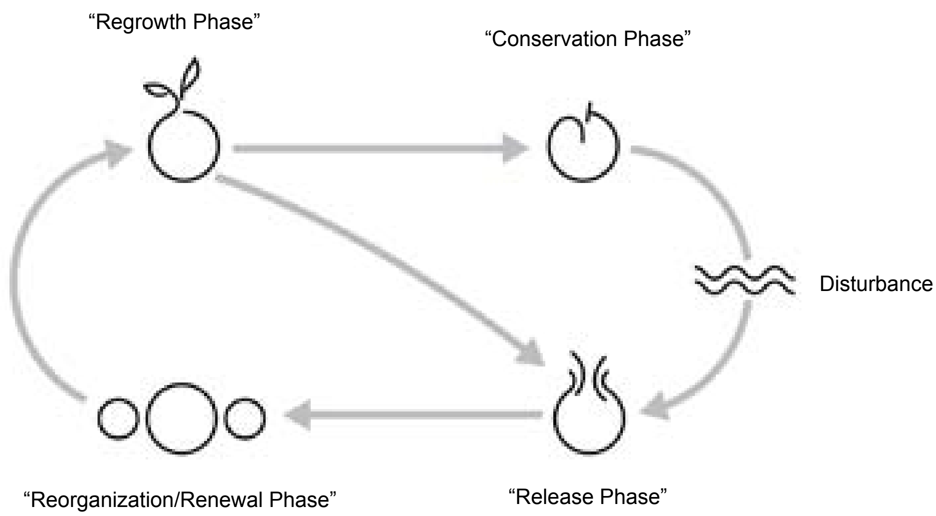
Prior to the early 1900s, the American chestnut dominated 25-50 percent of the canopy of the northeastern U.S. forests. This important keystone species provided an abundant supply of high-quality food for a great many creatures. Secondarily, it stabilized soil, provided habitat, and sunk a tremendous quantity of carbon into its large, long-lived structure.

Unfortunately, the accidental introduction of a pathogenic fungus to which the trees had no resistance killed all the trees within 40 years. Today, all that remains are sprouts from the original rootstock unable to reach sexual maturity before again being attacked and stunted by the fungus.

When the chestnut trees died, the forest canopy opened up, the food web deteriorated and soil erosion ensued. Over the last 70 to 80 years, however, tree species that were not susceptible to the fungus but were in the same functional group (abundant food producers and soil stabilizers) began to fill in the canopy and are now dominant. Oak trees, sugar maples, serviceberry, and black cherry have replaced the American chestnut and now serve as primary food sources for forest creatures. A dense understory assists in soil stability. In this ecosystem, a catastrophic biological event was resolved because of the redundant functional roles that existed in the community of species.

- The American chestnut is a native keystone species of the U.S. temperate broadleaf forest.
- The chestnut performs multiple functions for the ecosystem.
- A blight affecting the American chestnut has radically altered the structural and functional relationships in the northeastern U.S. forests.
- Functional diversity and response diversity allowed the forest to recover and persist as a temperate broadleaf ecosystem.

Adaptive Response Cycle



design principle

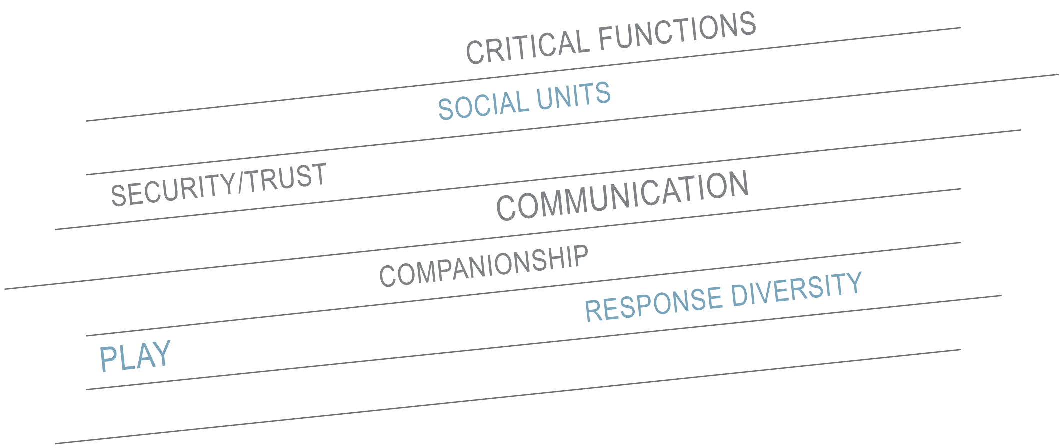
redundant performers of key functions foster resilience

Critical functions within a system are supported by multiple elements. These elements are organized into functional groups according to the primary functions they perform. Elements within the same functional group that respond differently to the same disturbance foster resilience. If one element in a functional group fails, for example, others can fill the gap and the overall performance of that function can continue.

Major disturbances often cause instability, but can also create the opportunity for innovation during the reorganization process.

Related design principles:

- Redundant functional roles secure resilience.
- Critical functions are highly supported by redundant elements.
- Functional diversity and response diversity foster resilience.
- Adaptive response cycle fosters resilience.



BaDT brainstorm

design ideas

Application Ideas

- From a social perspective, evaluate the critical functions that make a social unit strong. These functional groups could include security/trust, communication, companionship, play, and support in times of need. Are there structural, programmatic, or planning elements that can support and foster these functions (critical elements that are well-supported), and are there multiple ways of supporting each one (functional diversity)?
- Bringing together groups of people with different skill sets, socioeconomic backgrounds, interests, and personalities within each functional group will build response diversity.

CITY SERVICES

Redundant or multiple systems service a city

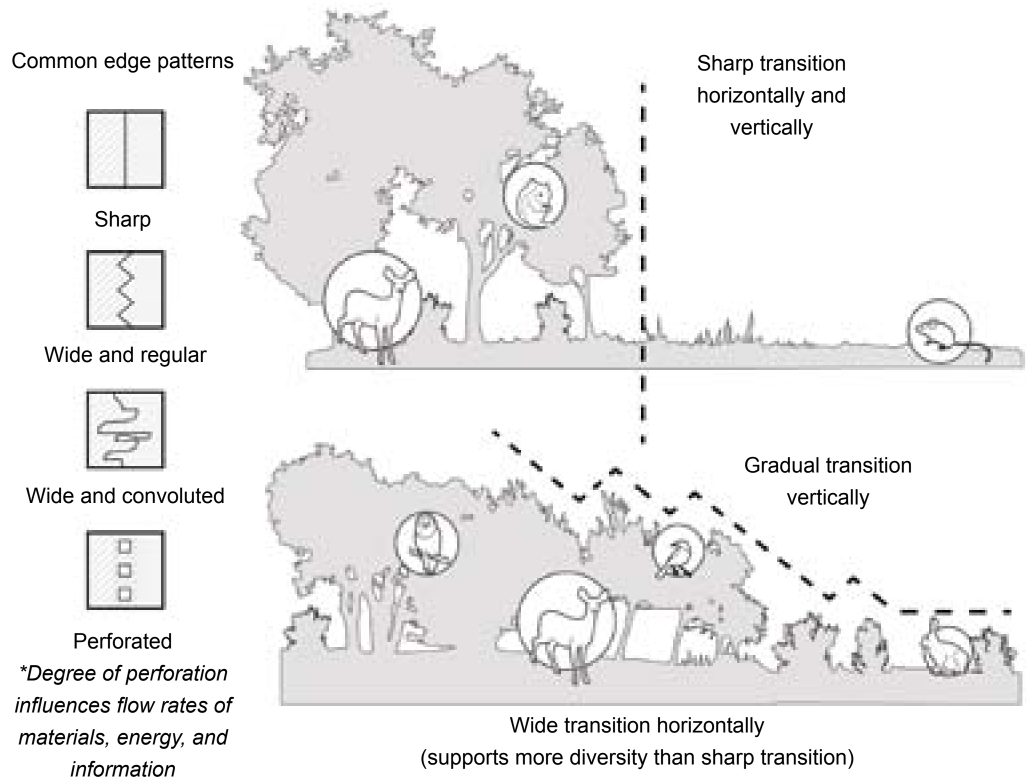
Transport

- A system offering overlapping, redundant modalities creates resilience.
- Redundant or multiple systems serve a city: Rail, road, water, air, bike and pedestrian ways should be flanked with as many modalities as possible. For example, rail can be flanked by bike/ pedestrian paths flanked by roads for cars -- all within a greenway.
- Intermodal nodes bring together diverse populations.
- What results from overlapping modalities? Intermodal transfers create conditions for civic life, commercial activities, amenities, and housing.

design a well-functioning system

ecotones

Ecotones support tremendous diversity and species interaction while creating robust systems capable of buffering disturbance.



nature's design

ecotone fosters social diversity

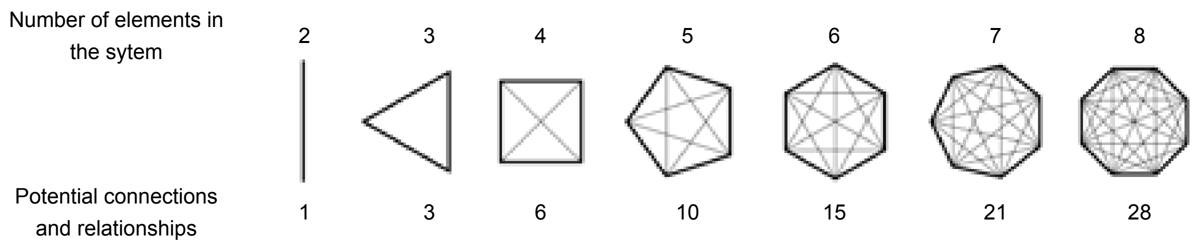
An example of an ecotone, or edge, is the transition between a wet meadow system and a drier upland wooded system. Such meadow-forest edges are rich, diverse habitats where species interact. The complexity and interdependency of relationships in ecotones, as well as the physical structure of the transition zone, result in an accumulation of energy, materials, and information, providing food, mates, communication, and shelter.

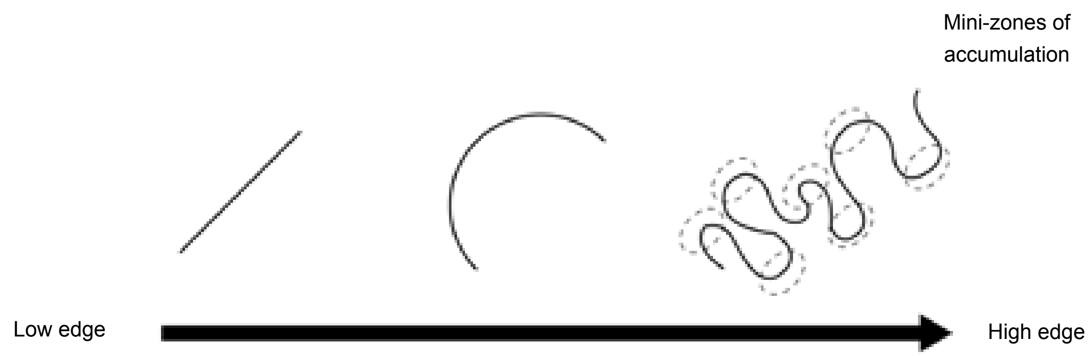
Horizontally, the ecotone transition can be narrow (a sharp change, as in a forest abutting an agricultural field), or it can be wide (gradual change, as in natural meadow-to-forest transition). Vertically, ecotones show transitions in vegetation height from grasses and herbaceous ground cover in the wet meadow to woody shrubs and herbs with variable soil moisture, to dry upland canopy species in the forest.

The degree of "perforation" in an ecotone inhibits or enhances dispersal of energy, materials, and information across the edge. For example, an expansive patch of brambles inhibits dispersal, whereas a large tree fall or flowing stream create space and enhance dispersal. A wet meadow to upland forest can buffer flood damage or resource depletion resulting from prolonged drought.

The greater the contrast between transitions, the more robust and diverse the ecotone. When there are wider transitions, there is more capacity to support diversity and buffer disturbances.

- Ecotones are "hot spots" where organisms interact to get food, find mates, communicate, rest, and take shelter.
- Ecotones are diverse, robust systems.
- Perforation in an ecotone inhibits or enhances the flow of material, energy, and information.
- Ecotones help the ecosystem buffer disturbances.





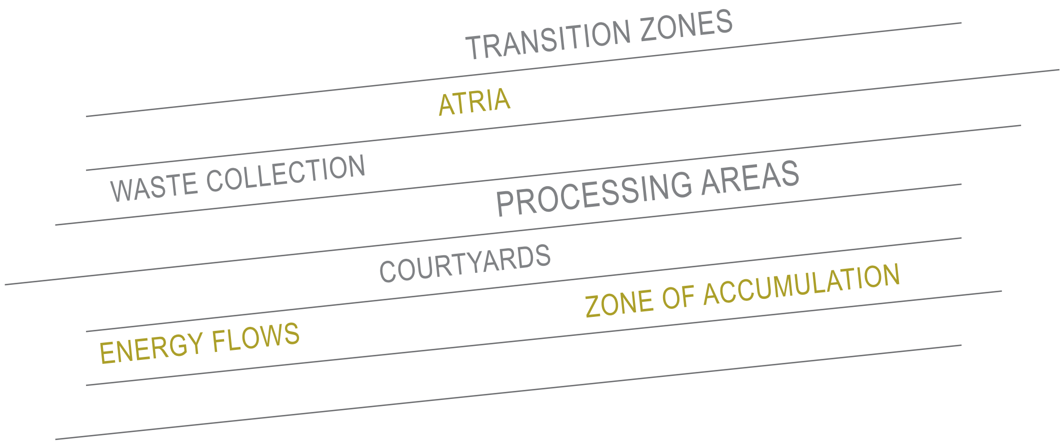
design principle

transition areas within a community foster social diversity

Transition zones represent opportunities to leverage and optimize diversity and interconnectedness. The two main elements that contribute to a robust, resilient edge system are its physical structure and highly interconnected, interdependent relationships among its users. Edge systems with wide transitions between different environments support higher diversity and have more capacity to absorb disturbance. The greater the differences between transitioning environments, the higher the potential for a rich edge system. Adjusting the degree of open areas within the transition zone will influence the rate and ease with which energy, materials, and information can flow.

Related design principles:

- Edges are zones where materials, energy, and information accumulate.
- Edges support diversity because it is easy to find resources that meet needs for survival and well-being.
- Wide transition zones are more robust and resilient than sharp transition zones.
- Adjusting “perforations” in a transition zone influences rates of material, energy, and information transfer.
- Highly interconnected relationships result in robust transition zones.



BaDT brainstorm

design ideas

Application Ideas

- Identify transition zones within a building or group of buildings. Examples may include entry ways or atria, waste collection/processing areas, laundry areas, elevator/stair corridors, plazas, courtyards, parking zones, and shipping and receiving areas. Each of these represent an opportunity to direct the flows of energy, materials, and information in ways that increase interactions and connections among building users.
- Integrate the “back building” activities (waste, laundry, shipping/receiving) with “front building” activities to create opportunities for users to interact in new ways, and have access to new information that may change behaviors and consumption patterns.
- Create a seamless transition between inside and outside of a building, and between buildings. This can involve transitions within the structures themselves, but can also integrate a landscaping component to help connect different “environments.”
- Use the concept of increasing edge to create “zones of accumulation” where material, energy, and information can accumulate in ways that give people greater capacity to meet their needs (food, water, rest, communication) in non-traditional ways.

Project site occurs in an ecotone. Can it be used as a metaphor for creative exchange reinforced through building landscape expression? The 'perforation' of the ecotone is defined by linkages, views, and informal gathering spaces.

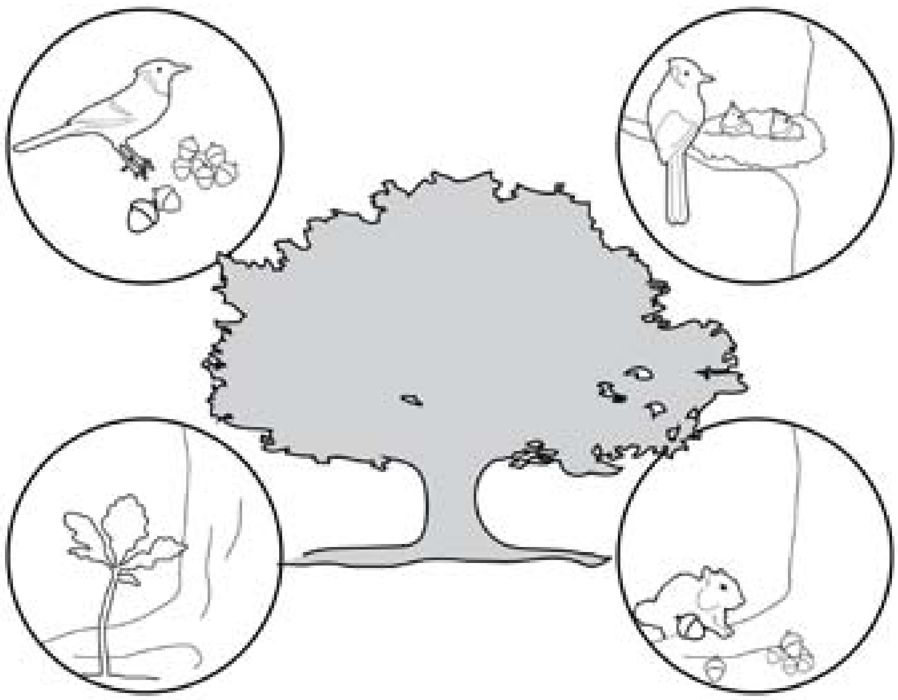
The transition is the body of the building.

The ecotone porosity must occur three-dimensionally, not just on the ground plane.

foster cooperative relationships

jay and oak

Blue jays and pin oaks have a cooperative relationship that not only enhances the survival of each, but also provides increased opportunity and benefi ts to the ecosystem as a whole.



nature's design

cooperative arrangement enhances social networks

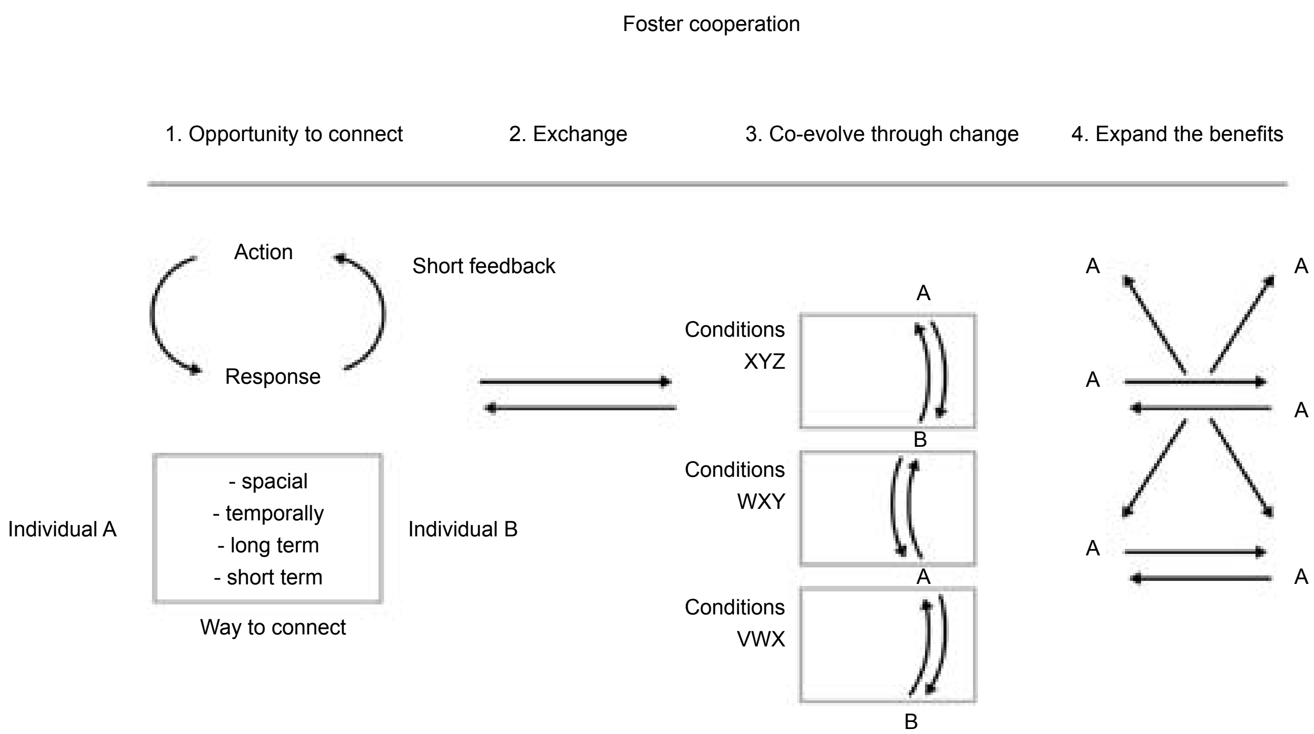
The jay is a common inhabitant of the temperate forest that benefits from its association with oak trees. The jay collects acorns and caches them underground near its nest for consumption through the winter and spring. Caches are often along gap edges (mini-ecotones) because they are easy to rediscover.

Jays are efficient seed collectors. In one study, 50 jays were estimated to transport and cache 150,000 acorns from 11 oak trees over 28 days, carrying the seeds more than 13 miles away from the parent tree. Because jays can be forgetful, some acorn caches are left undisturbed and the seeds germinate into new oak trees.

This relationship benefits the oak not only because its seeds are being widely distributed, but also because the jays are masters at selecting the best acorns (the highest nutrition for themselves and their young), which means the most fit seeds have the greatest chance of carrying on their genes.

Mutualistic relationships play a critical role in moving energy and nutrients across ecosystem borders and thus have a large impact on the structure and function of those systems. Likewise, this relationship benefits many other species, such as increased habitat and a food source for creatures such as rodents that raid jay caches.

- Mutualistic interactions benefit both organisms.
- Blue jays and oaks both derive direct benefits from being in association.
- The relationship results in increased fitness for both species.
- Additional benefits from the alliance are realized by myriad other species.
- The cooperative relationship influences the overall structures and functions of the ecosystem.



design principle

mutualistic relationships enhance social networks

Cooperation works when both individuals in a relationship experience enhanced chances of survival, which means that there is twice the incentive to support the behaviors and actions that create those benefits. At some level, both parties must be cognizant of the benefits of working together. Interestingly, the benefits gained are generally different for both parties.

To foster cooperation, the following conditions must be met:

1. Potential cooperators must be able to connect. This is accomplished through increasing the number of ways they can connect and keeping short feedback loops, or information flows.

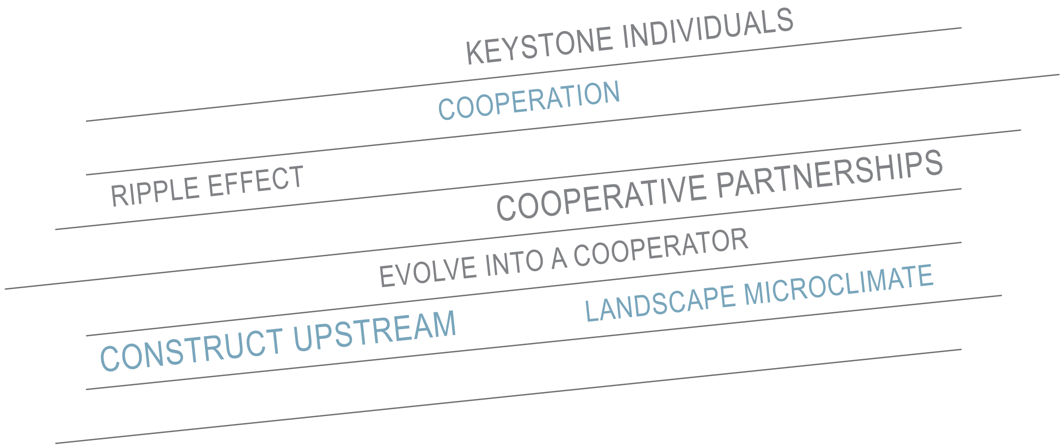
2. The benefits must be exchanged and realized.

3. The relationship co-evolves over time while adapting to changing conditions.

4. The higher the multi-functionality of the relationship, i.e., the more benefits it creates for the greatest number of other individuals, the higher the likelihood that relationship will persist over time. Highly successful cooperative relationships between keystone individuals define the structure and function of a system and also how resources and energy move through it.

Related design principles:

- Foster interaction between different groups to increase survival and success.
- Avoid competition (expensive and lose-lose for both parties) to conserve resources and relationships.
- Enhance system dynamics to foster cooperation.
- Cooperation enhances adaptation to changing conditions over time.



BaDT brainstorm

design ideas

Application Ideas

- Identify “keystone” individuals, businesses, or industries operating within a building or within a development and encourage their cooperation. The exchanges of these entities will likely have beneficial ripple effects for the whole community.
- Similarly, HOK can identify other keystone entities in the architecture industry and consider the type of of collaborative partnerships that could emerge. This could be especially powerful if an entity viewed as a competitor could evolve into a cooperator.

NEIGHBORHOOD EVOLUTION

Information from old building used to inform neighborhood

Neighborhood Scale

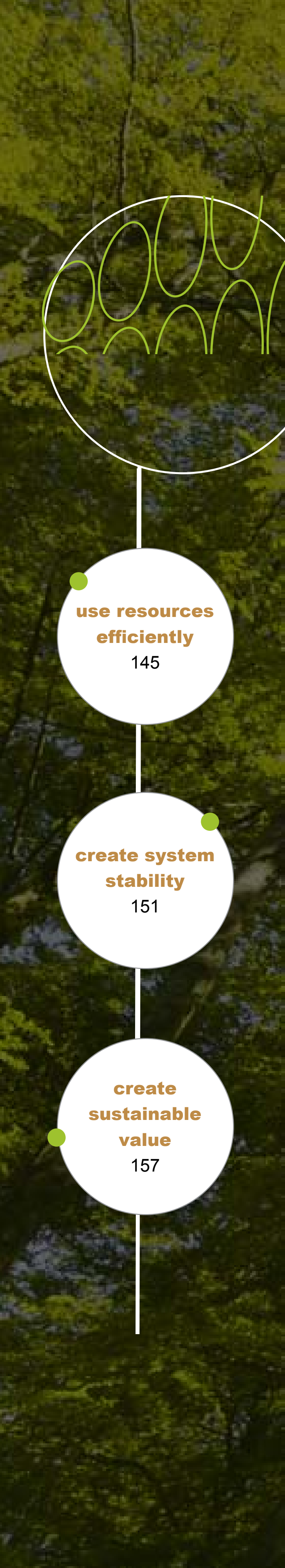
Acorn is a metaphor of transferring data/knowledge.

Information from old building used to inform new neighborhood construction.

Buildings 'evolve' in neighborhood because of "oak"- main source of information.

Why not run energy analysis on existing buildings before new construction?

- How does the embodied composition (material make-up, embodied carbon) inform new construction?
- Can/should the old buildings be more valued as social hubs?
- Can a financial model be developed to support them (air rights transfer, tax incentives, etc.) as depositories of information?



ECONOMIC

Economics describes the flow of goods and services that creates the potential for people to meet their needs. Humans use monetary capital to facilitate these transactions. Nature uses relationship capital. This is an interesting juxtaposition to consider when it comes to evaluating “the bottom line” and the non-negotiable break point. What would our economic transactions look like if relationships, not money, were the bottom line? How can relationships be leveraged to meet needs without a requisite monetary transaction?

Organisms’ relationships to each other and to the resources they need to survive determine their success. Competition and rapid use of resources can be effective ways for a species to get established, especially after a disturbance. Over the long term, though, this is an expensive and wasteful mode of action. The rate of resource use has the greatest implications for maintaining that resource and for cultivating its long-term value. Cooperation and interdependence are the least expensive means of transacting.

Project management is connected to economics, and represents how materials, capital, time, and individuals are utilized during the period of transition from one system state to another. In nature, this process is called succession. This section includes one entry that describes the mechanisms of succession as a model for project phasing and arriving at some desirable future state. Succession in nature can help us plan for potential disturbances in projects, and appreciating limitations as opportunities for creative abundance through cooperative relationships. More explanation about the various succession models are given in the notes in the appendices.

- Incorporate succession.
- Create diverse structures.
- Sustain value with limits.

ECONOMIC

LIFE'S PRINCIPLES

REFERENCE THE DEFINITIONS

EVOLVE TO SURVIVE

Integrate the unexpected

Learn from unexpected disturbance events and take advantage of resources that result from the disturbance.

INTEGRATE DEVELOPMENT WITH GROWTH

Self-organize

Be responsive to levels of resource availability to concentrate on development as well as growth.

BE RESOURCE-EFFICIENT (MATERIALS AND ENERGY)

Find the limiting resource and tailor projects to prevent overconsumption of that resource.

BE LOCALLY ATTUNED AND RESPONSIVE

Use readily available materials and energy

Start slowly and set the stage for efficient use of resources by developing cooperative relationships.

ADAPT TO CHANGING CONDITIONS

Embody resilience through variation, redundancy, and decentralization

Incorporate variation to lessen chances of future disruption in services.

USE LIFE-FRIENDLY CHEMISTRY

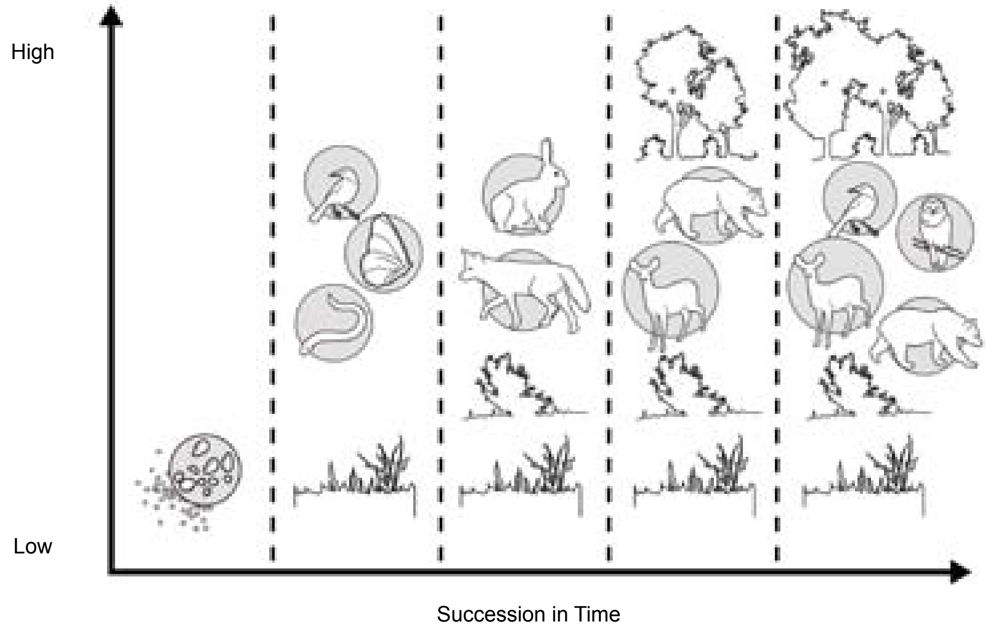
Break down products into benign constituents

During development and growth, capture waste material and use it as a resource for future stages.

use resources efficiently

ecosystems

Ecological succession moves ecosystems through phases of development, including pioneering bare soil and responding to resource availability and changing conditions over time.



nature’s design

succession phases development

Ecological disturbances disrupt ecosystem, community or population structure, and available resources. After a disturbance, ecosystems respond by following one or more models of succession.

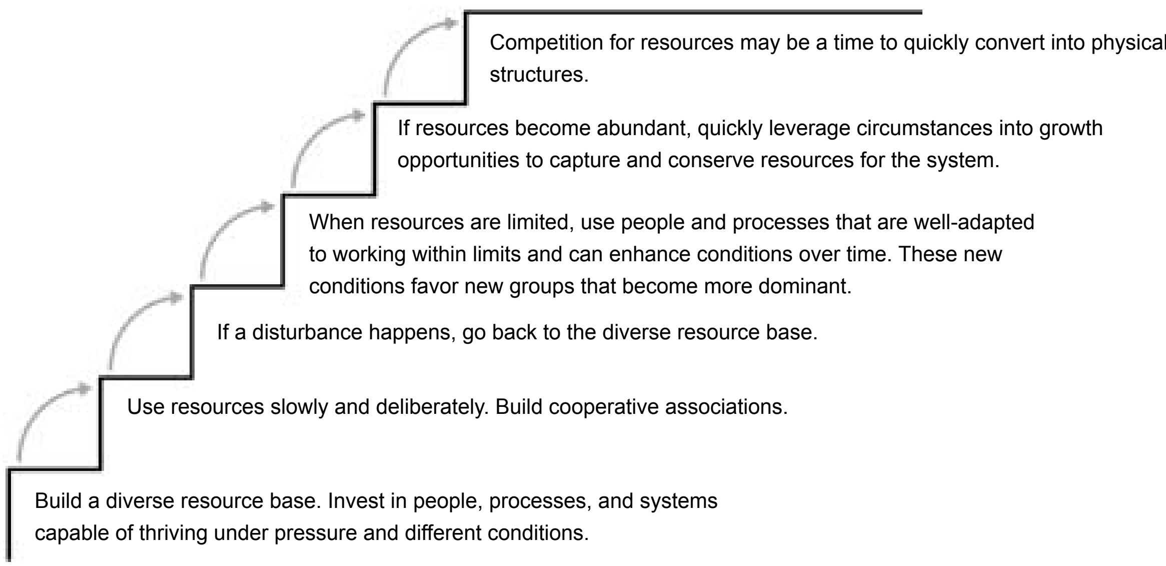
In the classic linear model of succession, pioneer species colonize bare soils, producing nutrients and habitat suitable for the next stage of succession. In turn, these species produce organic matter and are colonized by mutualistic, nitrogen-fixing mycorrhizae. Soil nutrients and seeds accumulate in the soil, acting as biological legacies available to restart succession after future disturbances. Succession arrives at a climax of highly adapted species that replace themselves.

The relay floristics model suggests that pioneer species modify the environment of bare ground and create conditions for the next group of species, which modify the environment. The initial floristics model occurs following minor disturbances. Though nearly all species that will ever be present in the soil seed bank already exist there as biological legacies, they will only grow when the conditions are right.

The adaptive characteristic model describes three strategic adaptations of plants. Short-lived species colonize environments with plentiful resources and allocate most of their energy and resources to reproduction, not growth. Competitor species devote themselves to gathering resources, storing just enough energy and resources to flourish the next year and then aggressively consuming as much space as possible, exhausting resources. Stress-tolerant species are adapted to limited resources and invest in self-maintenance and cooperative relationships. They can absorb and store nutrients when not growing and eventually replace competitors. For more information, see **Notes**.

Factors influencing the extent and severity of disturbance events are:

- Location of biomass reserves (above or below ground) at time of disturbance
- Resource base
- Niche strategies of species (how they respond to disturbance)
- Relative competitive abilities
- Landscape characteristics
- Scale



design principle

plan for efficient use of finite resources

- How efficiently and effectively a project grows or responds to disturbances depends on having a diverse resource base, resources distributed throughout the system, investment in legacy strategies, and people, processes, and systems capable of thriving under different pressures and conditions.
- Skipping important stages of development, especially foundational stages that create a system's long-term resource base, can reduce overall productivity and system stability. Slow and deliberate use of limited resources in early stages results in more long-term cooperative associations than a fast and indiscreet use of resources. The latter, based on an inaccurate representation of actual resource capacities, can actually slow or reverse progress.
- Where resources are limited, a project can include people and processes that are well-adapted to working within limits and can enhance conditions over time. These new conditions favor a new group of individuals or processes that shift into a more dominant role.
- A project could bring together all of the people and processes that will at some point have a role to play. The prevailing conditions at any given time determine which will be the most active change agents.
- If resources are abundant, a phasing process that can quickly leverage circumstances into growth opportunities can capture and conserve resources for the system.
- Competition for resources can play an important role in establishing a presence by quickly converting resources into physical structures. If left unchecked or unbounded, this could quickly exhaust resources.
- During stable circumstances in which most of a system's resources are bound up in infrastructure, processes that foster cooperative relationships have the greatest advantage. They can find or create opportunities to accumulate resources even during periods of no growth.

Related design principles:

- Adaptive characteristics of individuals determine optimum roles.
- Mutualistic relationships lead to success.
- Create resource foundations that contribute to the next stage of planning.
- Invest in legacy strategies to improve performance and resilience to disturbance.
- **Key slow variable** sets the pace for change.
- Adaptive roles determine which species flourish under various conditions.
- Disturbances are an integral part of determining appropriate adaptive response.

LONG-TERM STABILITY
TURN UP BARE SOIL
CREATE OPPORTUNITIES FOR PIONEERS
FOUNDATIONAL ROLE
BIO-LEGACIES
SUDDEN BURSTS OF RESOURCES
BUILD UP THE SOIL

BaDT brainstorm

design ideas

Application Ideas

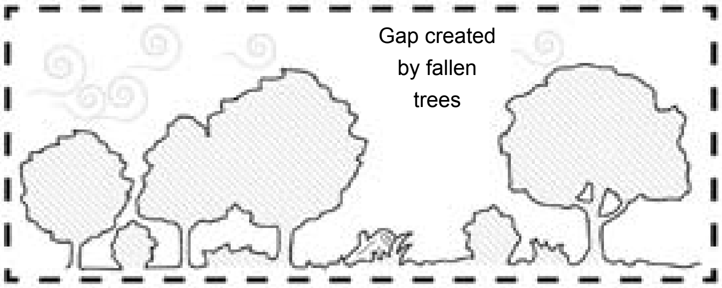
- Build as resources become available. When value-producing buildings go in first, they can create short-term yields that support long-term stability.
- Metaphorically, consider whether your actions or decisions are continually turning up bare soil, forcing the system back to early stages of development and encouraging “weeds” to get established. That can be desirable if you’re trying to create opportunities for new pioneer individuals to enter the project, but detrimental if you’re trying to move forward.
- Identify key pioneer individuals or elements that should be responsible for creating, storing, and cycling resources in the project’s early phases. Encourage conditions that allow them to function well and recognize that they play a foundational role for long-term project success.
- What “bio-legacies” or inheritances could a design firm invest in, both as a whole company and on a project-by-project basis? This idea of a bio-legacy is essentially any strategy, practice, or management technique that makes the system less susceptible to major setbacks in the face of minor disturbances. In this case, it may mean changes to the budget, sick employees, or a trade embargo on an exotic building material. The legacies for any given project may differ from one to the next, as they often depend on the context.
- When doing green space planning, phase landscaping to first build up soil by planting pioneer species and then phase to grasses and herbs.

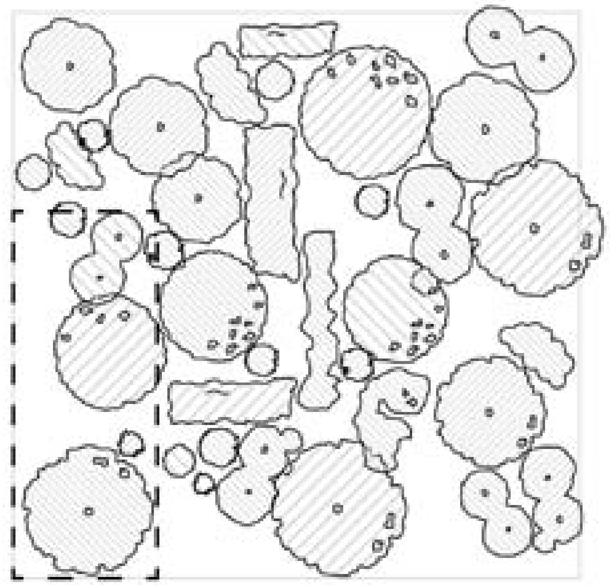
future design ideas

create system stability

forests

Diverse structures form in response to abiotic disturbances, resulting in an overall structure that creates a more resilient system.





nature's design

diverse structures mitigate disturbance

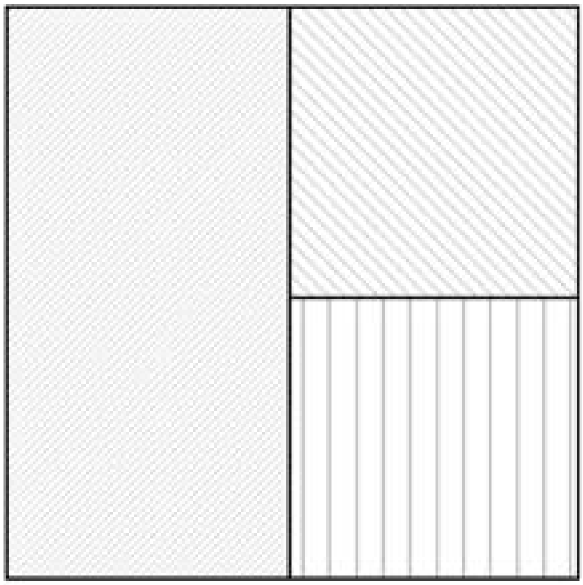
Forests are subjected to many disturbances, including insect attacks, fire, ice storms, herbivores, severe thunderstorms, tornadoes, and hurricanes. Individual trees are sometimes weakened, killed, or toppled. Whole stands of trees can be destroyed.

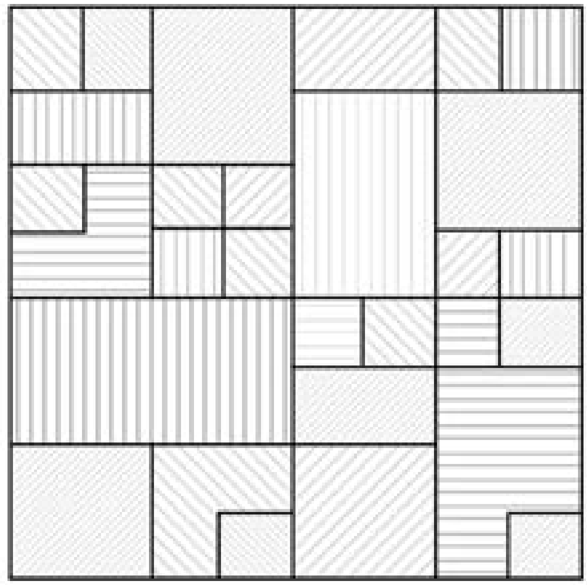
Native trees and forests tend to be more resistant. Fallen trees create opportunities for plants and animals to gain resources such as sunlight, stirred up soil, and decayed wood. The tree itself becomes part of the process, adding nutrients and holding water. Groups of trees provide protection downwind for other trees, while trees on the outside of a patch protect inner trees. The result of these disturbances is a mosaic of habitat patches rather than a uniform forest.

A patchy forest is made up of a variety of species, spacing, ages, heights, densities, and stages of succession. Combined with equally diversified abiotic elements such as soil types, topography, and microclimates, the forest becomes more resilient.

Tree roots link together, trunks thicken, and fallen trees become habitat for other organisms. At the forest scale, the combination of these adaptations with fallen trees creates a heterogeneous pattern that becomes more resilient and resistant to disturbances. At the ecosystem level, a heterogeneous structure creates more resilience to disturbances.

- Native trees and forests are adapted to local disturbances.
- Trees exhibit adaptive growth to strengthen against wind.
- Tree roots interlock, providing mutual support against wind.
- Gaps created by fallen or broken trees increase species diversity.
- An ecosystem pattern of different densities, species, and ages increases resiliency.





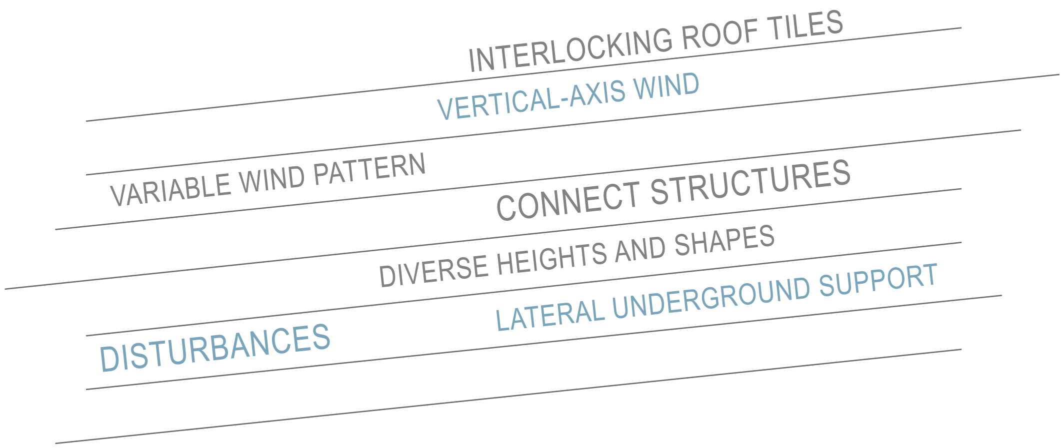
design principle

variety of structures/responses provides resilience after disturbance

Diversity in physical structures results in a variety of responses to disturbances. The same is true of a diversity of services provided within a system. When structures and services are homogeneous, there is an increased likelihood of some sort of disturbance causing widespread harm and difficulty. Having a diversity of structures and services, on the other hand, creates a more resilient system.

Related design principles:

- Disturbances create opportunities.
- Holistic response provides resilience.
- Added material and deep, wide, flexible, interlocked footings provide stability.



BaDT brainstorm

design ideas

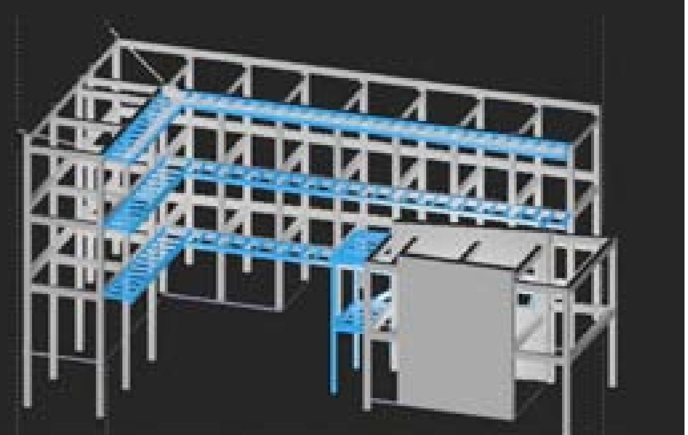
Application Ideas

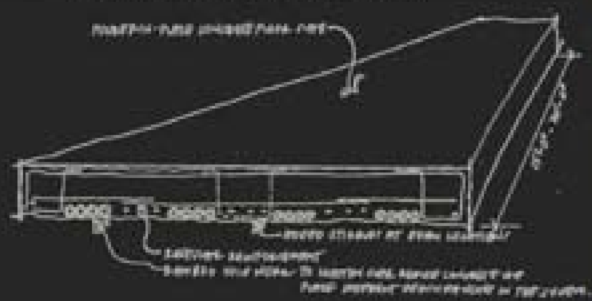
- Incorporate variation into designs to lessen the chances of future disruptions in services.
- Design to create multi-functional products, processes, structures, and infrastructure.
- When an unexpected event occurs, find value by learning lessons for the future or taking advantage of resources that have been made available.
- Look for opportunities to connect structures and communities with others for mutual benefits. This can be as literal as making underground connections between buildings or bridges between buildings or as metaphorhical as creating neighborhood parties or traffic structures.
- Create community-wide diversity in structure heights, shapes, and materials, and in sources of community services such as water or waste removal to provide resiliency in the face of different types of disturbances.
- Design structures subject to wind damage, such as streetlights, bus shelters, and power poles, to have deep, flexible footings with lateral underground supports in a bracket shape on the leeward side.
- Design roofing tiles to be interlocking.
- Use vertical-axis wind turbines in densely populated areas with variable wind patterns.

Structural Systems

CREATE SYSTEM STABILITY by leveraging local capabilities:

- Improve the current building systems approach in Haiti with local materials to make the structure more robust with less waste and embodied energy.
- Site- fabricated leave- in-place formwork with improved reinforcement techniques will create more resilient systems.
- Wood and concrete hybrid systems create a degree of diversity and supports the low emissivity strategy.

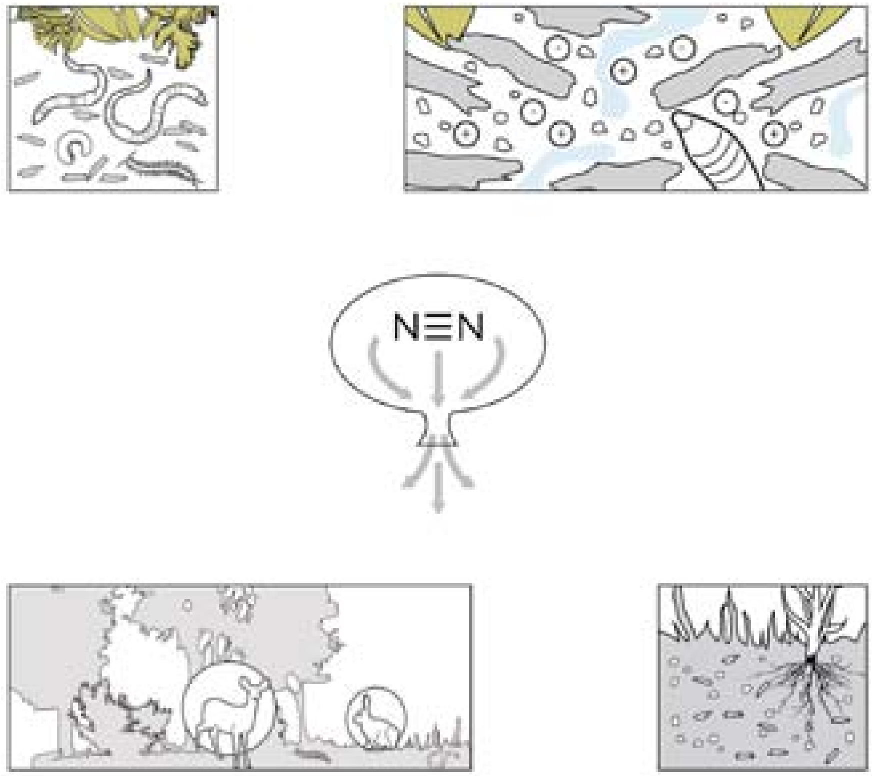




create sustainable value

organic soil

Organic matter in the soil moderates renewal rates for nitrogen, which is the key slow variable in the forest biome.



nature's design

limit-based value system sustains value

Plants, organic matter, and soil organisms create fertile soil. But it is the limitation of nitrogen that maintains fertility. In other words, the forest maintains its resources by growing within the limits of a key slow factor—in this case, nitrogen.

Organic matter is formed as a result of the decaying process of once-living organisms. The primary broker is the organic matter that determines which, and at what rate, biogeochemical processes function. Organic matter creates and stabilizes soil structure, maintains and regulates nutrient cycling, and provides a habitat for soil organisms. Collectively, these processes create conditions conducive for plant growth.

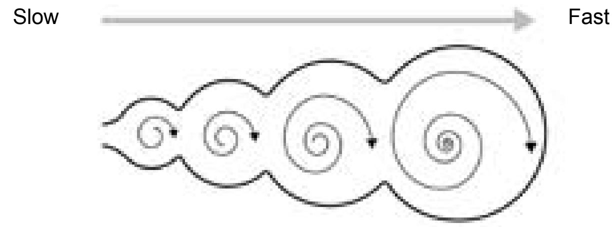
Plants are the primary consumers of soil nutrients. Their rate of growth is regulated by the amount of nitrogen available in the soil. Nitrogen is thus a key slow variable that regulates the rate of growth based on the rate of nitrogen renewal in the system. Rates of nitrogen renewal depend on available organic matter and soil organism activity. Because nitrogen is such a powerful limiting factor, all plants have evolved mechanisms to conserve nitrogen and to operate within a tight nitrogen budget.

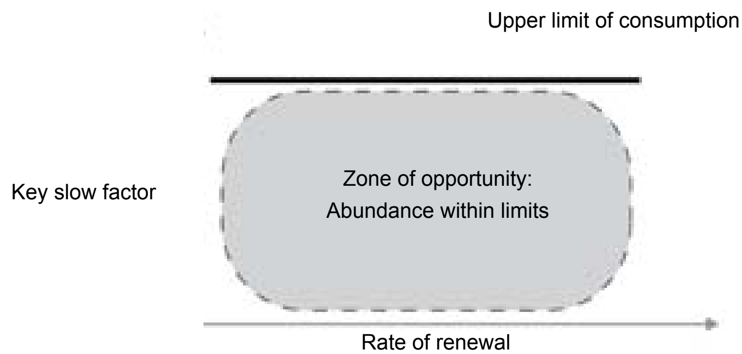
This process occurs at the level of the individual plant species all the way through to the ecosystem level. The key slow variable of nitrogen in soils is heavily influenced by agricultural, industrial, and urban ecosystems.

- Soil types typical of the temperate broadleaf forest are historically high in organic matter.
- Organic matter in the soil is responsible for its physical structure, its nutrient cycling capabilities, and its capacity to support life.
- Soil nitrogen is the key slow variable that affects the rate of forest growth.
- The quantity of organic matter in the soil is a key factor in rates of nitrogen renewal.

Rates of Renewal

Interdependent processes can only go as fast as the slowest process will allow (like a system of gears)





design principle

limits based on a key leverage point maintain value

Rate of consumption, not just amount, is a critical factor in maintaining resources. If the rate of consumption exceeds the rate of renewal, long-term deficits, imbalances, and systemic instability will result. The element with the slowest rate of renewal can be used to set an appropriate rate of consumption for all the other resources linked to that slowest element. The mechanism that is responsible for renewing the slowest element is often a key leverage point in the system, and should be cultivated, conserved, and protected.

Limitations such as key slow variables are not meant to be “overcome” or “gone around,” which are actions that have consequences similar to excessive rates of consumption. Limitations are opportunities for creative abundance through cooperative relationships.

Related design principles:

- The factor with the slowest rate of renewal defines appropriate rates of consumption for all other resources.
- The primary mechanism responsible for mediating the key slow variable should be cultivated, conserved, and protected.
- Limitations provide the opportunity for creative abundance, which is most effectively achieved through interdependent, cooperative relationships.

DOES NOT USE CREDIT
PRODUCTIVITY
RENEWAL EXCEED CONSUMPTION
TRUE COST ACCOUNTING
SLOW VARIABLES
FINANCIAL INFRASTRUCTURE

BaDT brainstorm

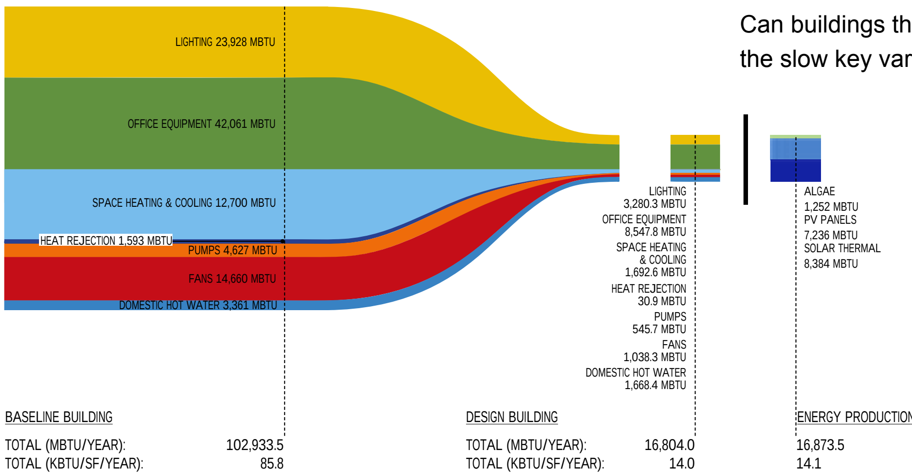
design ideas

Application Ideas

- The role that soil organic matter and nitrogen play in overall biome productivity illustrates what nature DOES NOT do. Nature does not use credit. Credit is essentially a mechanism that allows a rate of consumption to exceed the rate of renewal.
- Look for ways to affect the financial infrastructure of buildings so that use of credit is avoided. Are there ways to foster economic transactions for the users, managers, and builders that do not rely on credit? True-cost and real-time accounting is one method. Trade and barter is another.
- A mechanical application of this strategy is to identify the key slow variables in mechanical systems. Are they water, energy, maintenance, or equipment? Think not only in terms of immediate building needs and performance, but also about overall patterns in resource availability and consumption/renewal rates. Design mechanical systems that work within the limits of this factor and that cultivate, conserve, and protect it. This process of inquiry may lead to solutions that solve multiple problems with a single solution, including energy, water, material, social, and economic concerns.
- Use organic and regenerative practices in landscaping to build up organic matter in the soil around the site, and create or restore natural nitrogen cycling processes by mimicking the structure-function relationships of native temperate broadleaf biome species. Use income from a building to support soil conservation and restoration in a nearby area. By investing and re-investing in these natural systems, over time you build capacity to draw from these resources at an appropriate rate for building materials and social capital resources.

PROCESS ZERO

Energy is Slow Key Variable



Can buildings that produce energy adopt the slow key variable concept?

Algae-producing facade geometries are tuned for exposure and environmental conditions.

Can radical transformations of existing buildings offer more design freedom through constraints?

APPENDICES

TEMPERATE BROADLEAF FOREST

notes

ECONOMIC

USE RESOURCES EFFICIENTLY • ECOSYSTEMS

Succession was first described in the early 1900s as a directional, predictable progression from a pioneer stage to a stable and self-replacing climax. While this linear theory of succession has since given way to more dynamic and cyclic theories, many of the observations proposed over 100 years ago remain relevant. This appendix describes succession models that are represented in the temperate broadleaf forest.

Ecological disturbance is defined as “any relatively discrete event in time that disrupts ecosystem, community, or population structure, and changes resources, substrate availability, or the physical environment.” Disturbance is an inevitable, inseparable element of all succession models — disturbance stimulates succession. Various factors influence the extent and severity of disturbance events, including location of biomass reserves (above or below ground) at time of disturbance, resource base, niche strategies of species (how they respond to disturbance), relative competitive abilities, landscape characteristics, and scale.

While every disturbance can have negative impacts on individuals, mild to intermediate disturbances can have an overall beneficial impact on an ecosystem’s health and vigor by stimulating larger successional processes. Research suggests that species richness is greatest in communities that experience an intermediate level of disturbance.

The largest-scale disturbances in the temperate broadleaf biome are fire, ice storms, tree fall gaps and blow-downs, insect attacks, human development and resource exploitation.

Application Ideas for Disturbance and Succession

- We are not suggesting that one purposefully introduce disturbances into the project management process. Instead, we are suggesting that inevitable disturbances in the project management process be taken into account. Consider what kind of disturbances might occur in a given project, how bad they might be, and what systems are currently in place (or could be developed) that would allow a team to respond effectively. These disturbances could include changes to project funding, staffing changes, timeline modifications, permitting issues, land use conflicts, and trade embargos. Adopting strategies that distribute resources throughout the system (avoiding all eggs in one basket), fostering a strong resource base, and encouraging individuals that thrive in varying levels of “chaos” will help support a strong response strategy.
- As mentioned in the description, an intermediate level of disturbance on a regular basis has the potential to create “species richness,” which in this case could translate to “interdisciplinary richness,” because that much disturbance would demand a diverse team of individuals working together to solve problems, adapt, and advance. That much disturbance would probably be counterproductive to a team’s efforts, but proceeding as if that is how it was going to be could result in an extremely robust system.

Linear Model of Succession

In the linear model, succession begins when pioneer species colonizes barren soils. Pioneer species include bacteria, algae, lichen, and moss. These species produce nutrients and habitat suitable for grasses and herbs to become established. Grasses and herbs produce organic matter that further improves soil fertility and prevents nutrients from leaking out of the system.

As the diversity of plant species increases, nitrogen-fixing microorganisms called mycorrhizae colonize the soil and develop mutualisms with plants. Soil nutrients and seeds in the soil accumulate. These resources can be drawn on to stimulate succession after a disturbance. The seed bank acts as a biological legacy that influences the pace and pattern of succession.

notes

In the linear model, succession arrives at a climax, or end point, of highly adapted species that continually replace themselves, resulting in a stable system where the character of the plant community remains largely unchanged over time, unless a disturbance sets succession back to the beginning.

Application Ideas for Linear Model

- Build as resources become available and with value-producing buildings going in first. This creates short-term yields that support long-term stability.
- Metaphorically, consider whether your actions or decisions are continually turning up bare soil, forcing the system back to early stages of development, and encouraging "weeds" to get established. That may be desirable if you're trying to create opportunities for new pioneer individuals to enter the project, but detrimental if you're trying to move forward.
- Identify key pioneer individuals or elements that should be responsible for creating, storing, and cycling resources in the early phases of the project. Encourage conditions that allow them to function well and recognize that they play a foundational role for long-term project success.
- Tie rate of project development to availability of resources such as money, work force, time, materials, and client buy-in. Are available resources "released" into the project at rates that represent their long-term availability/renewability, or are there sudden bursts of resources that may paint a false picture of long-term capacity? The most important resource to watch is the most limited one. Is there a way to pace your use of the key resources?
- What "bio-legacies" or inheritances could you invest in, both as a whole company and on a project-by-project basis? This idea of a bio-legacy is essentially any strategy, practice, or management technique that makes the system less susceptible to major setbacks in the face of minor disturbances. In this case, that may mean changes to the budget, sick employees, or a trade embargo on an exotic building material. The legacies for any given project may differ from one to the next, as they are often context dependent.

When doing green space planning, phase landscaping to first build up soil by planting pioneer species, then phase to grasses and herbs.

Relay and Initial Floristics Models of Succession

Another two models of succession are relay floristics and initial floristics. These models describing mechanisms of vegetation change over time.

The relay model suggests that the actions of pioneer species present in a grassy meadow create conditions favorable for shrubs. As the shrub community is established, changing dynamics make shrub growth possible but make the environment unfavorable for species in the grass community; grasses gradually die off. Dominance is passed like a relay baton to shrub species. Over time, the shrub community will alter the environment in a way that favors a tree community, inevitably "passing the baton" once more, shifting the dominance away from shrubs and toward trees.

The initial floristics model suggests that nearly all species that will ever be present in the habitat already exist in the soil seed bank, but only grow when the right conditions are present. These biological legacies of seeds in the soil define the composition and character of the successional pathway. As environmental conditions evoke the growth of certain plants, those plants slowly change the character of the system and create the opportunity for the next wave of plants to grow.

Relay floristics tend to occur more during the primary succession of bare ground, whereas initial floristics tend to prevail in established habitats that experience minor disturbances.

Application Ideas for Relay Floristics Model

- The type of architecture or planning project can determine which model might be most useful. A project that is starting from scratch or introducing a significant departure from the status quo may benefit from the relay model. This model may involve a larger input of resources and management, but it is orderly and direct.
- If a project is with a well-established client or is in a familiar area, the "initial floristic" model may be more relevant. It may take more time to arrive at a specific objective, but the potential to create a flexible team responsive to changing conditions could pay off in the long run.
- Strategically, blending both approaches would likely result in the most optimized team dynamics and the best use of resources.

Adaptive Characteristics Model of Succession

An adaptive characteristics model describes three strategic adaptations of plants: ruderal, competitor, and stress-tolerant types.

Ruderals are short-lived plants that allocate most of their energy into reproduction. Their seeds remain viable in the soil for long periods, which allows them to take advantage of random disturbances and other rapidly changing conditions. They spend little energy on resource gathering (root and shoot growth) because their ideal disturbed environments tend to have plentiful resources. They capture and hold nutrients by quickly generating lots of organic matter.

Competitors have an adaptive advantage in areas where disturbance is less frequent. They devote themselves to resource gathering, with reproduction a secondary priority. Rapid growth quickly converts available resources into body tissue, but very little energy goes into building longevity into those tissues. They store just enough energy and nutrients to get going the following year, quickly and aggressively consuming as much space as possible. This can exhaust resources.

As more resources are bound up, there are fewer readily available resources. Plants that grow rapidly are now at a disadvantage. Stress-tolerant plants are adapted to limited resources and invest much of their

notes

energy into self-maintenance and cooperative relationships. They can absorb and store nutrients when not growing and eventually replace competitors.

Application Ideas for Adaptive Characteristics Model

- A given system such as a building project will likely experience “pockets” of different conditions. Some aspects will have been recently disturbed, with others growing quickly, and others progressing slowly or struggling with limited resources.

Understanding the distribution of “pockets” and the circumstances surrounding them can help determine which individuals (based on personality type and professional experience) are best suited to move the project into the next phase.

glossary of terms

This glossary includes common words, phrases, and comparisons that we suggest may be useful in the Genius of Biome project. All are written from the perspective of biology, but can be extracted and applied to design and engineering.

3.8 billion years –
the amount of time life has been on Earth; the research and development period of life.

Abiotic –
not associated with or derived from living organisms. Abiotic factors in an environment include sunlight, temperature, wind patterns, and precipitation.

Arbuscule –
intricately branched, threadlike structures of fungi that penetrate plant root cells like a glove to trade nutrients in a symbiotic relationship.

Biodiversity –
the variety of life and its processes. It includes the variety of living organisms, the genetic differences among them, and the communities and ecosystems in which they occur.

Biologist at the Design Table (BaDT, pronounced "bat") –
a biologist uniquely adept at combing through nature's solutions and translating nature's strategies into strategies that effectively meet the needs of human challenges.

Biologize the design challenge –
take a human need or function and rephrase it so that an answer may be found in biology. For example, "How can I make the fabric red?" becomes "How is color created in the natural world?"

Biology to design –
the biomimicry approach to design that starts with discovering natural models and goes through the steps of abstracting the design principles, brainstorming potential applications, emulating nature's strategies, and evaluating the design against Life's Principles.

Biotic –
associated with or derived from living organisms. The biotic factors in an environment include the organisms themselves as well as such processes as predation, competition for food resources, and symbiotic relationships.

Bryophyte –
land plants that do not have true vascular tissues that transport water; mosses, liverworts and hornworts.

Challenge –
a specific issue or need that an organism faces, and a specific issue or need that humans face in their designs.

Design principle –
a deep principle from nature stated in non-biological terms.

Detritus –
non-living particulate organic material, including dead organisms and fecal material that act to decompose the material.

glossary of terms

Ecosystem –
a community of organisms and its nonliving, physical environment; a dynamic complex of plant, animal, fungal, and microorganism communities and their associated non-living environment interacting as an ecological unit.

Ecosystem engineer –
any organism that creates or modifies habitats by either mechanically changing materials from one form to another, as beavers do, or by modifying themselves, such as trees that create habitat for other living things.

Ecosystem services –
benefits to humans from a multitude of resources and processes that are supplied by natural ecosystems, such as clean drinking water and processes such as the decomposition of wastes. Ecosystem services are divided into four broad categories: provisioning, such as the production of food and water; regulating, such as the control of climate and disease; supporting, such as nutrient cycles and crop pollination; and cultural, such as spiritual and recreational benefits.

Ecosystem structure –
the physical patterns of life forms at all scales from the individual physiognomy of an organism to the vertical layers of vegetation to the horizontal distribution across the landscape.

Ecotone –
a transition area between two adjacent but different patches of landscape, such as forest and grassland.

Emulate –
to mimic deep patterns or principles rather than directly copy them.

Food web –
the complex network of interactions among species observed in nature that represent food relationships such as herbivory and predation.

Function –
the action for which an organism is specifically fitted or used, or for which a thing exists; purpose. The mode of action by which something fulfills its purpose. Also in generalized application, as contrasted with structure.

Functional taxonomy –
a function-based organization scheme exploring how organisms meet different challenges. Information on AskNature.org is organized by this taxonomy, also called the Biomimicry Taxonomy.

Habitat –
the natural environment or place where an organism, population, or species lives.

Key slow variable –
a crucial, key element involved in a gradual change occurring in an ecosystem. The element can either act as a driver in the functioning of a system, or be involved in a process that produces a negative outcome such as the gradual rise in the salt-water table to the surface in agricultural lands. Some examples of slow variables include climate, land use, nutrient stocks, human values, and policies. Slow variables are difficult to track and detect and usually only recognized after a threshold has been crossed and large-scale ecological and social changes have occurred.

Keystone species –
a species that has a disproportionate effect on its environment relative to its biomass. Such species play a critical role in maintaining the structure of an ecological community, affecting many other organisms in an ecosystem and helping to determine the types and numbers of various other species in the community.

Life, nature –
interchangeable terms referring to biota and the community and ecosystems in which it lives.

Life's Principles –
a set of patterns exhibited by life that contributes to life's ability to survive and thrive.

Nature as model, measure, mentor –

- **Model** – applying, imitating or taking inspiration from nature's designs and processes to solve human problems.
- **Measure** – using an ecological standard to judge the "rightness" of our innovations.
- **Mentor** – valuing nature for what we can learn from it and not for what we can extract from it.

Niche –
the functional role of a species within a community, dependent on the organism's structural adaptations, physiological responses, and behavior.

glossary of terms

Pattern –
a reoccurring form, strategy, or principle. Also, an example or model to be imitated or emulated.

Principle –
a fundamental source from which something proceeds; a primary element, force, or law which produces or determines particular results; the ultimate basis upon which the existence of something depends; cause.

Shifting mosaic habitat –
the theory that landscapes change and fluctuate, and are dynamic in nature.

Strategy –
a behavior or set of behaviors or solutions used by an individual to deal with an important life history challenge such as acquiring water, accommodating growth, managing disturbance, rearing young, or obtaining food.

Sustainability –
the intention and ability to continue the economic, social, institutional, and environmental aspects of human society while meetings the needs of the present without compromising the ability of future generations to meet their own needs.

Symbiotic –
an intimate relationship between two or more organisms of different species. The symbiotic relationship may be categorized as mutualistic (in which each organism benefits from the relationship), commensal (in which one organism benefits from the relationship but the other organism neither benefits nor is harmed), or parasitic (in which one organism benefits at the expense of the other).

scientific references

WATER

TEMPERATE BROADLEAF FOREST

Arthus-Bertrand, Y. [video] Of Forests and Men. 2011, The International Year of Forests. Yves Rocher Foundation. http://www.offorestsandmen.org/ and http://bit.ly/mBURSW

Biome map authority. Accessed February 28, 2011. October 9, 2010. http://commons.wikimedia.org/wiki/File:Vegetation.png

Hassan R; Scholes R: Ash N. 2005. Millennium ecosystem assessment. Volume 1. Ecosystems and human well-being. Washington: Island Press.

Olson DM; Dinerstein E; Wikramanayake ED; Burgess ND; Powell GVN; Underwood EC; D'amico JA; Itoua I; Strand HE; Morrison JC; Loucks CJ; Allnutt TF; Ricketts TH; Kura Y; Lamoreux JF; Wettengel WW; Hedao P; Kassem KR. 2001. Terrestrial ecosystems of the world: a new map of life on earth. BioScience 51(11): 933-938.

Olson DM; Dinerstein E. 2002. The global 200: priority ecoregions for global conservation. Annals of the Missouri Botanical Garden 89(2): 199-224.

Wikipedia contributors. Biome [Internet]. Wikipedia, The Free Encyclopedia; 2011 February 28, 12:00 MST [cited 2011 Apr 01]. Available from: http://en.wikipedia.org/w/index.php?title=Biome&oldid=421074614

MINIMIZE EROSION • VEGETATION

D'Odorico P; Laio F; Porporato A; Ridolfi L; Rinaldo A; Rodriguez-Iturbe I. 2010. Ecohydrology of terrestrial ecosystems. BioScience 60(11): 898-907.

Neary DG; Ice GG; Jackson CR. 2009. Linkages between forest soils and water quality and quantity. Forest Ecology and Management 258: 2269–2281.

Schaetzl RJ; Johnson DL; Burns SF; Small TW. 1989. Tree uprooting: review of terminology, process, and environmental implications. Canadian Journal of Forestry Research 19: 1-11.

MINIMIZE EROSION • BEAVERS

Hay DL; Philippi NS. 1995. Flood reduction through wetland restoration: the Upper Mississippi River Basin as a case study. Restoration Ecology 3(1): 4-17.

Johnston CA; Naiman RJ. 1987. Boundary dynamics at the aquatic-terrestrial interface: the influence of beaver and geomorphology. Landscape Ecology 1(1): 47-57.

Naiman RJ; Johnston CA; Kelley JC. 1988. Alteration of North American streams by beaver. BioScience 38(11): 753-762.

MINIMIZE NEGATIVE IMPACTS OF RAIN WATER • LICHEN

Gerson U. 1973. Lichen-arthropod associations. Lichenologist 5: 434-443.

Henderson A; Hackett DJ. 1986. Lichen and algal camouflage and dispersal in the Psocid nymph Trichadenotecnum fasciatum. Lichenologist 18(2): 199-200.

scientific references

Shirtcliffe NJ; Pyatt FB; Newton MI; McHale G. 2006. A lichen protected by a super-hydrophobic and breathable structure. Journal of Plant Physiology 163: 1193—1197.

OPTIMIZE WATER RESOURCES • RIVERS

Allan, J.D. 1995. Stream ecology: structure and function of running waters. Chapman & Hall, London. 388 pp.

Driessen, P.M., and Dudal, R. eds. 1991. Lecture notes on the major soils of the world. Produced by National Resources Management and Environment Department. FAO Corporate Document Repository. http://www.fao.org/DOCREP/003/Y1899E/y1899e07.htm

Wikipedia contributors. Meander [Internet]. Wikipedia, The Free Encyclopedia; 2011 Apr 11, 16:49 UTC [cited 2011 Apr 29]. Available from: http://en.wikipedia.org/w/index.php?title=Meander&oldid=423537334

DEHUMIDIFY IN SUMMER • BRYOPHYTES

Cornelissen JHC; Lang SI; Soudzilovskaia NA; During HJ. 2007. Comparative cryptogam ecology: a review of bryophyte and lichen traits that drive biogeochemistry. Annals of Botany 99: 987-1001.

Glime JM. 2007. Bryophyte Ecology. Volume 1. Physiological Ecology. Ebook sponsored by Michigan Technological University and the International Association of Bryologists. Accessed on February 21, 2011 at http://www.bryoecol.mtu.edu/.

Lindo Z; Gonzalez A. 2010. The bryosphere: an integral and influential component of the earth's biosphere. Ecosystems 13: 612-627.

ENERGY

ADJUST TO TEMPERATURE CHANGE • LEAVES

Lawson, T. 2008. Guard cell photosynthesis and stomatal function. New Phytologist 181: 13-34.

Outlaw, WH. Jr. 2010. Integration of cellular and physiological functions of guard cells. Critical Reviews in Plant Sciences 22(6): 503-529.

ADJUST TO TEMPERATURE CHANGE • TREES

Bonan GB. 2008. Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320: 1444-1449.

Dawson TE. 1993. Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. Oecologia 95: 565-574.

Humidity Provinces. http://commons.wikimedia.org/wiki/Media:Lifezones_Pengo.svg
Life zone. Wikipedia contributors. Life zone [Internet]. Wikipedia, The Free Encyclopedia; 2011 Feb 21, 13:43 UTC [cited 2011 Mar 30]. Available from: http://en.wikipedia.org/w/index.php?title=Life_zone&oldid=415129074.

Imhoff ML; Zhang P; Wolfe RE; Bounoua L. 2010. Remote sensing of the urban heat island effect across biomes in the continental USA. Remote Sensing of Environment 114: 504–513.

Savage VM; Bentley LP; Enquist BJ; Sperry JS; Smith DD; Reich PB; von Allmen EI. 2010. Hydraulic trade-offs and space filling enable better predictions of vascular structure and function in plants. PNAS 107(52): 22722-22727.

RESPOND TO SEASONAL CHANGE • PLANTS AND ANIMALS I

Carey HV; Andrews MT; Martin SL. 2003. Mammalian hibernation: cellular and molecular responses to depressed metabolism and low temperatures. Physiological Reviews 83(4): 1153-1181.

Morell M. 2001. The fragile world of frogs. National Geographic. 199(5): 106-23.

Shuker KPN. 2001. The hidden powers of animals: uncovering the secrets of nature. London: Marshall Editions Ltd. 240 p.

scientific references

RESPOND TO SEASONAL CHANGE • ANIMALS

Davenport, J., O'Halloran, J., Hannah, F., McLaughlin, O. and Smiddy, P. 2009. Comparison of plumages of white-throated dipper Cinclus cinclus and blackbird Turdus merula. Waterbirds 32(1):169-178.

Morrison, S.F., Forbes, G.J., Young, S.J., and Lusk, S. 2003. Within-yard habitat use by white-tailed deer at varying winter severity. Forest Ecology and Management. 172(2-3):173-182.

RESPOND TO SEASONAL CHANGE • PLANTS AND ANIMALS II

Wikipedia: Hibernation: http://en.wikipedia.org/wiki/Hibernation

Wildlife Online: European Hedgehog Erinaceus europaeus: http://www.wildlifeonline.me.uk/hedgehogs.html

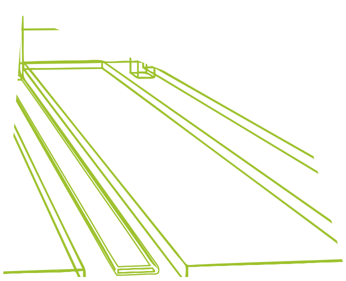
Winter: http://en.wikipedia.org/wiki/Winter

OPTIMIZE LIGHT • TREES

Jackson LWR. 1967. Effects of shade on leaf structure of deciduous tree species. Ecology 48(3): 498–499.

Sack L; Melcher PJ; Liu WH; Middleton E; Pardee T. 2006. How strong is intracanopy leaf plasticity in temperate deciduous trees? American Journal of Botany 93(6): 829–839.

Vogel S. 2009. Leaves in the lowest and highest winds: temperature, force and shape. New Phytologist 183: 13–26.



MATERIALS

REDUCE EMBODIED ENERGY • PAPER WASPS

Hansell MH. 1996. Wasps make nests: nests make conditions. Pages 272-289 In: Turillazzi S; West-Eberhard MJ, editors. Natural History and Evolution of Paper-Wasps. Oxford: Oxford Science Publications.

Jeanne RL. 1975. The adaptiveness of social wasp nest architecture. The Quarterly Review of Biology 50(3): 267-287.

Kudo K; Yamane S; Yamamoto H. 1998. Physiological ecology of nest construction and protein flow in per-emergence of colonies of Polistes chinensis (Hymenoptera Vespidae): effects of rainfall and microclimates. Ethology, Ecology and Evolution. 10(2): 171-183.

McGovern JN; Jeanne RL; Effland MJ. 1988. The nature of wasp nest paper. Tappi Journal 71(12): 133-139.

Singer TL; Espelie KE; Himmelsbach DS. 1992. Ultrastructural and chemical examination of paper and pedicel from laboratory and field nests of the social wasp Polistes metricus Say. Journal of Chemical Ecology 18(1): 77-86.

REGENERATE MATERIALS • EPHEMERAL HERBS

Blank JL; Olson RK; Vitousek PM. 1980. Nutrient uptake by a diverse spring ephemeral community. Oecologia 47: 96-98.

Constable JVH; Peffer BJ; DeNicola DM. 2007. Temporal and light-based changes in carbon uptake and storage in the spring ephemeral Podophyllum peltatum (Berberidaceae). Environmental and Experimental Botany 60: 112-120.

Muller RN; Bormann FH. 1976. Role of Erythronium americanum Ker. in energy flow and nutrient dynamics of a northern hardwood forest ecosystem. Science 193(4258): 1126-1128.

Teklela S. Spring Ephemerals. S. http://www.naturesmart.com/articles/04_16_04.htm

Wikipedia contributors. Ephemeral plant [Internet]. Wikipedia, The Free Encyclopedia; 2011 Mar 15, 10:33 UTC [cited 2011 Mar 30]. Available from: http://en.wikipedia.org/w/index.php?title=Ephemeral_plant&oldid=418934115.

scientific references

SOCIAL

FOSTER SOCIAL INTEGRATION • FUNGI

Falconer RE; Bown J; White N; Crawford J. 2011. Linking individual behavior to community scale patterns in fungi. Fungal Ecology 4: 76-82.

Hodge A; Helgason T; Fitter AH. 2010. Nutritional ecology of arbuscular mycorrhizal fungi. Fungal Ecology 3: 267-273.

Öpik M; Vanatoa A; Vanatoa E; Moora M; Davison J; Kalwij JM; Reier Ü; Zobel M. 2010. The online database MaarjAM reveals global and ecosystemic distribution patterns in arbuscular mycorrhizal fungi (Glomeromycota). New Phytologist 188: 223-241.

FOSTER SOCIAL INTERGRATION • POLLINATORS

Jacke D; Toensmeier E. 2005. Edible forest gardens, Volume 1. White River Junction, VT: Chelsea Green Publishing.

Mollison B. 1988. Permaculture: a designer's manual. 1988. Tyalgum, Australia: Tagari Publications.
Perry DA. 1994. Forest ecosystems. Baltimore, MD: Johns Hopkins University Press.

Wiki: http://en.wikipedia.org/wiki/Guild_%28ecology%29

DESIGN A WELL-FUNCTIONING SYSTEM • TREE COMMUNITY

Adaptive Cycles. http://www.resalliance.org/. Accessed February 2011.
Agrawal A; Stephenson SL. 1995. Recent successional changes in a former chestnut-dominated forest in Southwestern Virginia. Castanea 160(2): 107-113.

Wikipedia contributors. Chestnut blight [Internet]. Wikipedia, The Free Encyclopedia; 2011 Apr 4, 11:17 UTC [cited 2011 Apr 4]. Available from: http://en.wikipedia.org/w/index.php?title=Chestnut_blight&oldid=422299478.

Jackson RB. BIO 217 Ecology and Global Change. Duke University Biology Department [Online]. Avail from http://www.biology.duke.edu/bio217/2002/bmm10/blight.htm. Created April 2002.

DESIGN A WELL-FUNCTIONING SYSTEM • ECOTONES

Jacke D; Toensmeier E. 2005. Edible forest gardens, Volume 1. White River Junction, VT: Chelsea Green Publishing.

Oden EP. 1971. Fundamentals of ecology. Philadelphia: WB Saunders Co.

Wikipedia contributors. Ecotone [Internet]. Wikipedia, The Free Encyclopedia; 2011 Feb 17, 19:43 UTC [cited 2011 Apr 4]. Available from: http://en.wikipedia.org/w/index.php?title=Ecotone&oldid=414486013.

FOSTER COOPERATIVE RELATIONSHIPS • JAYS AND OAKS

Kubler J; Baumeister D; Klein R. 2009. Competition versus cooperation. Bioinspired Newsletter; April.
Baumeister D. Mechanisms of cooperation in nature. Personal interview February 2011.

Perry DA. 1994. Forest ecosystems. Baltimore, MD: Johns Hopkins University Press.

Wikipedia contributors. Mutualism (biology) [Internet]. Wikipedia, The Free Encyclopedia; 2011 Feb 28, 22:31 UTC [cited 2011 Apr 4]. Available from: http://en.wikipedia.org/w/index.php?title=Mutualism_(biology)&oldid=416453170.

ECONOMIC

USE RESOURCES EFFICIENTLY • ECOSYSTEMS

Bormann FH; Likens GE. 1979. Pattern and process in a forested ecosystem. New York: Springer-Verlag.

Botkin DB. 1993. Forest dynamics: an ecological model. New York: Oxford University Press.

Jacke D; Toensmeier E. 2001. Edible forest gardens, Volume 1. White River Junction, VT: Chelsea Green Publishing.

Luken JO. 1990. Directing ecological succession. New York: Chapman and Hall.

Perry DA. 1994. Forest ecosystems. Baltimore, MD: Johns Hopkins University Press.

Pickett STA; McDonnell MJ. 1989. Changing perspectives in community dynamics: a theory of successional forces. Trends in Ecology and Evolution 4: 241-245.

Pickett STA; Collins SL; Armesto JJ. 1987. Models, mechanisms and pathways of succession. The Botanical Reviews 53(3): 336-71.

Pickett STA; White PS. eds. 1985. The ecology of natural disturbance and patch dynamics. New York: Academic Press.

CREATE SYSTEM STABILITY • FORESTS

Duryea M; Kampf E. 2007. Wind and trees: lessons learned from hurricanes. Report FOR 118, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Available from http://edis.ifas.ufl.edu/fr173

Foster DR; Boose ER. 1992. Patterns of forest damage resulting from catastrophic wind in central New England, USA. Journal of Ecology 80(1): 79-98.

Mattheck C. 1998. Design in nature: learning from trees. Berlin: Springer-Verlag. 276 p.

Merry K; Bettinger P; Hepinstall J. 2009. Physical and biological responses of forests to tropical cyclones affecting the United States Atlantic Ocean and Gulf of Mexico coasts. American Journal of Environmental Sciences 5(1): 784-800.

Peterson CJ. 2000. Catastrophic wind damage to North American forests and the potential impact of climate change. The Science of the Total Environment 262: 287-311.

Schaetzl RJ; Johnson DL; Burns SF; Small TW. 1989. Tree uprooting: review of terminology, process, and environmental implications. Canadian Journal of Forestry Research 19: 1-11.

CREATE SUSTAINABLE VALUE • ORGANIC SOIL

Brady, NC. The nature and property of soils, 8th edition. 1974. New York: Macmillan Co.

Jacke, D., Toensmeier, E. Edible Forest Gardens, Volume 1. 2005. White River Junction, VT: Chelsea Green Publishing.

Smith, Smith. Elements of Ecology, 7th edition. 2009. Upper Saddle River, NJ: Pearson Education, Inc.

photography terms of use

Stock Photographs (indicated by Image ID number)
Shutterstock.com photographs appearing in this report are licensed for use by HOK only. To purchase Shutterstock photographs, please visit shutterstock.com and read their **terms of service** before use.

Architectural Renderings, Plans and Photographs (indicated by page number)
Architectural renderings, plans and photographs appearing in this report are intended to illustrate design ideas.

Creative Commons Photographs
Other photographs in this report are from the creative commons or the public domain.

GENIUS OF BIOME

BIOMES MAP
commons.wikimedia.org
Photograph by **Sten Porse**
Creative Commons **Attribution-Share Alike 3.0 Unported**

TEMPERATE BROADLEAF FOREST

Shutterstock.com
Image ID **77375050**

MINIMIZE EROSION • VEGETATION
Shutterstock.com
Image ID **37785349**

MINIMIZE EROSION • BEAVERS
Shutterstock.com
Image ID **810418**

MINIMIZE NEGATIVE IMPACTS OF RAIN WATER • LICHEN
flickr.com
Photograph by **Jason Hollinger**
Creative Commons **Attribution-ShareAlike 2.0 Generic**

OPTIMIZE WATER RESOURCES • RIVERS
Shutterstock.com
Image ID **70869514**

DEHUMIDIFY IN SUMMER • BRYOPHYTES
Shutterstock.com
Image ID **35170522**

ADJUST TO TEMPERATURE CHANGE • LEAVES
Shutterstock.com
Image ID **20219**

ADJUST TO TEMPERATURE CHANGE • TREES
Shutterstock.com
Image ID **31162285**

RESPOND TO SEASONAL CHANGE • PLANTS AND ANIMALS I
Shutterstock.com
Image ID **72262678**

RESPOND TO SEASONAL CHANGE • ANIMALS
Shutterstock.com
Image ID **26071756**

RESPOND TO SEASONAL CHANGE • PLANTS AND ANIMALS II
Shutterstock.com
Image ID **49700137**

OPTIMIZE LIGHT • TREES
Shutterstock.com
Image ID **62486344**

REDUCE EMBODIED ENERGY • PAPER WASPS
Shutterstock.com
Image ID **37899781**

REGENERATE MATERIALS • EPHEMERAL HERBS
Shutterstock.com
Image ID **1434369**

FOSTER SOCIAL INTEGRATION • FUNGI
commons.wikimedia.org
Photograph by **Msturmel**
Released into the **public domain**

FOSTER SOCIAL INTERGRATION • POLLINATORS
Shutterstock.com
Image ID **16923802**

DESIGN A WELL-FUNCTIONING SYSTEM • TREE COMMUNITY
Shutterstock.com
Image ID **19692841**

DESIGN A WELL-FUNCTIONING SYSTEM • ECOTONES
Shutterstock.com
Image ID **9221323**

FOSTER COOPERATIVE RELATIONSHIPS • JAYS AND OAKS
Shutterstock.com
Image ID **65688595**

USE RESOURCES EFFICIENTLY • ECOSYSTEMS
Shutterstock.com
Image ID **69516439**

CREATE SYSTEM STABILITY • FORESTS
Shutterstock.com
Image ID **62698858**

CREATE SUSTAINABLE VALUE • ORGANIC SOIL
Shutterstock.com
Image ID **74474260**

MINIMIZE EROSION • VEGETATION
HOK
Architectural Renderings **Page 33**

MINIMIZE EROSION • BEAVERS
HOK
Architectural Rendering **Page 39**

OPTIMIZE WATER RESOURCES • RIVERS
HOK
Architectural Plan **Page 51**

OPTIMIZE WATER RESOURCES • RIVERS
Alan Karchmer Architectural Photographer
Architectural Images **Page 51**

OPTIMIZED LIGHT • TREES
HOK
Architectural Plan and Rendering **Page 95**

REDUCED EMBODIED ENERGY • PAPER WASPS
HOK
Architectural Rendering **Page 103**

DESIGN A WELL-FUNCTIONING SYSTEM • ECOTONES
HOK
Architectural Plan and Renderings **Page 135**

CREATE SYSTEM STABILITY • FORESTS
HOK
Architectural Renderings **Page 155**

CREATE SUSTAINABLE VAUE • ORGANIC SOIL
HOK
Architectural Renderings **Page 161**

We thank the dozens of biologists and design professionals who contributed to this report, including Andrea Leggitt, Jessica Jones, Robyn Klein, Rose Tocke, Sherry Ritter, and Taryn Mead from Biomimicry 3.8 and Blake Gallagher, Bokki Son, Brett Leonhardt, Carolina Simon, Derek Prior, Mary Ann Lazarus, May Xu, Shashi Narayanan, Thomas Knittel, and Tyler Meyr from HOK.

Contact

For more information regarding the content of this report, please contact:

Thomas Knittel, AIA
HOK
+1 206 493 1773
thomas.knittel@hok.com
1218 Third Avenue, Suite 1315
Seattle, WA 98101 USA

Jamie Dwyer
Biomimicry 3.8 (a dba of Biomimicry Group, Inc.)
+1 406 543 4108
jamie.dwyer@biomimicry.net
PO Box 9216
Missoula, MT 59807 USA