Design Concepts Learned from **Pacific Northwest Forests**

seedkit

55-5 Consulting RUSHING URBAN greenPRINT

What can our cities become?

Illustration by Stefano Boeri Architetti, 2015

When we imagine our ideal city 50 years from now, what do we imagine? What do we see and hear? What kind of city do we want to walk through with our grandchildren?

Regardless of background, most people agree that fresh air, clean water, birds singing, trees and flowers — healthy abundant nature —is fundamental.

“Look deep into nature, and then you will understand everything better.”

- Albert Einstein

We know this vision of a city, replete with vibrant nature, is possible.

What do we need to do to transform it into reality?

As we plan for this future, let's learn from Nature. What can nature tell us about how to design for place and how to bring health and balance to our city ecosystems?

biomimicry

How does nature do what it does?

and

How can we emulate those strategies in our own designs to be more sustainable?

One way to listen to Nature is through
the practice of Biomimicry.

In this practice, we shift our perspective from learning about nature to learning *from* nature. We become curious about what nature can teach us. We learn how organisms accomplish specific functions, abstract those principles into our own design language, and then mimic those functions in our products, forms and materials. Nature's wisdom can be observed at every scale—from organism to ecosystem—and it is applicable to any type of design thinking we can imagine.

URBAN
greenPRINT

The **Urban Greenprint** applies biomimicry to the built environment, learning from nature at an ecosystem scale and applying nature's strategies at a building scale.

Funded by the Bullitt Foundation and underway in Seattle, this project is taking lessons from nature about how the region's ecosystem functioned before urban development and applying that understanding to current building, infrastructure, and open space design. Research is being done in the areas of water flows, carbon flows, and biodiversity.

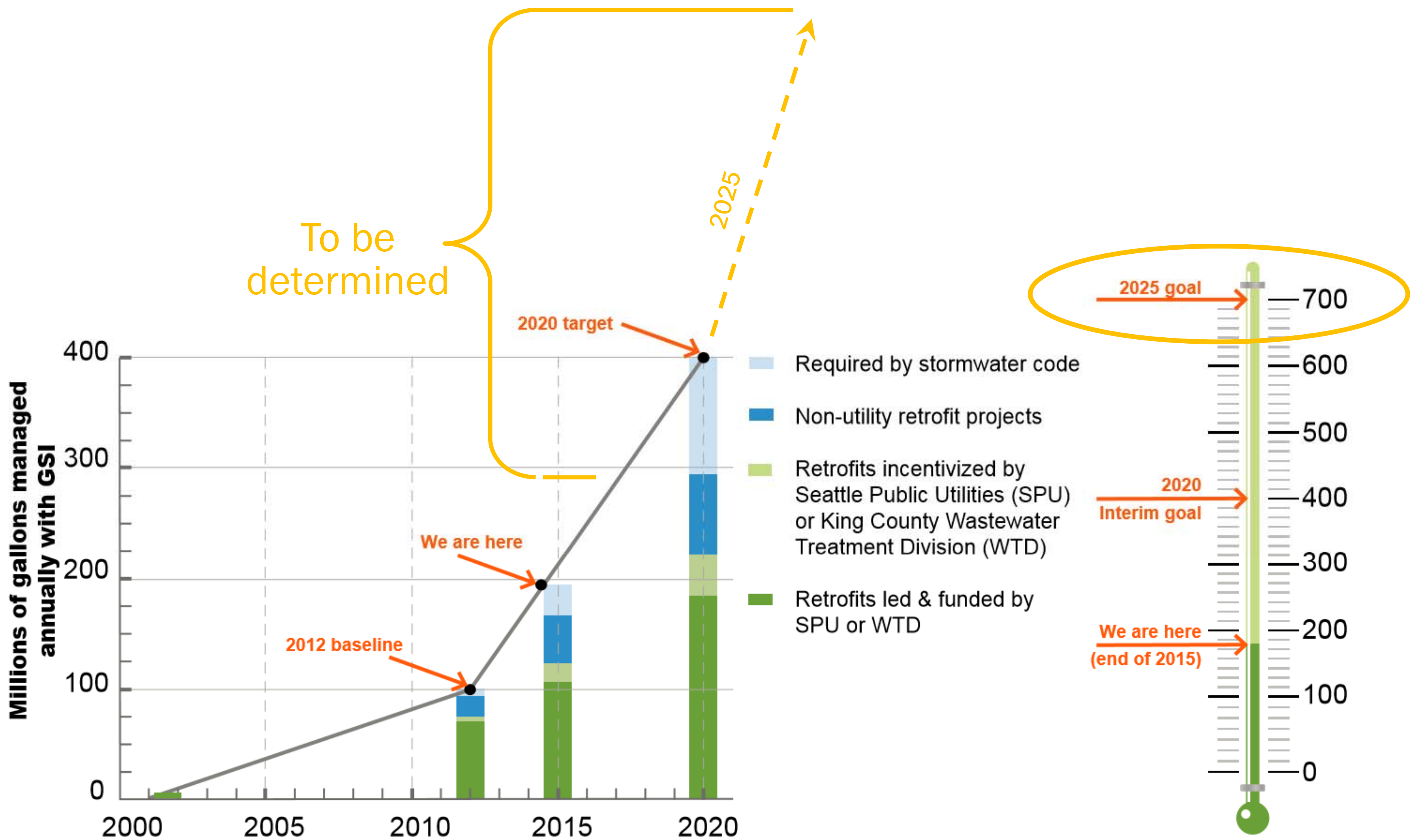
This SeedKit (v1) is part of the Urban Greenprint project. It explores strategies related to water flows, specifically related to **evaporation.**


17%
83%
0%
Photograph courtesy of Daniel Schwen, 2010

CURRENT

When it rains in developed areas of Puget Sound, the vast majority of that rainfall hits and runs across roofs or pavement into storm and sewer systems. In impervious areas, more than **4/5 of rainfall becomes runoff** (Beyerlein, 2012) **.** By the time the water has reached the storm or sewer conveyance systems, it has likely flowed across polluted surfaces, picking up oils, metals, and other pollutants on its way. In many parts of Puget Sound, this water goes directly into larger water bodies without being cleaned.

Polluted runoff is arguably Puget Sound's largest environmental problem.

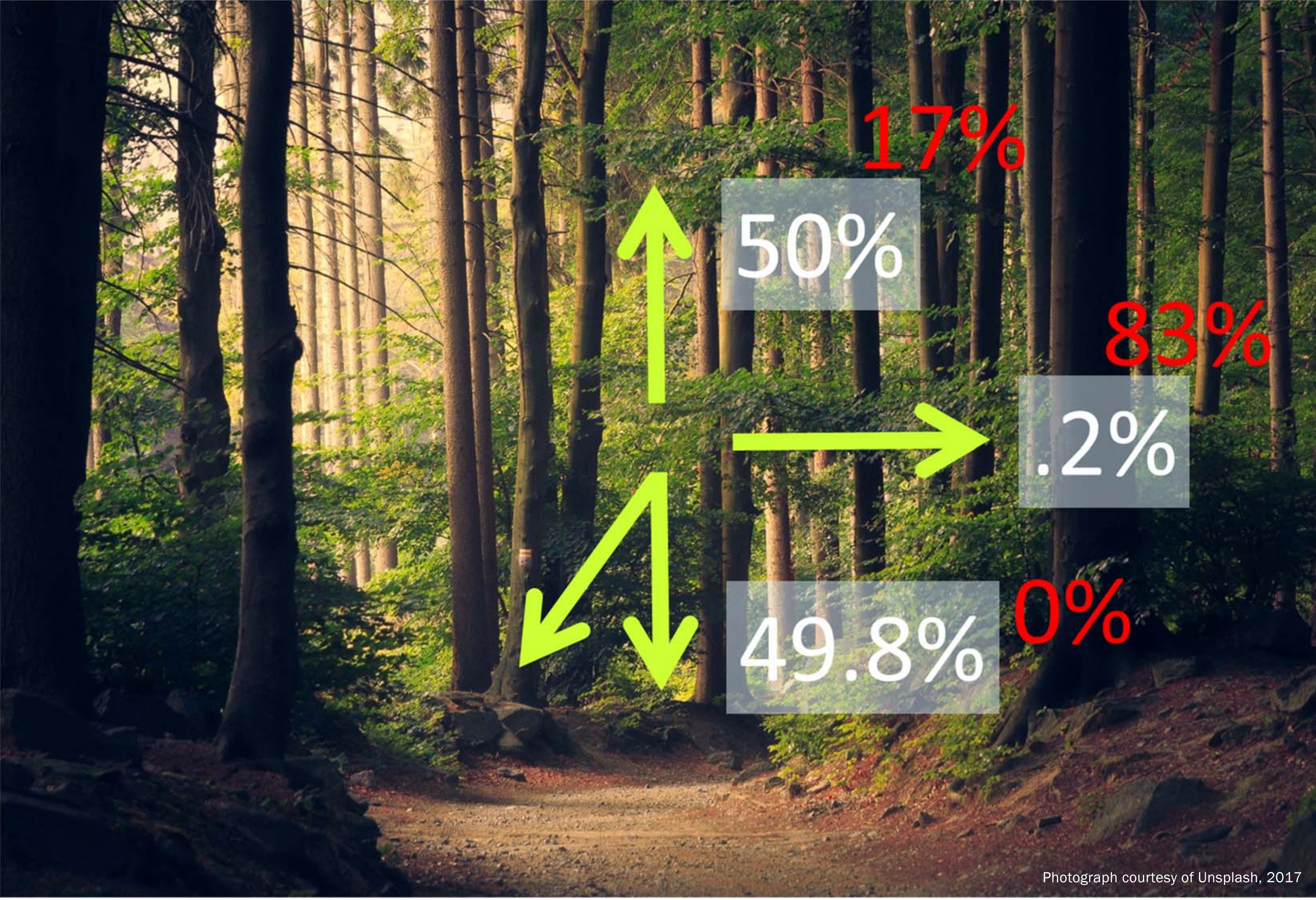


Graphic courtesy of SPU, 2016 - Orange graphics added for emphasis

To address the problem of polluted runoff, in 2013 the City of Seattle passed a resolution requiring the City's **Green Stormwater Infrastructure** to manage 700 million gallons of runoff by 2025 (SPU, 2015). Although the beneficial results of green infrastructure are increasing significantly, there is still a large "to be determined" gap to fill.

Green Infrastructure is incredibly important.
But it is not enough.

How will we close this gap?



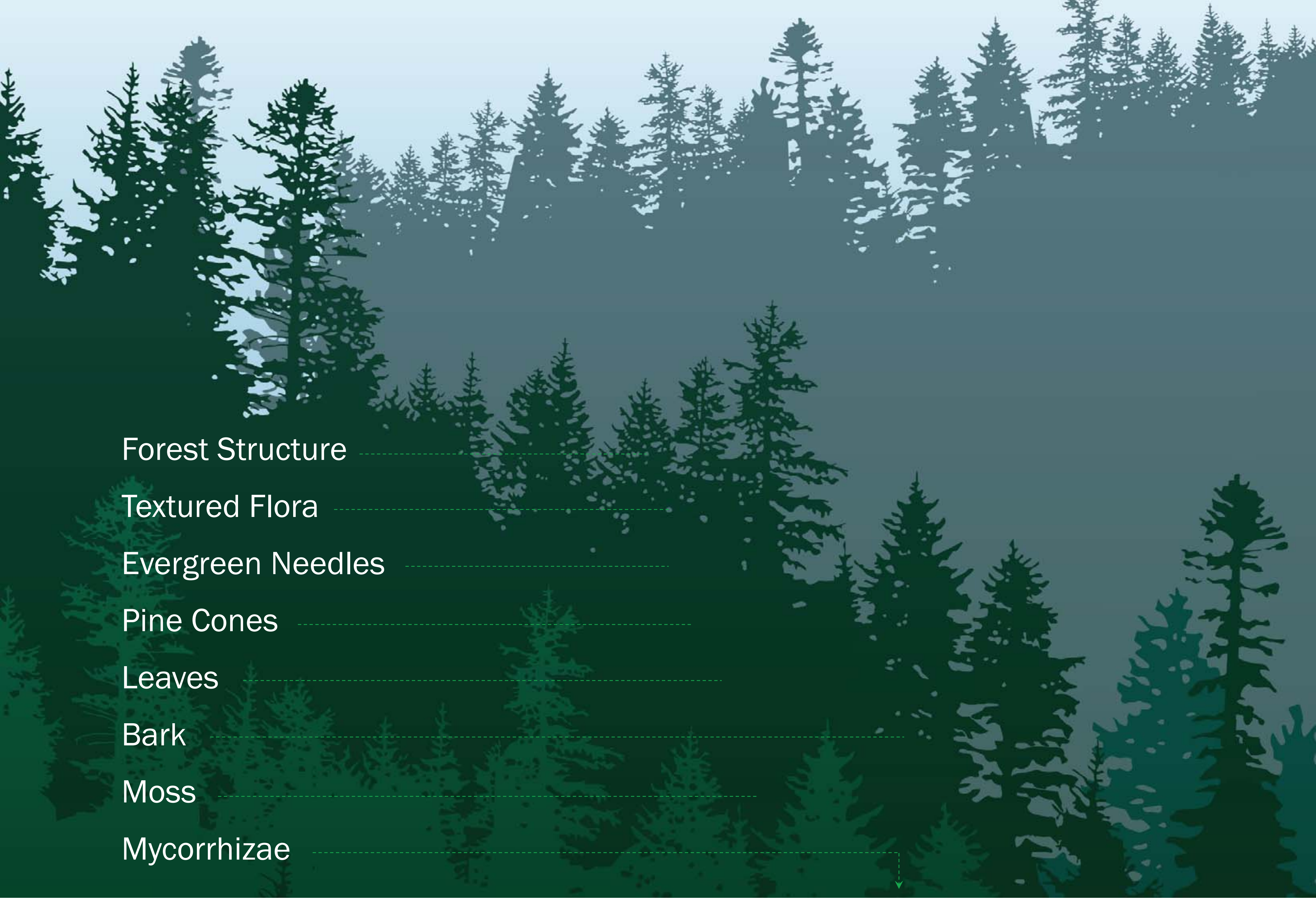
Photograph courtesy of Unsplash, 2017

PRE-DEVELOPMENT

Not surprisingly, when we look at pre-development conditions around Puget Sound, water flows were much different. In a native, healthy, Northwest forest, nearly half of rainfall infiltrates, a tiny amount runs off in large storm events, and a full **50% returns to the atmosphere** due to evaporation or plant transpiration (Beyerlein, 2012). Rather than concentrating our efforts to reduce polluted runoff by *cleaning* water, we might be better served by evaporating the water before it becomes polluted.

This leads us to the question:

How can we design our buildings & infrastructure to mimic the evaporation rate of the Northwest forest?


Forest Structure
Textured Flora
Evergreen Needles
Pine Cones
Leaves
Bark
Moss
Mycorrhizae

FOREST MENTORS

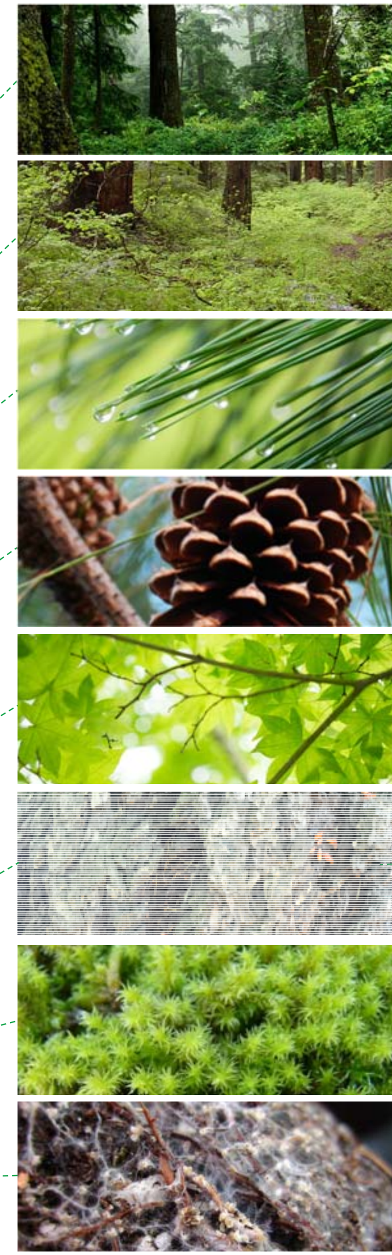
Nature is decentralized and redundant. Every process in nature, such as the process of evaporation in forests, occurs across multiple points in a system. In the native Northwest forests, textures that hold water, large surface areas, and absorptive qualities of surfaces all create favorable conditions for evaporation. These characteristics can be found throughout the system, from the top of the canopy down into the structure of the soil.

When considered in combination with general conditions that affect evaporation, such as air movement and time of exposure, these forest elements can be mentors for us to learn from. Their forms and processes suggest new strategies designers can employ to promote evaporation in the built environment.

DESIGN CONCEPTS

The design ideas on the following pages are inspired by forest mentors as new ways to promote evaporation. Perhaps more important than the concepts themselves is the inspiration they can generate for other strategies and applications appropriate for specific projects.

- Forest Structure
- Textured Flora
- Evergreen Needles
- Pine Cones
- Leaves
- Bark
- Moss
- Mycorrhizae



See following pages for photo credits

CONTENTS

METRICS

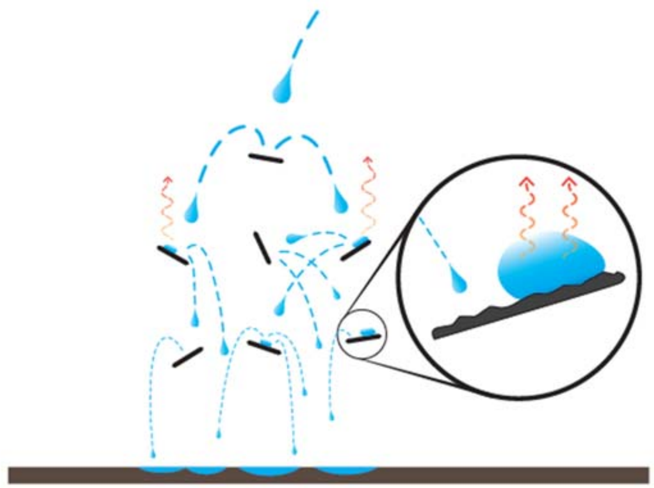
- A typical forest canopy in the Pacific Northwest can hold 264,000 ga/acre at one time, equivalent to 1-1/4” precipitation (Franklin et al., 1981).
- The canopy layers account for about 10-20% of annual interception loss in a typical Pacific Northwest forest (Allen, 2012). Interception loss is the amount of precipitation that does not reach the ground because of interception, pooling, and eventual evaporation.

Lesson for the Built Environment

How can a building mimic the forest’s layered canopy structure, slowing, dividing, and holding raindrops as they strike multiple surfaces at varying levels?

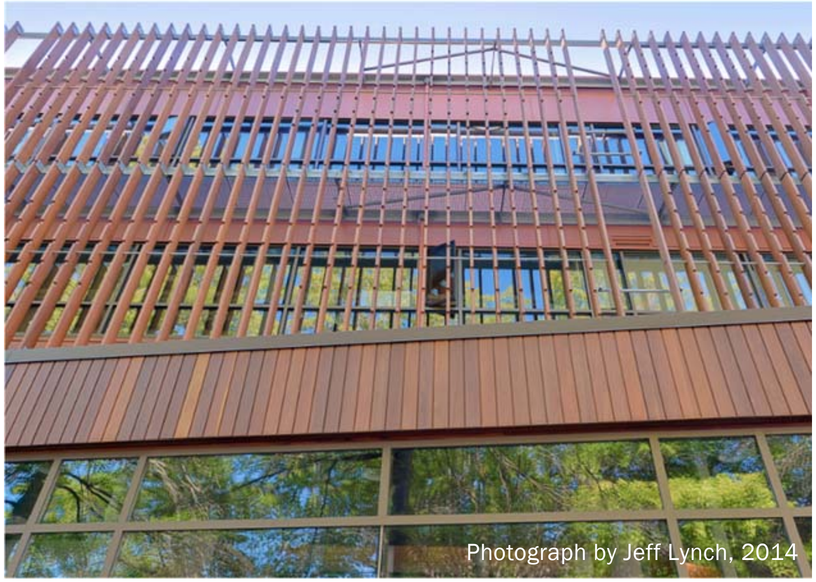
BIOLOGY

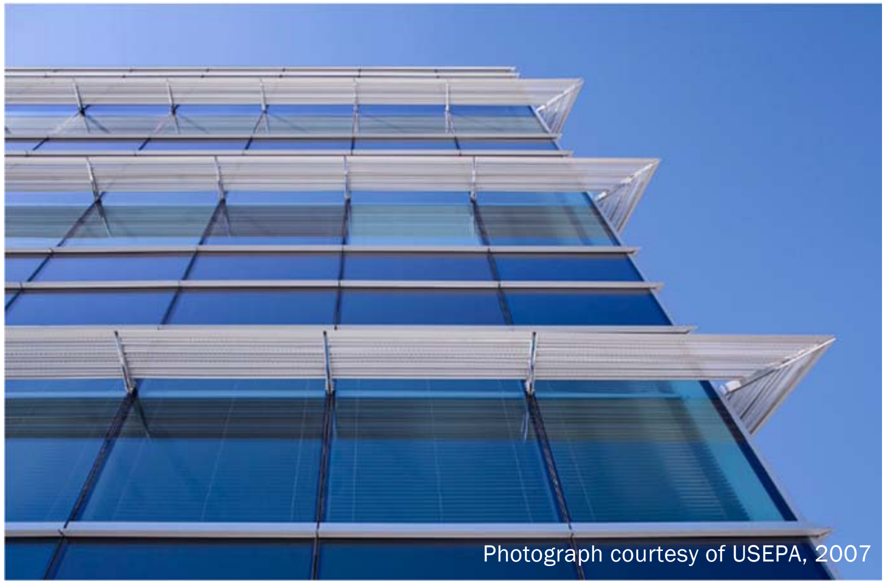
The structure of the Northwest forest is made up of thousands of staggered tiers of leaves, branches, bark, mosses, downed wood, lichens, bryophytes, and other organic elements. These create a complex, multi-layered canopy which serves to intercept, divide, slow, and hold rainwater, preventing it from ever striking the forest floor. The key layers of this structure include the emergent layer, canopy layer, subcanopy layer, shrubs, and the forest floor (Dawson, 2007). Each of these strata plays a part in breaking, holding, and intercepting raindrops.



FUNCTION: CASCADING SURFACES

Illustration by Biomimicry Oregon, 2013


Photograph by Jeff Lynch, 2014


Photograph courtesy of USEPA, 2007

What existing strategies can be modified?

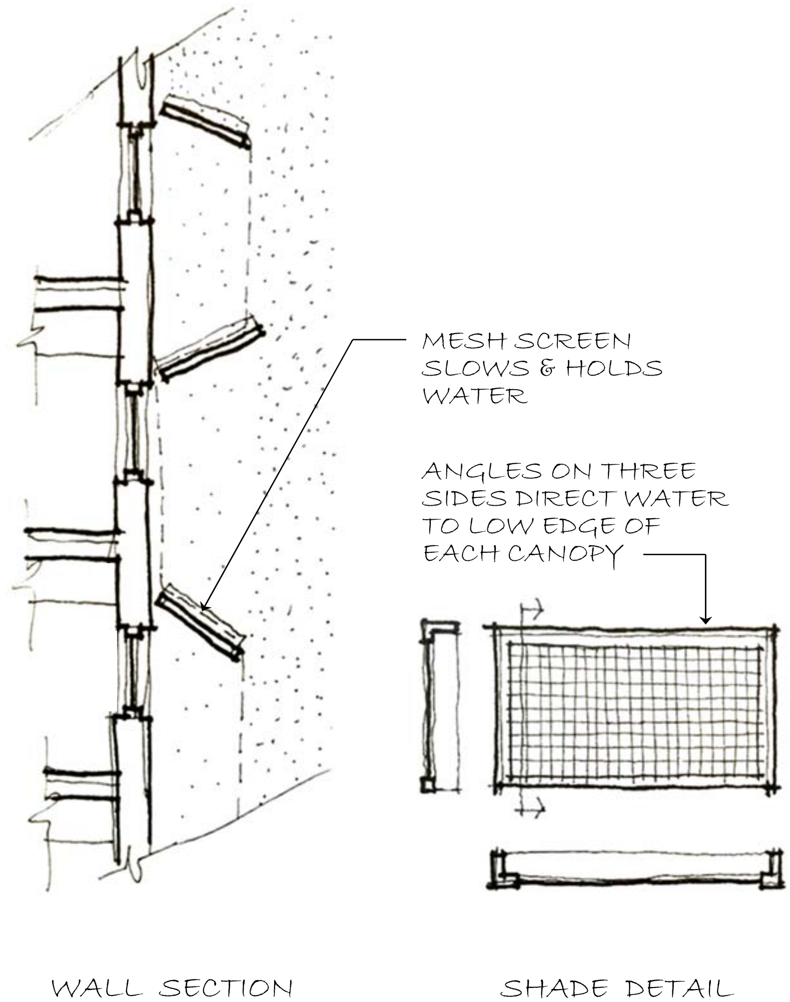
- Shading devices
- Canopies


Photograph courtesy of Alan Karchmer, 2013

Photograph courtesy of David Patte, 2010

APPLICATION OF NATURE'S FUNCTION

The forest's multiple canopy layers and their intercepting and slowing qualities can be mimicked in building design with the use of cascading shading devices. These layered forms will slow water flow, as well as shielding sunlight, increasing the opportunity for rainwater to evaporate before it reaches the ground level. A bioswale or landscaped planter at ground level can capture the water that would trickle off the last array of cascading canopies.

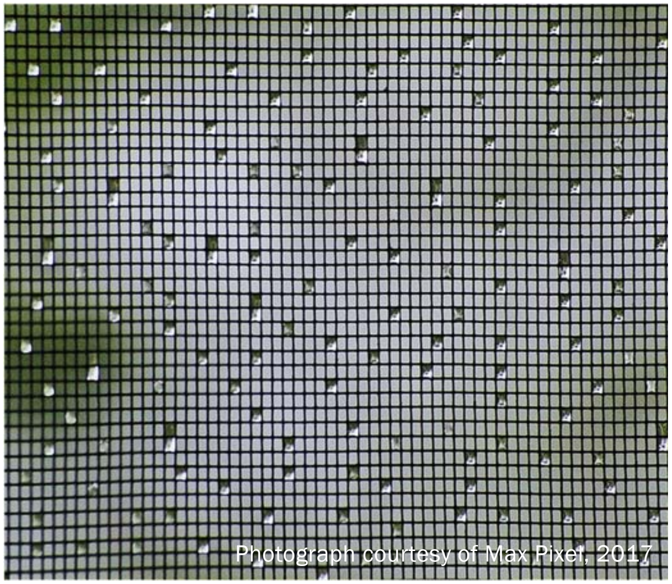


CASCADING SHADING DEVICES: RAIN/SUNSCREEN

Image by Jennifer Barnes, 2016

EXPLORATION & RESEARCH OPPORTUNITIES

1. Design Exploration
    a. What existing materials could be used to create cascading surfaces that slow water flow?
    b. How could shading devices be shaped or positioned for ideal flow of water from one to another?
    c. What's the best resolution for the water at ground level (bioswale planters, fountain, evaporation pool)?
2. Research/Experimentation
    a. How much water would a mesh material hold? How long would it be held in different weather conditions?
    b. How much would cascading shading devices improve evaporation? How much water would be diverted from hitting the ground?
3. Material/Product Development
    a. What kind of new materials could be used or developed for shading devices which would slow the water flow without causing mold growth or splashing?



What would facilitate product development for this strategy?

Textured Flora

METRICS

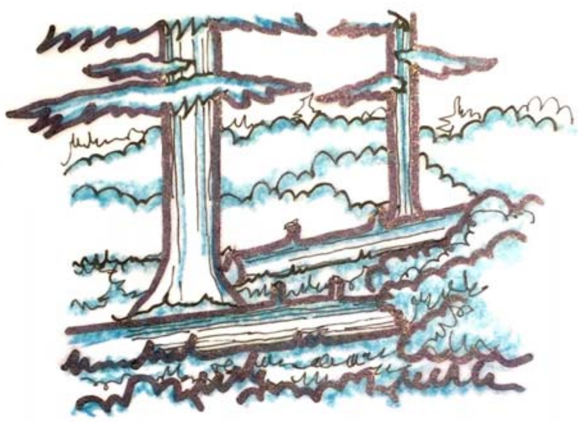
- Leaf and bark litter can absorb 150% of their dry weight in water (Pypker, 2004).
- Downed, rotting wood can collect 5% of a rainfall event (Pypker, 2004).
- Runoff is slight within a Pacific Northwest forest (0.2%) and occurs only in extremely heavy storm events (Beyerlein, 2012).

Lesson for the Built Environment

How can a building mimic the redundant, textured surfaces of the forest, slowing water as it descends from canopy to ground plane?

BIOLOGY

Northwest forests exhibit complex layers of varied surface textures. Thick vegetation is found from the canopy to the forest floor. Trees, shrubs, mosses, and lichen have year-round foliage and complex surface profiles, holding water on their surfaces for long periods of time, supporting a high incidence of evaporation.



FUNCTION: ABSORBING TEXTURES

Image by Jennifer Barnes, 2017


Photograph courtesy of G-02 Living Walls, 2015


Photograph by Alexandra Ramsden, 2008


Photograph courtesy of Max A, 2007

What existing strategies can be modified?

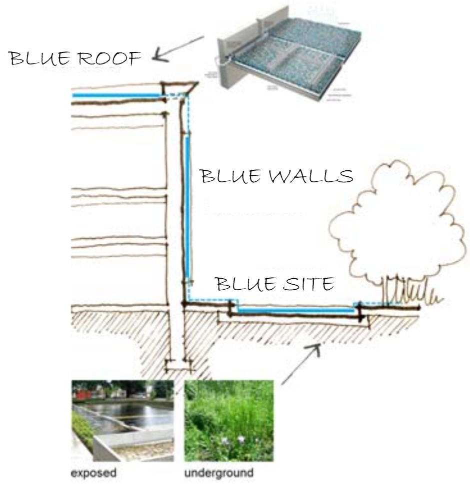
- Gutters & downspouts
- Living Walls


Photograph courtesy of T.R. Hamzah & Yeang, 2014

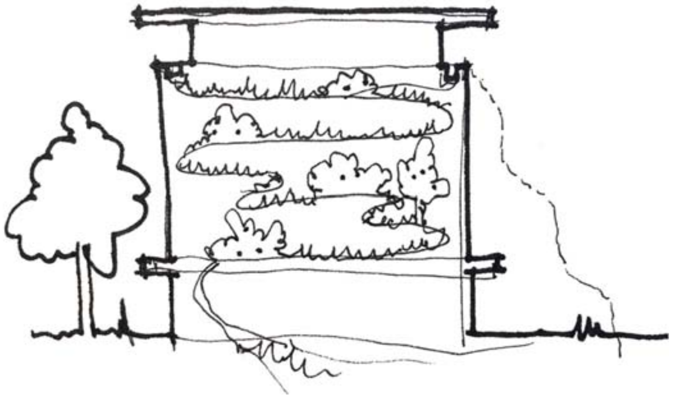
Photograph courtesy of Nickpdx, 2006

APPLICATION OF NATURE'S FUNCTION

Sculpted or vegetated gutters and downspouts, living walls, and wall surfaces can be designed to slow rainwater as it moves from the roof to the ground plane. Integrating stormwater strategies into the exterior design of the building will generate a unique aesthetic, whether planted or otherwise. When green or blue roofs link to textured surfaces on the walls which then connect with water strategies at the ground plane, the entire building envelope and site are conducive to evaporation.



1— BLUE ROOF - BLUE WALLS - BLUE SITE



2—MEANDERING DOWNSPOUT

Images by Jennifer Barnes, 2016

EXPLORATION & RESEARCH OPPORTUNITIES

1. Design Exploration
   a. What existing materials could be used to hold and slow water as it makes its way from the roof to the storm system that would not degrade the underlying materials?
   b. How could the wall surface undulate or step out and down incrementally to slow the path of water?
2. Research / Experimentation
   a. What type of vegetation or other absorptive media could be held purposefully in gutters, and how much water could be evaporated from each?
3. Material/Product Development
   a. What kinds of new gutters and downspouts could be developed to hold vegetation or to hold and slow water through modifications to its structure?
   b. What new materials could be developed to attach to existing surfaces that would slow water flow without encouraging mold growth or material degradation?

What would facilitate product development for this strategy?


Photograph courtesy of danna & curios tangles, 2013

Evergreen Needles

Photograph courtesy of Pippalou, 2013

METRICS

- Douglas fir trees within a "closed-canopy", or typical forest canopy, intercept an average of 26% of rainfall (Bixby, 2011).
- The interception rate of a stand-alone Douglas fir, with more needles available for the raindrops to strike, averages at 31% (Bixby, 2011).
- White pines, 60 years or older, intercept 3 times as much rainfall as mixed hardwood trees (Swank, 1968).

Lesson for the Built Environment

How can a building mimic evergreen needles by dividing, splashing, and holding onto rain droplets as they fall on the site?

BIOLOGY

Northwest forests are characterized by evergreens. Douglas fir are among the most common, and several species of pine, including the Lodgepole and White Bark Pines, are found in dry areas. One shared attribute of these trees is their needle-like leaves. Needles slow the path of raindrops by breaking them into smaller droplets, increasing opportunities for evaporation. When aggregated, needles also provide substantial surface area for droplets to suspend from. The water's surface tension causes them to cling to the needles, increasing evaporation time.

FUNCTION: SPLITTING & SUSPENDING DROPS

Image by Alexandra Ramsden, 2016

Evergreen Needles | Wire Sculpture


Photograph courtesy of Bs0u10e01, 2012


Photograph courtesy of Janelle, 2004

What existing strategies can be modified?

- Canopies/awnings
- Rooftop sculptures
- Amenity area screens
- Landscape features
- Mechanical enclosures


Photograph courtesy of Arnoldius, 2011

Photograph courtesy of Pippalou, 2013

APPLICATION OF NATURE'S FUNCTION

The splitting and suspending functions of evergreen needles of Pacific Northwest forests can be mimicked with sculptural elements and canopies made of mesh. This material would serve a similar function of breaking and splashing raindrops as they hit the surface, enhancing evaporation and preventing the full water volume from reaching the ground.

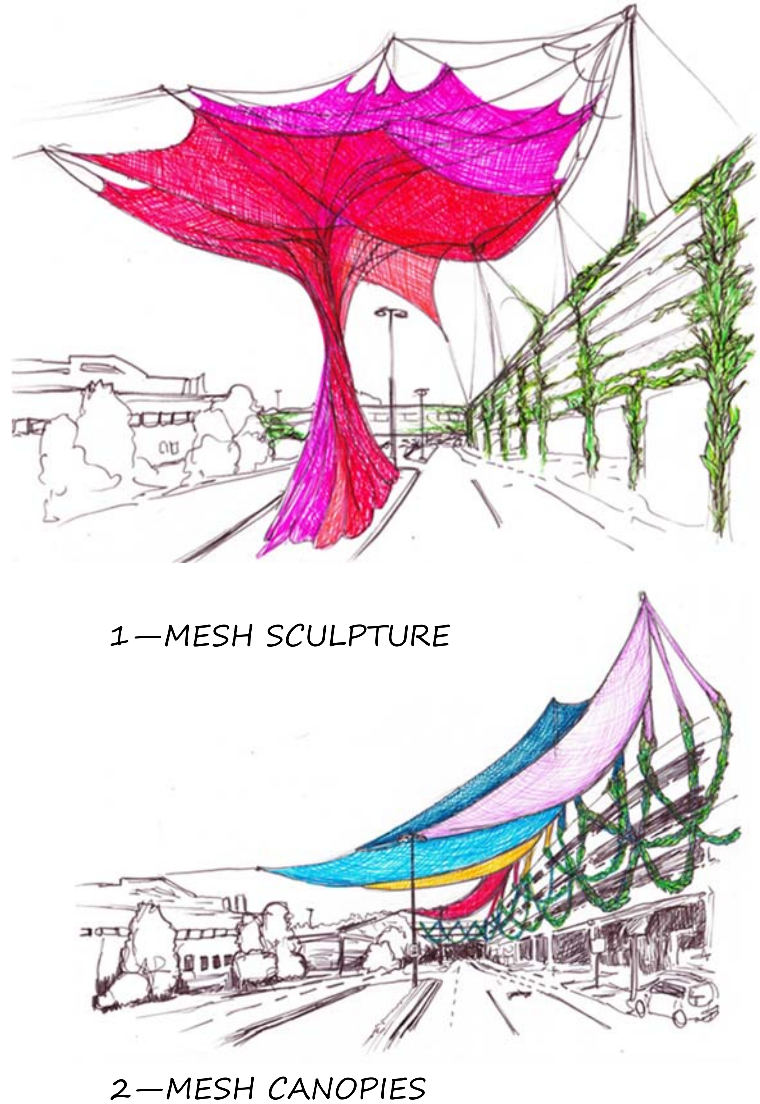


Image by Tim McGee, 2015

EXPLORATION & RESEARCH OPPORTUNITIES

1. Design Exploration
   a. How can we change the way we design rooftops to break up raindrops before they begin their path towards the ground?
2. Experimentation
   a. How do water droplets stick to materials?
   b. How much can evaporation be increased by breaking and splashing raindrops?
3. Material/Product Development
   a. What materials cause water droplets to stick to them?
   b. Is there a new type of canopy material which could be developed to divide/aerate raindrops?


Photograph courtesy of Jorge Royan, 2007

What would facilitate product development for this strategy?

Conifer Cones


Photograph courtesy of Pippalou, 2014

METRICS

- About 86 percent of Washington's forests (19 million acres) are softwood conifer forest types (Campbell et al., 2010).
- These conifers include four types: Douglas-fir, fir/spruce/mountain hemlock, western hemlock/sitka spruce, and ponderosa pine (Campbell et al., 2010).

Lesson for the Built Environment

How can buildings mimic conifer cones by responding to moisture in order to slow, pool and/or make better use of the water which falls on a site?

BIOLOGY

Cones, pine and evergreen, are plentiful in Pacific Northwest forests. In order to protect and release their seeds at the right time, cones open and close. This action is prompted by the level of moisture in the air.

Each spine of a pine cone is made up of two layers, and each of those layers is structurally different. When it gets wet, the spines' outer layers elongate more than the inner layers, and the spines close in on themselves, narrowing the shape of the entire cone (Chen, 2015).

Because of this, pine cones are seen as indicators of forest fire potential. If the cones on a forest floor are all open, it means the forest is dry and the fire danger is high.

FUNCTION: DYNAMIC RESPONSE TO MOISTURE

Photographs courtesy of Fieryn, 2005, Wunee, 2014

Conifer Cones | Moisture Responsive Cladding


Photograph courtesy of Eleckhh, 2010

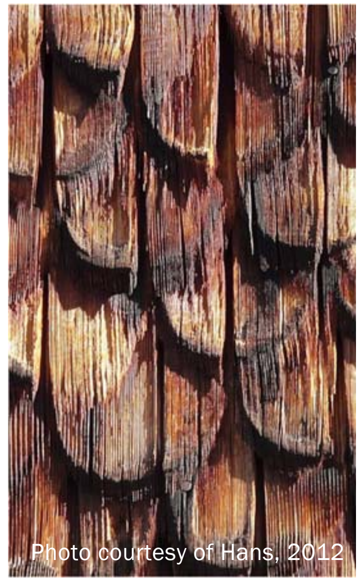


Photo courtesy of Hans, 2012


Photograph courtesy of NordNordWest, 2013

What existing strategies can be modified?

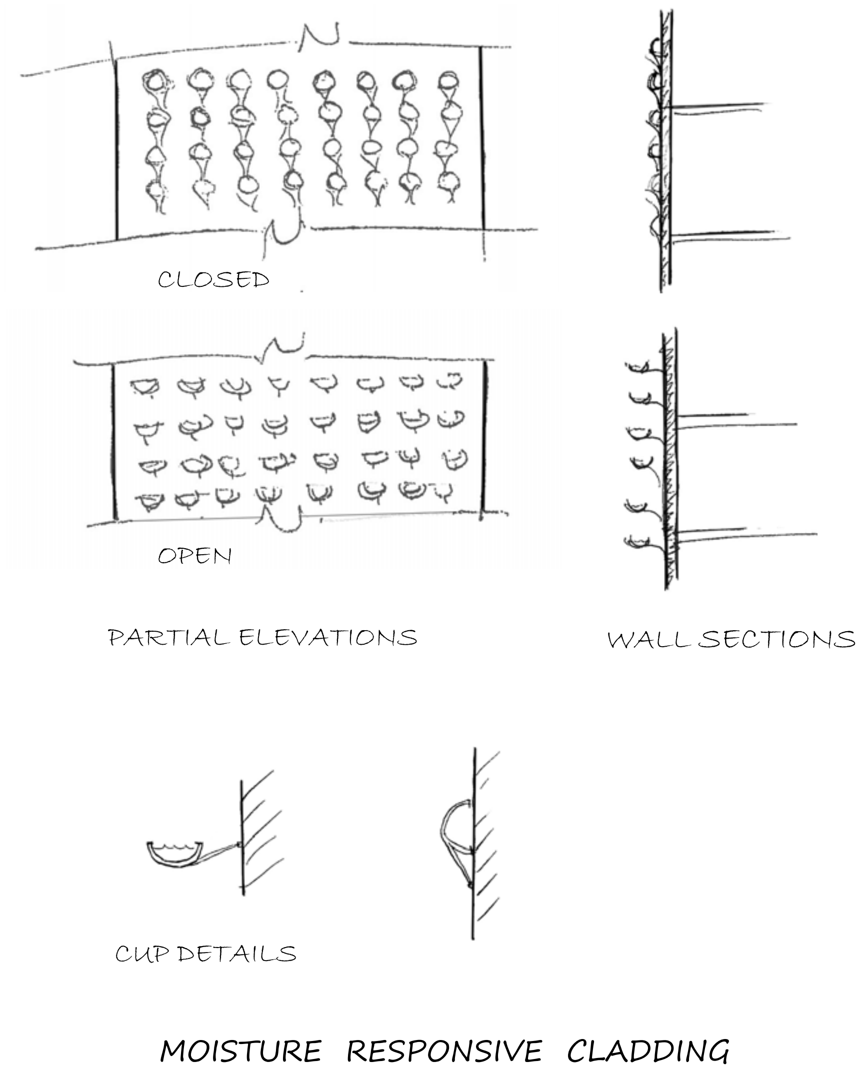
- Facades which respond to sunlight—via apertures, opening and closing shades, or by growing algae (!).
- Canopies which respond to wind providing different degrees of shading.

Photograph courtesy of Dalbera, 2008


Photograph courtesy of Pippalou, 2014

APPLICATION OF NATURE'S FUNCTION

By mimicking conifer cones' moisture responsive function, buildings could be designed to capture, slow, and pool water only when it is present. This dynamic response would create countless opportunities for artistic expression relating to the presence of water. For example, certain openings or views might remain fully exposed during dry periods and then shift or close during wet weather, or the cladding material on entire facades might open and close as humidity changes.



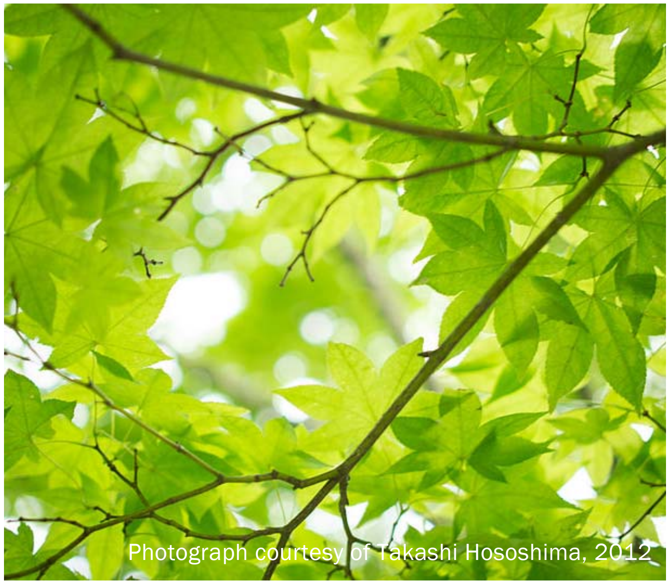
Images by Alexandra Ramsden, 2016

EXPLORATION & RESEARCH OPPORTUNITIES

1. Design Exploration
    a. How would a building façade ideally respond to pool water during a rain event?
2. Experimentation
    a. Investigation of the use of “smart materials”. Smart materials have properties that react to changes in their environment. This means that one of their properties can be changed by an external condition, such as temperature, light, pressure or electricity. This change is reversible and can be repeated many times (BBC, 2014).
3. Material/Product Development
    a. What type of material would bend when it gets wet and assume its original shape when dry?


Photograph courtesy of S. Juhl, 2014.

What would facilitate product development for this strategy?



Photograph courtesy of Takashi Hososhima, 2012

METRICS

- Worldwide, transpiration accounts for 10% of the moisture in the air (USGS, 2016).
- Leaves release many times their weight in moisture during the growing season. A mature oak tree can transpire 40,000 ga/year (USGS, 2016).
- Leaves may have up to 400 stomata/mm^2, openings typically on the underside of the leaf to reduce water loss (Plant & Soil Sciences, 2017).

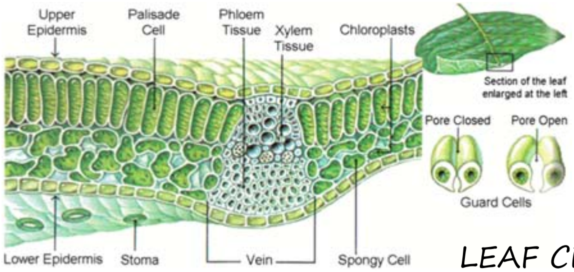
Lesson for the Built Environment

How can a building mimic the forest's leaves, releasing water from its cladding after the water has been used?

BIOLOGY

Only a small amount of water that moves through a plant is used and retained by the plant itself. Nearly 99% of that water returns to the atmosphere (NOAA, 2010). This transpiration process reduces the amount of water saturating the soil, and it also returns moisture to the air, allowing it to be precipitated in other areas.

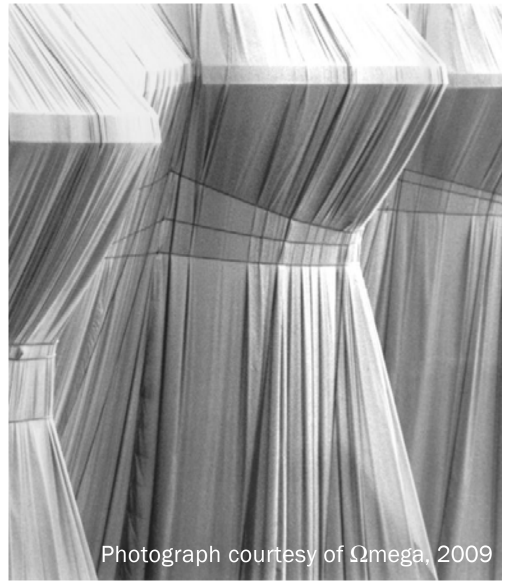
During transpiration, water is pulled up into the leaves through the xylem from other parts of the plant or from the soil. 95% of transpiration occurs through pores, or stomata, on the leaf which open and close depending on weather and plant conditions (Crops Review, 2016). Stomata are present in the needles of evergreens as well as in the leaves of deciduous plants. Environmental conditions and plant species generate differences in transpiration rates. Waxy leaves, for example, allow less water to pass through them than do non-waxy leaves (Crops Review, 2016).



LEAF CROSS SECTION

Image courtesy of World Book Encyclopedia, 1979

Photograph courtesy of Majonaise, 2004

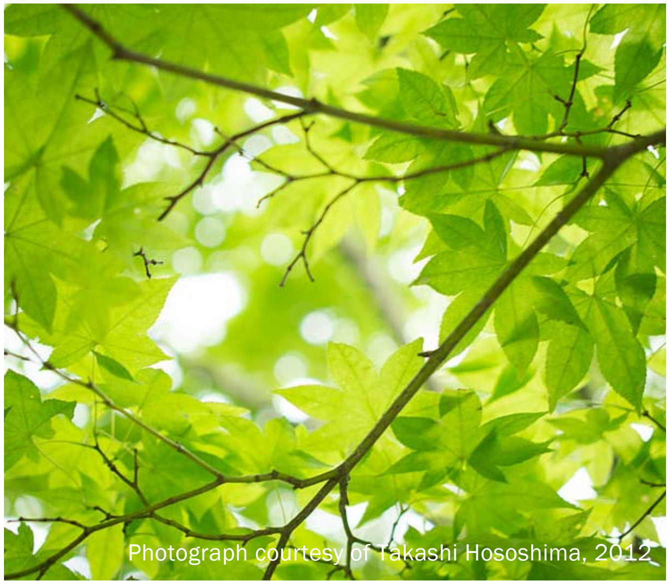

Photograph courtesy of Ωmega, 2009


Photograph courtesy of Morris Pearl, 2005

What existing strategies can be modified?

- Banners & flags
- Fabric wrapped walls
- Fabric canopies


Photograph courtesy of timquijano, 2011


Photograph courtesy of Takashi Hososhima, 2012

APPLICATION OF NATURE'S FUNCTION

Just as a plant moves water out to its leaves, pipes can move water from the roof or out from the building itself onto an absorbent fabric on the building's façade. This flexible material would be loosely attached, allowing it to move in the wind and have air movement behind it. Moisture on this fabric would be exposed to wind and sun, evaporating rather than being piped into the storm/sewer systems (Moddemeyer, 2016).

Image by Jennifer Barnes, 2016

EXPLORATION & RESEARCH OPPORTUNITIES

1. Design Exploration
    a. What existing materials that absorb and hold water, and that also resist mold, could be attached loosely to a building exterior to hold water until it evaporates?
    b. Are there any materials currently used underground by civil and stormwater engineers that might be applied to building exteriors or other above ground locations?
    c. How could attachment assemblies be designed to facilitate fabric replacement if needed?
2. Experimentation—Build a mock-up. Test and monitor the assembly:
    a. How much water is diverted from stormwater collection?
    b. How does the absorptive material change over time?
    c. If gray water is conveyed to the material, how frequently will the cladding need to be cleaned or replaced?
    d. How do varying temperatures and sun/wind exposures effect the evaporation rate?
3. Material/Product Development
    a. What fabric-like material could be developed to absorb large amounts of water and release it easily to the air?

What would facilitate product development for this strategy?


Photograph courtesy of Forgemind ArchiMedia, 2013

METRICS

- An old Douglas fir may live more than 1000 years, reach heights over 300', and have bark as thick as 14" (Van Pelt, 2007, 53).
- Although only about an inch thick, western redcedar bark is furrowed and very fibrous, peeling easily into long fuzzy strips (Chase, 2008).

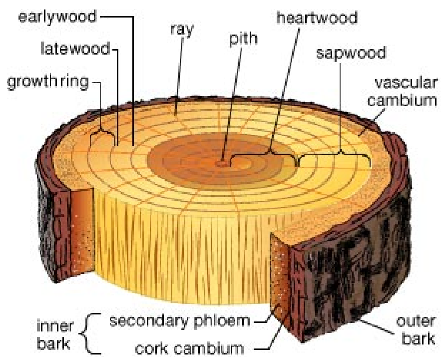
Lesson for the Built Environment

How can a building exterior mimic the form of the Northwest forest's fissured bark, slowing and holding water as it flows over the cladding?

BIOLOGY

Textured surfaces of the Pacific Northwest forests, including trunks of the predominant tree species in the region, provide multi-scalar grooves and pockets where moisture can be held until it evaporates.

Temperate climates and abundant rainfall extend growing seasons in this region, and trees grow larger than in many other parts of the world. When trees grow, new growth occurs from the cambium, a layer between the core and bark. As the tree diameter increases, the outermost layers of the tree split or fracture as they are pushed farther and farther from the core (Van Pelt, 2007, 53). Consequently, the outermost bark of many Pacific Northwest trees is fissured, with large amounts of surface area available for evaporation.



TREE STRUCTURE

Image courtesy of Merriam Webster, 2006

Bark | Textured Rainscreen (Building Bark)


Photo courtesy Max Pixel, 2017


Photo courtesy Bark House, 2017

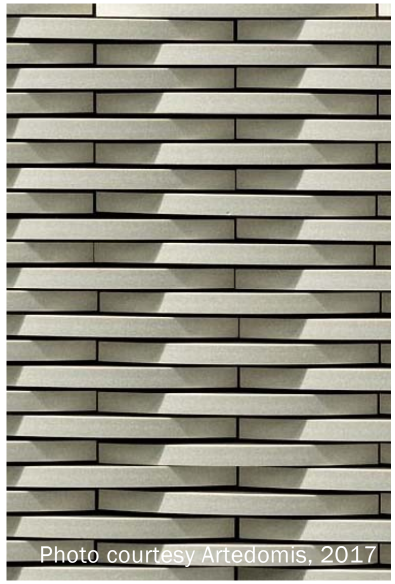
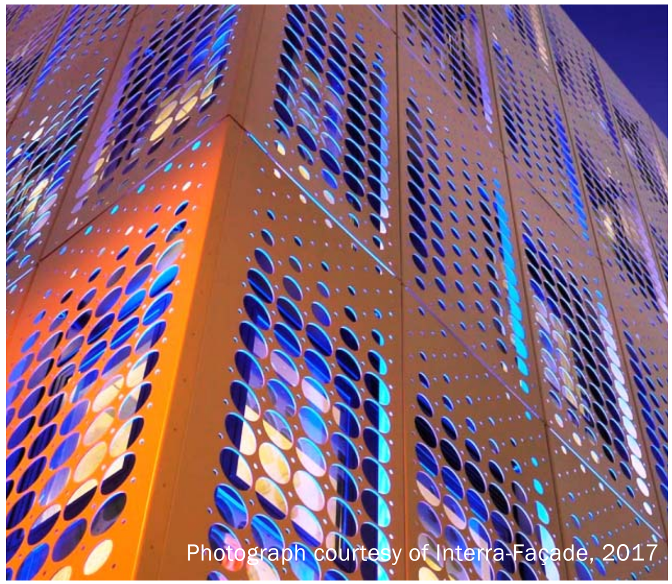


Photo courtesy Artedomis, 2017


Photo courtesy James Brittain, 2013

What existing strategies can be modified?

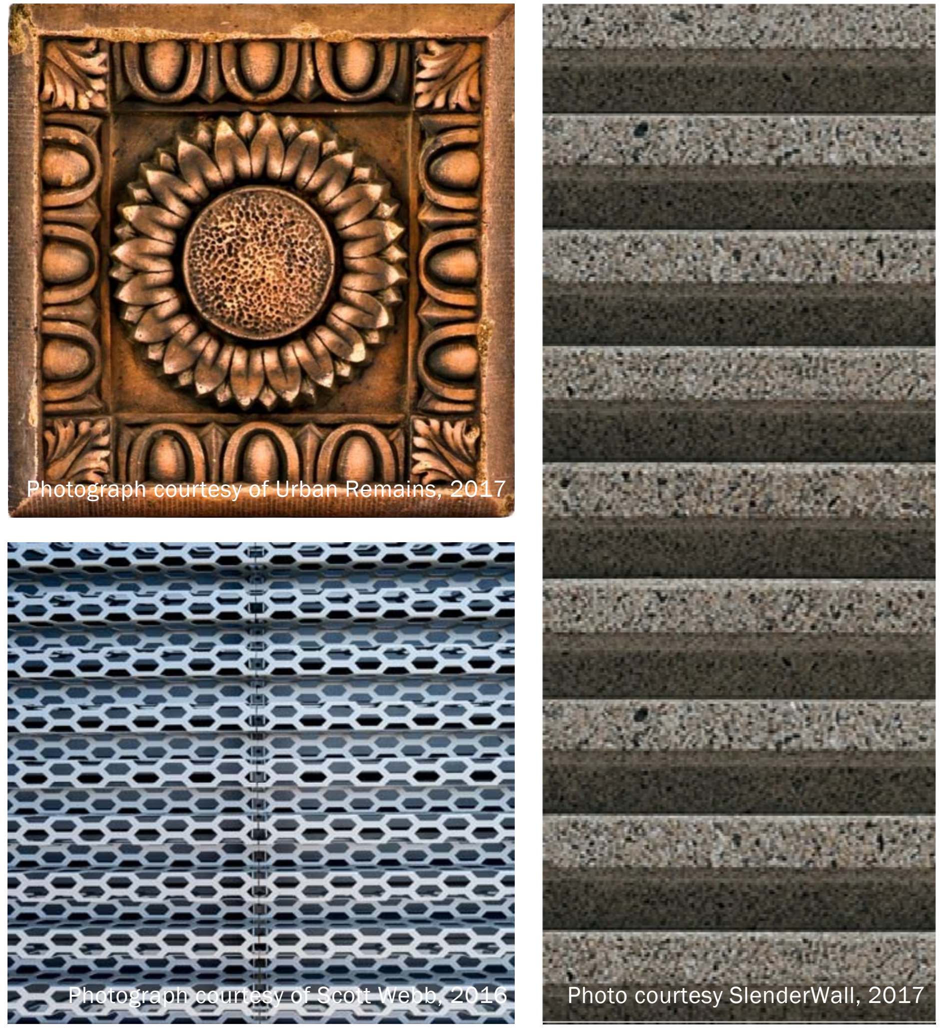
- Textured building cladding
- Stamped metal panels
- Stamped ceramic panels
- Poplar bark


Photograph courtesy of Interra-Façade, 2017

Photograph by Jennifer Barnes, 2016

APPLICATION OF NATURE'S FUNCTION

Exterior metal, concrete, or ceramic panels can be stamped with texture to slow rainwater surface flow and allow small amounts of rainwater to pool until the moisture evaporates.



Photograph courtesy of Urban Remains, 2017

Photograph courtesy of Scott Webb, 2016

Photo courtesy SlenderWall, 2017

TEXTURED RAINSCREEN: CLADDING TEXTURES

EXPLORATION & RESEARCH OPPORTUNITIES

1. Design Exploration
   a. What existing cladding materials are deeply textured or stamped?
2. Research / Experimentation
   a. What is the depth/size of indentation needed in a vertical metal (or concrete, ceramic, etc) panel for water to be held there temporarily by its surface tension?
   b. What water volume could reasonably be held per sf on that vertical panel?
   c. How do varying temperatures and sun/wind exposures effect evaporation from that material?
3. Material/Product Development
   a. Identify a panel manufacturer who is willing to produce a more textured version of a panel already in production. Test the evaporation occurring from the panel at various exposures.

Photograph courtesy of Haver & Boecker

What would facilitate product development for this strategy?

METRICS

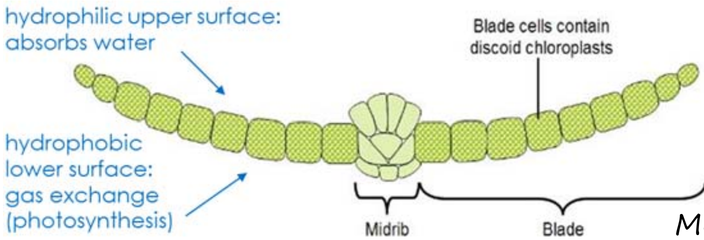
- There are approximately 12,000 species of moss (Goffinet, 2004).
- The water content of moss is typically in equilibrium with the atmosphere (Green et al, 2011).
- Sphagnum moss can hold 2000x its dry weight in water (Green et al).

Lesson for the Built Environment

How can a building mimic the forest's mosses, capturing and holding water near the building surface until it evaporates?

BIOLOGY

Mosses are dependent on water for survival. Although they can go dormant during dry periods, they need water for growth and for fertilization (Whitbeck, 2000). With no vascular system, tissues that transfer water and nutrients, mosses take the water and nutrients they need from the atmosphere and then transfer these resources by diffusion and osmosis from cell to cell (Penn State, 2017). Their lack of lignin makes them soft, and their lack of true roots, coupled with their ability to pull water and nutrients from the atmosphere, allows them to grow nearly anywhere (McCune, 2017). Each moss leaf is concave to collect and hold water. The underside of each leaf is hydrophobic, repelling water so that the lower surface can be used for photosynthesis (Green et al, 2011). Mosses provide many ecosystem services, including stabilizing disturbed soil; reducing stormwater runoff; being bio-indicators of air pollution, and nitrogen fixation (McCune, 2017).



MOSS CROSS SECTION

Image courtesy of Crondon, 2010. Blue notes added

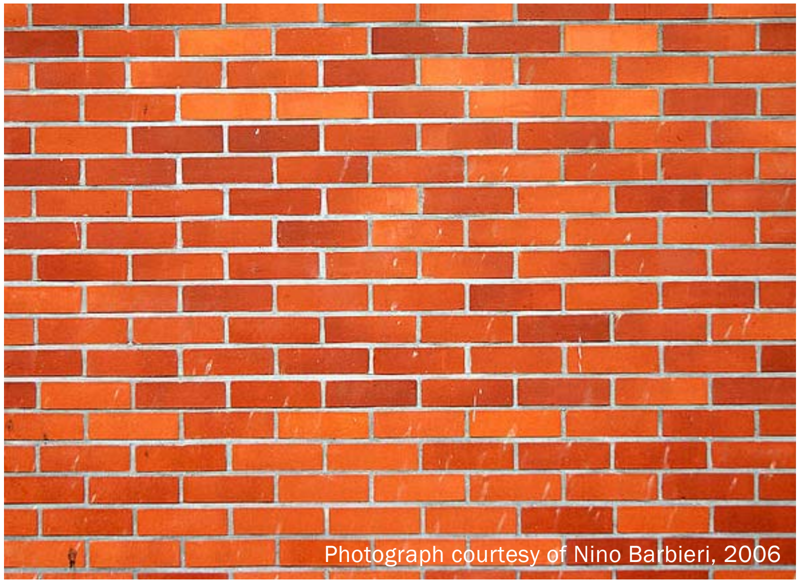

Photograph courtesy of Nino Barbieri, 2006


Photo courtesy of Vera Kratochvil, 2006


Photo courtesy of Workshop/APD

What existing strategies can be modified?

- Reservoir cladding— bricks and CMU are porous by nature
- Living walls
- Wood rainscreens
- Civil engineering and geotech materials such as Zeolite & Super Absorbent Polymers (SAPs)

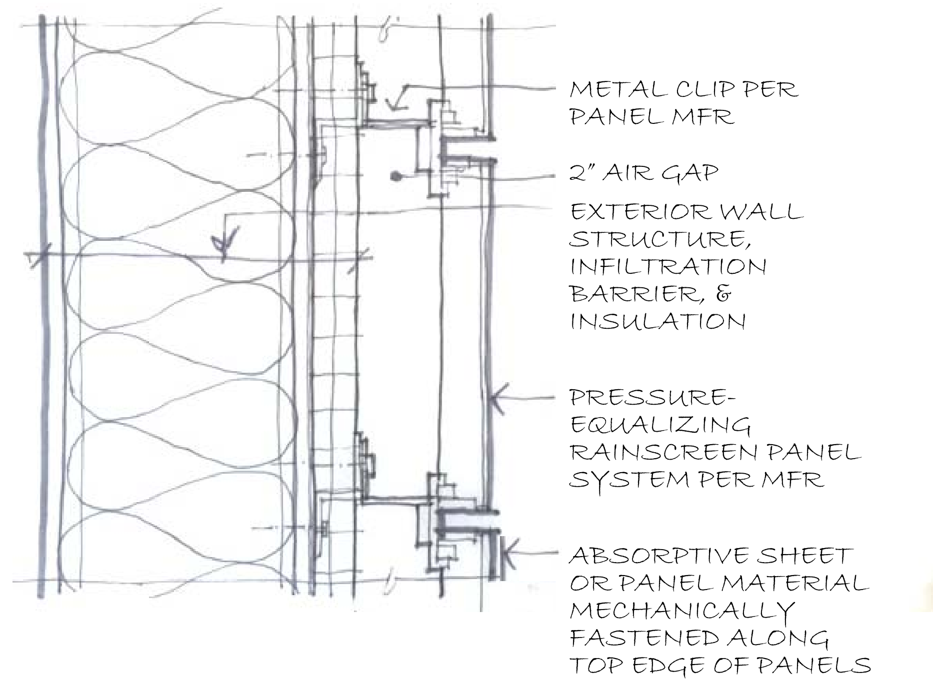

Photograph courtesy of JustAnother, 2006

Forest Structure
Textured Flora
Evergreen Needles
Conifer Cones
Leaves
Bark
Moss
Mycorrhizae
Northwest Forest

Photograph courtesy of Seyriu-en, 2010

APPLICATION OF NATURE'S FUNCTION

An absorptive material mechanically fastened to the building exterior could soak up and hold on to rainwater until atmospheric conditions allow the moisture to evaporate. Just as moss connects lightly to its substrate, the material could be mechanically fastened along one edge of exterior rainscreen panels, allowing it to be replaced if needed. This material has a water-repellent backing which prevents moisture from soaking through, although air circulation provided by rainscreen system would allow evaporation to occur from both sides.



ABSORBENT RAINSCREEN: EXTERIOR WALL SECTION

Image by Jennifer Barnes, 2016

opportunities

EXPLORATION & RESEARCH OPPORTUNITIES

1. Design Exploration
    a. What existing sheet or panel materials could be attached to exterior wall systems to absorb rainwater until it evaporates?
    b. How could a material be attached so that it is easily removed for cleaning or replacement?
    c. What materials, such as “Bio-Receptive Concrete” currently in development, could encourage moss or lichen growth and remain functionally undiminished?
2. Research / Experimentation
    a. What is the volume of rainwater that could be held by various sheet and panel materials?
    b. How would material composition and thickness impact evaporation rates?
3. Material/Product Development
    a. What new fabrics could be developed that are super-absorbent, release moisture easily to the air, inhibit mold growth, and are easy to clean and maintain?
    b. Working with an exterior rainscreen manufacturer, how can absorbent fabrics be integrated into currently-available panel systems?

What would facilitate product development for this strategy?

Photograph courtesy of Fred Hsu, 2009

METRICS

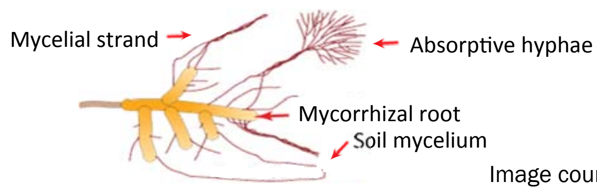
- 90% of land-based plants are connected in mycorrhizal networks. Those that aren't are typically in resource-rich ecosystems, where there is less perceived benefit, or pioneer species, where short-lived plants prepare the way for long-lived species succession (LaFantasie, 2017).
- One teaspoon of healthy soil can contain several miles of hyphae, tiny, branched filaments with enormous surface area (Amaranthus, 2000).

Lesson for the Built Environment

How can a building or district mimic the mycorrhizae of the forest soil, sharing information about the quality and availability of water as well as transferring the water itself?

BIOLOGY

Mycorrhizae are a symbiotic web of fungus and plants, where a fungus attaches to a plant's root system. Many species are typically connected in a single mycorrhizal relationship. This relationship allows an exchange of information and resources, generating mutual benefits between fungus and plants: 1) Plants provide sugars for the fungus; the fungus provides minerals and water for the plants. Comprised of long, branching filaments, the fungus explores the soil, bringing nutrients to the stationary plant it could not otherwise reach (Kendrich & Berch, 2011). 2) If resources are available to but not needed by one plant, the network can redistribute them to a plant in need, reducing competitive differences (Wakeford, 2001, 49; Douglas, 1994). 3) Information is exchanged between plants, such as warnings about harmful fungi or invading pests, allowing non-infected plants to develop advance immune responses (Sirinathsinghji, 2013; Johnson et al., 2015). Plants in mycorrhizal networks are much more likely to survive long-term than unconnected plants because of inevitable environmental disruptions, making these communities more resilient (Allen, 1991).



MYCORRHIZA
Image courtesy Brundrett, 2008

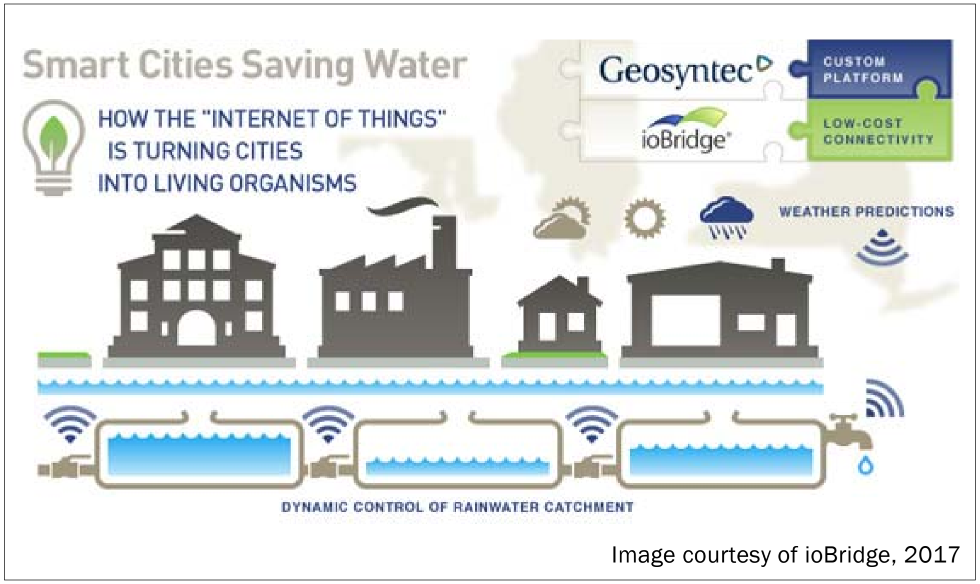


Image courtesy of ioBridge, 2017

Image by 2030 District, 2017

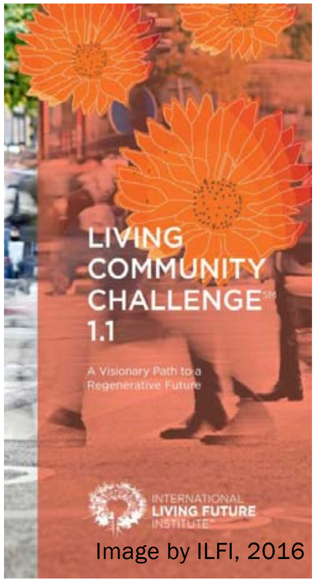


Image by ILFI, 2016

What existing strategies can be modified?

- Smart energy systems/IoT
- Building automated systems
- Monitors on detainment and conveyance systems
- Rainwater capture and use
- District-Scale Thinking

Image courtesy of IBM, 2013

Forest Structure

Textured Flora

Evergreen Needles

Conifer Cones

Leaves

Bark

Moss

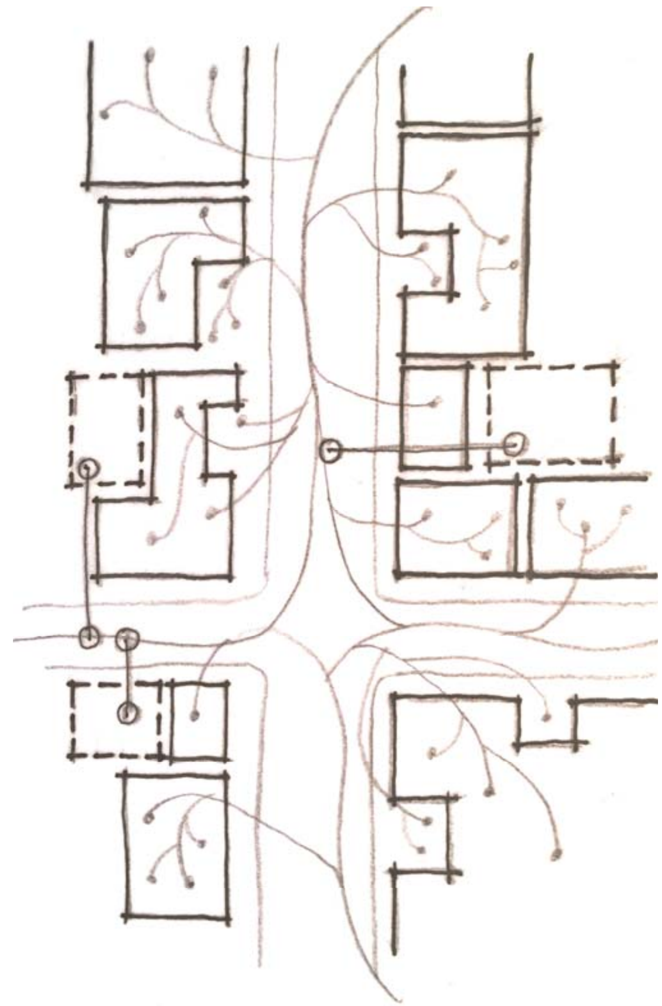
Mycorrhizae

Northwest Forest

Photograph courtesy of of André-Ph. D. Picard

APPLICATION OF NATURE'S FUNCTION

A smart network monitoring water and weather systems can provide data regarding water needs and availability and can activate system changes such as opening valves to redirect stormwater to empty vaults or rescheduling irrigation based on the rain forecast. Just as mycorrhizal inoculations prepare damaged soil for restoration, aggregated data from these networks can be used to inform urban planning. Mycorrhizal networks illustrate that when resources and information are shared among organisms, helping each member be its healthiest, the entire system thrives.



DISTRICT-SCALE CONNECTIONS: SMART WATER SYSTEMS

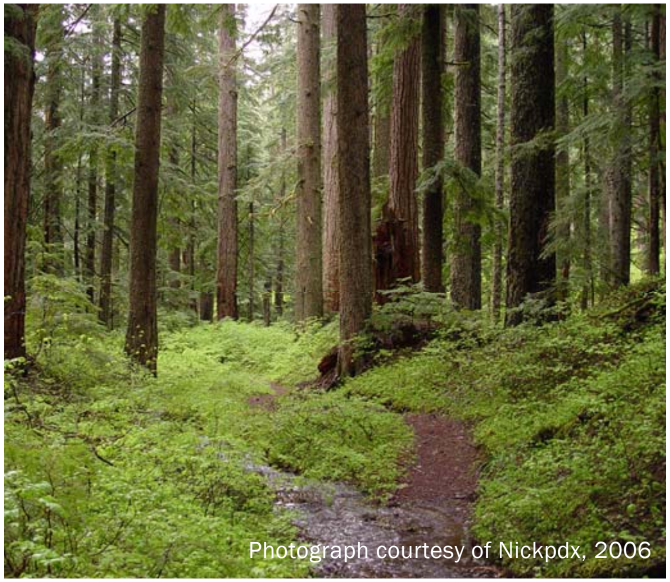
Image by Jennifer Barnes, 2017

EXPLORATION & RESEARCH OPPORTUNITIES

1. Design Exploration
   a. Current smart water systems focus on monitoring water usage and identifying leaks. What other benefits could be derived from monitoring water use and availability? What problems could be solved?
2. Research / Experimentation
   a. How could current smart monitoring technology be modified to synthesize data on potable and non-potable water delivery systems, irrigation systems, and weather systems?
   b. Because of microclimate variation, what is the best way to determine appropriate locations and quantities of weather monitoring equipment?
   c. 3D printing would make it possible to build a web that physically resembles mycorrhizae, with numerous long, thin filaments that, when aggregated, have enormous surface area. Would this structure benefit the transfer of resources?
3. Material/Product Development
   a. Software linking weather monitor data with water distribution data and pipe infrastructure.


Photograph courtesy of Brundett, 2008

What would facilitate product development for this strategy?



Photograph courtesy of Nickpdx, 2006

METRICS

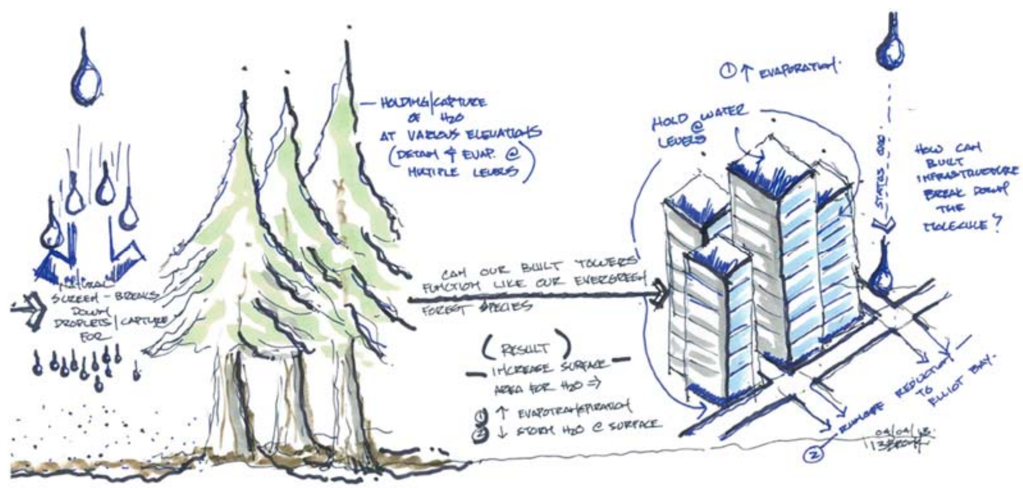
- As highlighted at the beginning of this document, in a healthy Northwest forest, 49.8% of the rainfall infiltrates, 0.2% runs off in large storm events, and 50% returns to the atmosphere due to evaporation or plant transpiration (Beyerlein, 1998).

Lesson for the Built Environment

How can buildings mimic not just one element of the forest, but the entire system, to eliminate almost all water run off?

BIOLOGY

A Pacific Northwest forest, and the millions of plants, fungi, and bacteria which make up its flora, is a highly successful system for managing water flows. The natural elements of these forests presented in this report, plus many, many more, combine to create an incredibly complex system that results in almost no runoff. It is the total function of these elements—the structure, the types of surfaces, and the evapotranspiration of the plants—which leads to a balanced water cycle.



BUILDING AS FOREST: EVAPORATION STRATEGIES

Image by Todd Bronk, 2014

What existing strategies can be modified?

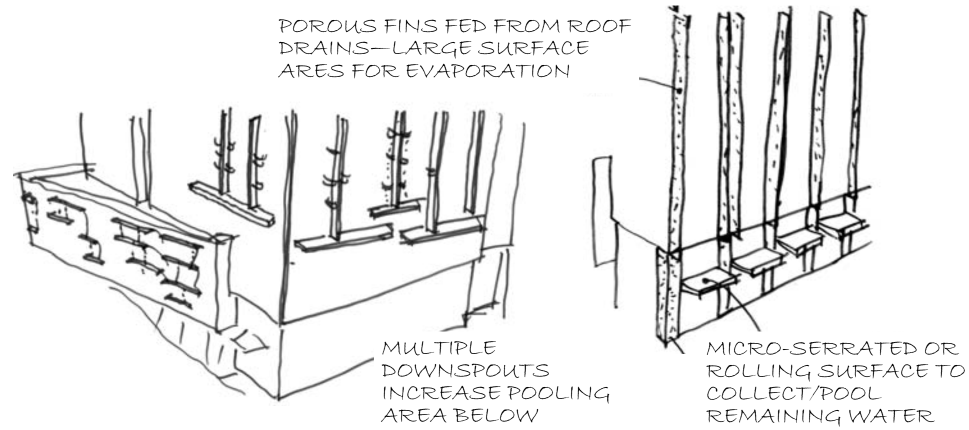
- Standard practice building and site water management can become much more integrated. A whole-building approach would consider the building envelope, landscape, roof, balconies, amenity areas, etc, as well as water use and conveyance.

The Watershed office building, in the Fremont neighborhood of Seattle, owned by COU, LLC, and designed by Weber Thompson, is being designed with stormwater mitigation as a primary goal. In pursuit of the Living Building Pilot, the approach to water use and treatment goes well beyond typical. In addition to the rainwater falling on the site, the project will treat runoff from the adjacent Aurora Bridge. Over 200,000 gallons of roof water will be collected and reused on site, and over 300,000 gallons of runoff from streetscapes, including the bridge, will be diverted and cleaned before entering nearby Lake Union.

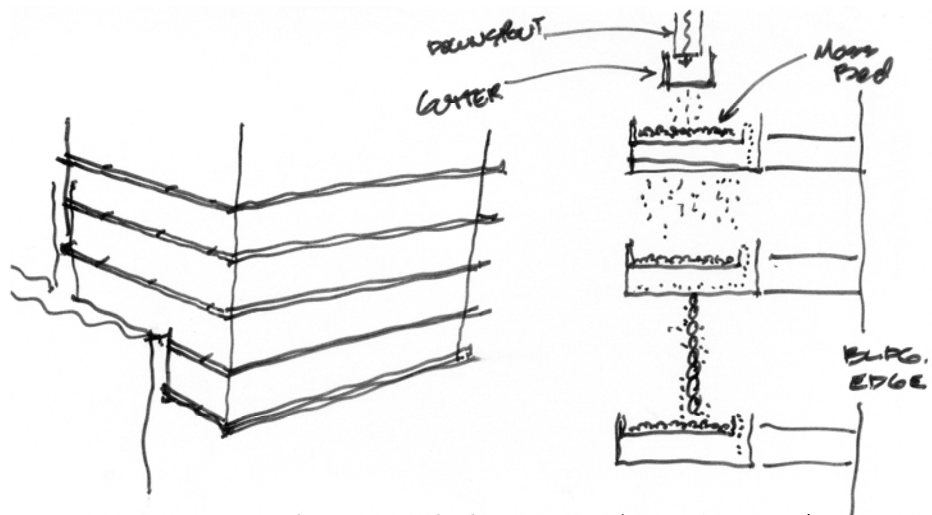
Photograph courtesy of Nickpdx, 2006

APPLICATION OF NATURE'S FUNCTION

When a building design is approached holistically, multiple strategies can work together to emulate complex natural processes such as the balanced water cycle created by local forests. During the design of the Watershed office building, Rushing and 55-5 Consulting collaborated with the team to explore how this particular building could mimic local forests to strengthen the design's stormwater mitigation strategies. Many innovative ideas were generated, including ways the façade could emulate the slowing, pooling, absorptive, and evaporative characteristics of the forest.



1 & 2 — MULTIPLE DOWNSPOUTS AND POROUS FINS WITH POOLING LEDGES



3 — PERCOLATING GUTTERS (WITH MOSS)

Images courtesy of Weber Thompson, 2017

EXPLORATION & RESEARCH OPPORTUNITIES

1. Design Exploration
   a. Identify projects which have already established a goal of advanced stormwater mitigation.
   b. Take the design team for a walk in your local forest.
   c. Invite biomimicks and/or biologists to the design table.
   d. Explore existing tools like AskNature.org, to gain knowledge about local ecosystem mentors which are applicable to your project.
   e. Try a strategy never done before and collect data for the rest of the industry to learn from—be the first to begin transforming the way we build buildings to support restorative cities, not just better ones.

Image by Weber Thompson, 2017

How can the exploration of nature's local design solutions be applied to a typical design process, to improve how buildings mitigate stormwater?

END NOTES

2030 District-Seattle, “District Boundary,” Seattle 2030 District, accessed March 1, 2017, http://www.2030districts.org/seattle/about

Allen, M. The Ecology of Mycorrhizae. Cambridge: University Press, 1991. In: Wiley, David, ‘Mycorrhizal networks and learning,’ iteration towards openness, July 21, 2011, accessed February 28, 2017, https://opencontent.org/blog/archives/1920.

Allen, Scott T and Barbara Bond. Trickle-down ecohydrology: complexity of rainfall interception and net precipitation under forest canopies. Oregon State University, 2012. https://ir.library.oregonstate.edu/xmlui/handle/1957/30309.

Amaranthus, Michael P., “A look Beneath the Surface at Plant Establishment and Growth,” Fungi Perfect, July 2000, accessed February 28, 2017, http://www.fungi.com/blog/items/mycorrhizal-management.html.

Arnoldius, “ThyssenKrupp_Quartier_Essen_07,” Wikimedia Commons, April 2011, last accessed February 28, 2017, https://commons.wikimedia.org/wiki/File:ThyssenKrupp_Quartier_Essen_07.jpg.

Artedomis, “Cresent Border,” 2017, accessed February 27, 2017, http://www.artedomus.com/products/inax-crescent-border.

Barbieri, Nino, “Brickwall,” Wikimedia Commons, March 2006, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File:-_Brickwall_01_-.jpg.

Bark House, “Poplar Bark Shingles,” 2017, accessed February 27, 2017, https://barkhouse.com/products/poplar-bark-shingles/.

Barnes, Jennifer, “Absorbent Rainscreen: Exterior Wall Cross Section,” 2017.

Barnes, Jennifer, “Absorbing Textures,” February 2017.

Barnes, Jennifer, “Blue Roof – Blue Walls – Blue Site” and “Meandering Downspout,” July, 2016.

Barnes, Jennifer, “District-Scale Connections,” January 2017.

Barnes, Jennifer, “Douglas Fir Bark,” June 2016.

Barnes, Jennifer, “Flapping Fabric,” June, 2016.

Barnes, Jennifer, “Rain/Sunscreen Sketch,” June 2016.

British Broadcasting Corporation (BBC), “Smart Materials,” Bitesize – Design & Technology, Materials, 2014, accessed March 2, 2017, http://www.bbc.co.uk/schools/gcsebitesize/design/electronics/materialsrev5.shtml.

Beyerlein, Doug (P.E. in Civil Engineering and Principal and Co-Founder of Clear Creek Solutions), in discussion with authors, 2012.

Biomimicry Oregon, “Canopy Structure,” Genius of Place Process Report: Nature’s Strategies for Managing Stormwater in the Willamette Valley, 2013, accessed February 27, 2017, http://oregon.biomimics.net/wp-content/uploads/2013/05/130430--GofP-process+appendices.pdf.

Bixby, Mitchell, Yeakley, J. Alan, Fountain, Andrew, and Maser, Joseph. Interception in Open-grown Douglas-fir (Pseudotsuga Menziesii) Urban Canopy. 2011, ProQuest Dissertations and Theses, accessed March 1, 2017, http://pdxscholar.library.pdx.edu/cgi/viewcontent.cgi?article=1036&context=open_access_etds.

Brittain, James, “The Old Market Square Stage,” 2013 [Frearson, Amy, “Old Market Square Stage by 5468796 Architecture,” DeZeen, May 25, 2013, accessed February 27, 2017, https://www.dezeen.com/2013/05/25/old-market-square-stage-by-5468796-architecture/.

Bronk, Todd, “Building as Forest: Evaporation Strategies,” Biomimicry Puget Sound Workshop, 2014.

Brundrett, Mark, “Highly magnified view of a Glomus Arbuscule,” Mycorrhizal Associations: The Web Resource, 2008, accessed February 28, 2017, https://mycorrhizas.info/ecm.html.

Brundrett, Mark, “Section 5. Ectomycorrhizas,” Mycorrhizal Associations: The Web Resource, 2008, accessed February 28, 2017, https://mycorrhizas.info/ecm.html.

Bs0u10e01, “The façade of the new Library of Birmingham designed by Mecanoo Architects,” Wikimedia Commons, 2012, last accessed February 28, 2017, https://commons.wikimedia.org/wiki/File:Library_of_Birmingham_Facade.jpg.

Campbell, Sally J., Waddell, Karen L, Gray, Andrew N, Azuma, David L, Forest Inventory Analysis Program, and Pacific Northwest Research Station. Washington's Forest Resources, 2002-2006: Five-year Forest Inventory and Analysis Report. General Technical Report PNW; 800. Portland, OR: U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Research Station, 2010, accessed March 1, 2017, https://www.fs.fed.us/pnw/pubs/pnw_gtr800.pdf.

Chase, Jeri, “Western Redcedar, ‘Tree of Life’,” Forests for Oregon, Oregon Department of Forestry, Salem, Oregon: Fall 2008, accessed February 28, 2017, https://www.oregon.gov/ODF/Documents/ForestBenefits/WesternRedCedar.pdf.

Chen, Chao, “Chao Chen creates Biomimetic water-reactive material using pine cones,” DesignBoom – Design, June 30, 2015, accessed March 1, 2017, http://www.designboom.com/design/chao-chen-biomimetic-water-reaction-material-pine-cones-06-30-2015/.

City of Seattle. Green Stormwater Infrastructure in Seattle: Implementation Strategy 2015-2020. Office of Sustainability and Environment and Seattle Public Utilities. Seattle: 2015. Accessed February 28, 2017, http://www.seattle.gov/Documents/Departments/OSE/GSI_Spreads_v2_July_2015_WEB.pdf.

Crondon, “Cross-section through a leaf of Funaria,” February 17, 2017, accessed March 1, 2017, https://cronodon.com/BioTech/Bryophytes.html

CropsReview.com, “Types of Transpiration in Plants: Stomatal, Cuticular and Lenticular,” 2016, accessed February 28, 2017, http://www.cropsreview.com/types-of-transpiration.html.

Cullen, Mark, “The Truth about Pine Cones,” February 13, 2014, accessed March 1, 2017, http://markcullen.com/the-truth-about-pine-cones/

Dalbera, Jean-Pierre, “Le muse de l’Institut du monde arabe a rouvert ses portes,” Flickr, April 2008, accessed March 1, 2017, https://www.flickr.com/photos/dalbera/6928017541.

danna & curios tangles, “Green Wall at Semiahmoo Library. Surry, B.C,” Flickr, September 20, 2013, accessed February 27, 2017, https://www.flickr.com/photos/curioustangles/9847269775.

Dawson, John, 'Conifer–broadleaf forests - Overview and features', Te Ara - the Encyclopedia of New Zealand, September 2007, accessed February 27, 2017, http://www.TeAra.govt.nz/en/diagram/11652/layered-forest.

Douglas, Angela. Symbiotic Interactions. Oxford: Oxford University Press, 1994. In: Wiley, David, ‘Mycorrhizal networks and learning,’ iteration towards openness, July 21, 2011, accessed February 28, 2017, https://opencontent.org/blog/archives/1920.

Eleckhh, “Surry Hills Library and Community Centre, Sydney, Australia. Design by FJMT,” Wikimedia Commons, 2010, accessed March 2, 2017, https://commons.wikimedia.org/wiki/File:Surry_Hills_Library_2010.jpg.

Fieryn, “Pine Cone,” MorgueFile, June 2005, accessed March 2, 2017, http://mrg.bz/2ktU3L.

Forgemind ArchiMedia, “Christo and Jeanne-Claude - Big Air Package - Construction 10,” Flickr, January 29, 2013, accessed February 27, 2017, https://www.flickr.com/photos/eager/8571278664/.

Franklin, Jerry F., and Pacific Northwest Forest Range Experiment Station. Ecological Characteristics of Old-growth Douglas-fir Forests. [General Technical Report PNW; 118. Portland, Or.]: U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, 1981.

GO-2 Living Walls, “G-O2 Living Wall Project Gallery - Prudential Tower – Newark, NJ,” 2015, accessed February 28, 2017, http://www.myplantconnection.com/green-wall-gallery.php#item73.

Goffinet, Bernard., Hollowell, Victoria C., and Magill, Robert E. Molecular Systematics of Bryophytes. Monographs in Systematic Botany from the Missouri Botanical Garden; v. 98. Saint Louis, Mo.]: Missouri Botanical Garden Press, 2004.

Green, T.G. Allan, Leopoldo G. Sancho, and Ana Pintado. “Chapter 6 Ecophysiology of Desiccation/Rehydration Cycles in Mosses and Lichens” 2011. In: Biomimicry Oregon, “Nature’s Strategies for Managing Stormwater in the Willamette Value: Genius of Place Project Report,” 2013, accessed February 28, 2017, http://oregon.biomimics.net/wp-content/uploads/2013/05/130425--GofP-projectsummary.pdf.

Gruber, Jennifer, “Non-Vascular Plants,” Penn State, Eberly College of Science, BIOL011, 2017, accessed March 1, 2017, https://online.science.psu.edu/biol011_sandbox_7239/node/7349.

Hamzah, T.R and Yeang, “The Cultivated Facade,” 2014 [Fairley, Peter, “Continuing Education: The Cultivated Façade: Greenery on buildings is graining traction, but needs validation,” Architecture Record, July 1, 2016, accessed February 27, 2017, http://www.architecturalrecord.com/articles/11762-continuing-education-the-cultivated-facade].

Hans, “Pine Cone,” Pixabay, January 2012accessed March 2, 2017, https://pixabay.com/photo-16196/.

Haver & Boecker, “Odysseum – Science Adventure Cologne,” Architect Kaspar Kraemer Architects, Germany, accessed February 27, 2017, http://www2.diedrahtweber.com/fileadmin/dw/dw_dateien/Datenblaetter/Architektur_Projekte/Odysseum_en.pdf

Hososhima, Takashi, “Japanese Garden of Showa Kinen Park, Tachikawa Tokyo Japan,” Wikimedia Commons, June 10, 2012, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File:Fresh_green_maple_leaves_(7185025589).jpg.

Hososhima, Takashi, “Photographed at Japanese Garden of Showa Kinen Park, Tachikawa Tokyo Japan,” Wikimedia Commons, June 10, 2012, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File:Fresh_green_maple_leaves_(7185025589).jpg.

Hsu, Fred, “Moss-covered retaining wall at Jinguashi,” Wikimedia Commons, November 2009, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File:Taiwan_2009_JinGuaShi_Historic_Gold_Mine_Moss_Covered_Retaining_Wall_FRD_8940.jpg

IBM, “IBM Ecosystem Infographic: Building a Smarter City and State,” March 2013, accessed February 28, 2017, https://www-03.ibm.com/press/us/en/photo/40634.wss.

International Living Future Institute, “Living Community Challenge 1.1: A visionary Path to a Regenerative Future,” 2016, accessed February 28, 2017, http://living-future.org/lcc.

Interra-Façade, “Proteus [5/19],” 2017, accessed February 27, 2017, http://www.interra-facade.com/gallery.

ioBridge, “Geosynec, OptiRTC – Smart City,” 2017, accessed February 28, 2017, http://iobridge.com/applications/.

Janelle, “Canopy by nARCHITECTS at P.S. 1 Contemporary Art Center,” Flickr, 2004, last accessed February 28, 2017, https://www.flickr.com/photos/janelle/210580648/in/photostream/.

Johnson, David and Lucy Gilbert, “Interplant signaling through hyphal networks,” New Phytologist, March 2015, 5:209. In: Awkwardbotany, “Plants Use Mycorrhizal Fungi to Warn Each Other of Incoming Threats,” March 2015, accessed February 28, 2017, https://awkwardbotany.com/2015/03/11/plants-use-mycorrhizal-fungi-to-warn-each-other-of-incoming-threats/.

Juhl, S., “Campus Kolding - Syddansk Universitet (University of Southern Denmark),” Wikimedia Commons, 2014, accessed March 2, 2017, https://commons.wikimedia.org/wiki/File:IBA_Hamburg_BIQ_(2).nnw.jpg.

JustAnother, “Concreteblocks,” Wikimedia Commons, November 1 2006, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File:Concreteblocks.jpg.

Karchmer, Alan, “Solar suncreen louvers in detail,” 2013 [Lau, Wanda, “A Detailed Look at the Solar Sunscreen on the Consolidated Forensic Laboratory: The high performance facility in Washington, D.C. by HOK uses a dynamic façade to draw in sunlight without the heat,” The Journal of the American Institute of Architects: ARCHITECT, January 09, 2013, accessed February 27, 2017, http://www.architectmagazine.com/technology/detail/a-detailed-look-at-the-solar-sunscreen-on-the-consolidated-forensic-laboratory_o].

Kendrick, B. & Berch, S.M. Mycorrhizae: Applications in agriculture and forestry. In: Robinson, C., ed., Comprehensive Biotechnology, volume 3. Pergamon, 1985. In: Wiley, David, ‘Mycorrhizal networks and learning,’ iteration towards openness, July 21, 2011, accessed February 28, 2017, https://opencontent.org/blog/archives/1920.

Kratochvil, Vera, “Green Living Wall,” Public Domain Pictures, accessed February 27, 2017, http://www.publicdomainpictures.net/view-image.php?image=14972.

LaFantasie, Jordana, “What are Mycorrhizae? Definition, Function & Products,” Study.com, Science Courses Chapter 23, Lesson 16, accessed February 28, 2017, http://study.com/academy/lesson/what-are-mycorrhizae-definition-function-products.html#transcriptHeader.

Lynch, Jeff, “University of Washington – Ethnic Cultural Center,” 2014.

Majonaise, “Front of the Metropolitan Museum of Art, New York, New York,” Wikimedia, May 30, 2004, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File:MET_NYC.jpg.

Max A, “In the student district of Dresden. Some artists designed the backyards,” Wikimedia Commons, May 30, 2007, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File:Kunsthofpassage_Dresden.jpg.

Max Pixel, “Grooves Stone Scuffed Steinplatte Ground Grey,” accessed February 28, 2017, http://maxpixel.freegreatpicture.com/Grooves-Stone-Scuffed-Steinplatte-Ground-Grey-801001.

Max Pixel, “Water Droplet Rain Pattern Mech Drops Fly Screen,” accessed February 28, 2017, http://maxpixel.freegreatpicture.com/Water-Droplet-Rain-Pattern-Mesh-Drops-Fly-Screen-443975.

McCune, Bruce and Kristen Whitbeck, “Living in the Land of Mosses,” [Pscheidt, J.W., and Ocamb, C.M. (Senior Eds.). Pacific Northwest Plant Disease Management Handbook. Oregon State University. Corvalis, OR: 2017] accessed February 28, 2017, https://pnwhandbooks.org/plantdisease/pathogen-articles/nonpathogenic-phenomena/living-land-mosses.

McGee, Tim, “Biophilic Design - Mesh Sculptures and Mesh Canopies,” Likolab, 2015.

Merriam Webster, “Wood,” 2006, accessed February 27, 2017, http://media.web.britannica.com/eb-media/51/72251-035-01722E17.jpg; http://kids.britannica.com/elementary/art-66141/cross-section-of-a-tree-trunk.

Moddemeyer, Steve (Landscape Architect and Principal at CollinsWoerman), in discussion with authors, 2016.

National Oceanic and Atmosphere Administration, “The Water Cycle,” U.S. Department of Commerce and National Weather Service, 2010, accessed February 28, 2017, http://www.srh.noaa.gov/jetstream/downloads/hydro2010.pdf.

Nickpdx, “Creek and old-growth forest on Larch Mountain in Oregon,” Wikimedia Commons, May 28, 2006, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File%3ACreek_and_old-growth_forest-Larch_Mountain.jpg.

NordNordWest, “BIQ mit Bioreaktorfassade *(Am Inselpark 17)* auf der IBA Hamburg in Hamburg-Wilhelmsburg,” Wikimedia Commons, 2013, accessed March 2, 2017, https://commons.wikimedia.org/wiki/File:IBA_Hamburg_BIQ_(2).nnw.jpg.

Patte, David, “Old Growth Forest, Oswald West State Park, Oregon,” U.S. Fish and Wildlife Services, Flickr, November 14, 2010, accessed February 27, 2017, https://www.flickr.com/photos/usfwspacific/5227596108.

Pearl, Morris, “The Gates,” Wikimedia, February 23, 2005, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File:Gates_f.jpg.

Picard, Andre, “Extraradical mycelia (white) on the roots of Picea glauca(brown)” Wikimedia Commons, October 19, 2011, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File:Mycorhizes-01.jpg.

Pippalou, “Pine Cone,” MorgueFile, January 2014, accessed March 1, 2017, http://mrg.bz/f66ee2.

Pippalou, “Pine Needle Water,” MorgueFile, September 2013, accessed February 28, 2017, https://morguefile.com/p/868915.

Plant & Soil Sciences eLibrary, “Transpiration – Water Movement through Plants,” U.S. Department of Agriculture, National Science Foundation, National Research Initiative Competitive Grants CAP project, 2017, accessed February 28, 2017, http://passel.unl.edu/pages/informationmodule.php?idinformationmodule=1092853841&topicorder=5.

Pypker, Thomas, “The Influence of Canopy Structure and Epiphytes on the Hydrology of Douglas fir forests,” Dissertation Abstract, Oregon State University: Forest Science, 2004, accessed February 28, 2017, http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/13137/PypkerThomasG2004.pdf?sequence=1.

Ramsden, Alexandra, “Function Diagram: Splitting & Suspending Drops,” 2016.

Ramsden, Alexandra, “Moisture Responsive Cladding,” 2016.

Ramsden, Alexandra, “Vine Street Downspouts by Buster Simpson,” May 2015.

Royan, Jorge, “Frei Otto Tensed structures for the Munich 72 Olympic Games. Olympic Stadium and park. Munich Germany,” Wikimedia Commons, 2007, accessed March 2, 2017, https://commons.wikimedia.org/wiki/File:Munich_-_Frei_Otto_Tensed_structures_-_5249.jpg.

Schwen, Daniel, “Seattle Skyline view from Queen Anne Hill,” Wikimedia Commons, February 17, 2010, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File:Seattle_4.jpg.

Seattle Public Utilities (SPU), “Green Stormwater Infrastructure: 2016 Overview and Accomplishment Report,” King County Department of Natural Resources and Parks, Wastewater Treatment Division, 2016, accessed February 28, 2017, http://www.700milliongallons.org/wp-content/uploads/2017/02/1702_8095m_2016-GSI-accomplishment-Report-pages.pdf.

Seyriu-en, “Bryophyte rhacomitrium canescen,” Wikimedia Commons, December 22, 2010, accessed February 27, 2017, https://commons.wikimedia.org/wiki/File:Racomitrium_canescens.jpg.

Sirinathsinghji, Eva, “Plants Warn One Another of Pest Attach through Mycorrhisal Fungal Network,” Science in Society Archive, October 2013, accessed February 28, 2017 http://www.i-sis.org.uk/mycorrhizae_and_plant_communication.php.

SlenderWall, “Precast Concrete,” 2017, accessed February 27, 2017, https://slenderwall.com/benefits/architectural-precast-finishes.

Stefano Boeri Architetti, “Bosco Verticale - Stefano Boeri Architetti,” UN Climate Change Conference (COP21), Paris [2015].

Swank, W. "The Influence of Rainfall Interception on Streamflow." Clemson University Council. On Hydrol., Hydrol. In Water Resources Manage. Conf. Proc. 102-112, 1968; Coweeta Hydrologic Laboratory, Southeastern Forest Experiment Station, Forest Service, USDA, North Carolina, Asheville: 1968, accessed March 1, 2017 http://coweeta.uga.edu/publications/458.pdf.

Timquijano, “Tibetan Prayer Flags,” Flickr, April 4, 2011, accessed February 27, 2017, https://www.flickr.com/photos/timquijano/5599885208.

U.S. Environmental Protection Agency (USEPA), “Exterior Light Shelves,” Flixr, July 21, 2007, accessed February 28, 2017, https://www.flickr.com/photos/usepagov/3900223997.

U.S. Geological Survey, “Transpiration – The Water Cycle,” U.S. Department of Interior, December 2016, accessed February 28, 2017, https://water.usgs.gov/edu/watercycletranspiration.html.

Unsplash, “Path through forest trees,” PEXELS, accessed March 1, 2017, https://www.pexels.com/photo/pattern-texture-metal-design-136098/.

Urban Remains, “Historically Important C. 1899 Exterior Brand Brewery Administration Building Brownish-Orange Ornamental Terra Cotta Block with Centrally Located Sunflower,” 2017, accessed February 28, 2017, http://www.urbanremainschicago.com/historically-important-c-1899-exterior-brand-brewery-administration-building-brownish-orange-ornamental-terra-cotta-block-with-centrally-located-sunflower.html.

Van Pelt, Robert “Identifying Mature and Old Forests in Western Washington: Douglas Fir (Pseudotsuga menziesii),” Washington State Department of Natural Resources, Olympia, WA, 2007: page 53; accessed February 28, 2017, http://file.dnr.wa.gov/publications/lm_hcp_west_oldgrowth_guide_df_hires.pdf.

Viau, Elizabeth Anne, “A Food Chain in the Temperate Rain Forest Biome,” Wood-Builders, Lessons, 2000, accessed March 2, 2017, http://www.world-builders.org/lessons/less/biomes/rainforest/temp_rain/tempweb.html.

Wakeford , T. Liaisons of Life : Liaisons of Life: From Hornworts to Hippos, How the Unassuming Microbe has Driven Evolution. New York: John Wiley & Sons, 2001. In: Wiley, David, ‘Mycorrhizal networks and learning,’ iteration towards openness, July 21, 2011, accessed February 28, 2017, https://opencontent.org/blog/archives/1920.

Washington Forest Protection Association (WFPA), “Tree Species – Coniferous Tree Species are Dominant in Washington,” Forest Policy, accessed March 1, 2017, http://www.wfpa.org/forest-policy/washington-forests/tree-species/

Webb, Scott, “Pattern texture metal design,” PEXELS, May 23, 2016, accessed February 28, 2017, https://www.pexels.com/photo/pattern-texture-metal-design-136098/.

Weber Thompson, “Watershed office building-1,” 2017.

Weber Thompson, “Watershed office building-2,” 2017.

Weber Thompson, “Watershed office building-3,” 2017.

Whitbeck, Kristen, “Basic Moss Biology,” Oregon State University - Botany 465/565; Corvallis, OR: Spring, 2000, accessed February 28, 2017, http://bryophytes.science.oregonstate.edu/page35.htm.

Workshop/APD, “Greenwich Green,” Houzz, accessed February 27, 2017, http://www.houzz.com/photos/187416/Greenwich-Green-contemporary-other; http://www.workshopapd.com/.

World Book Encyclopedia, “Inside a Green Leaf,” World Book-Childcraft International, Inc., Chicago: 1979, accessed February 27, 2017, http://www.robinsonlibrary.com/science/botany/anatomy/graphics/insideleaf.gif.

Wunee, “Pine Cone,” MorgueFile, January 2014, accessed March 2, 2017, http://mrg.bz/a49f77.

Ωmega, “Pont Neuf emballé par Christo 3 - 1985,” Flickr, November 18, 2009, accessed February 27, 2017, https://www.flickr.com/photos/23416307@N04/4116023544.

ACKNOWLEDGEMENTS

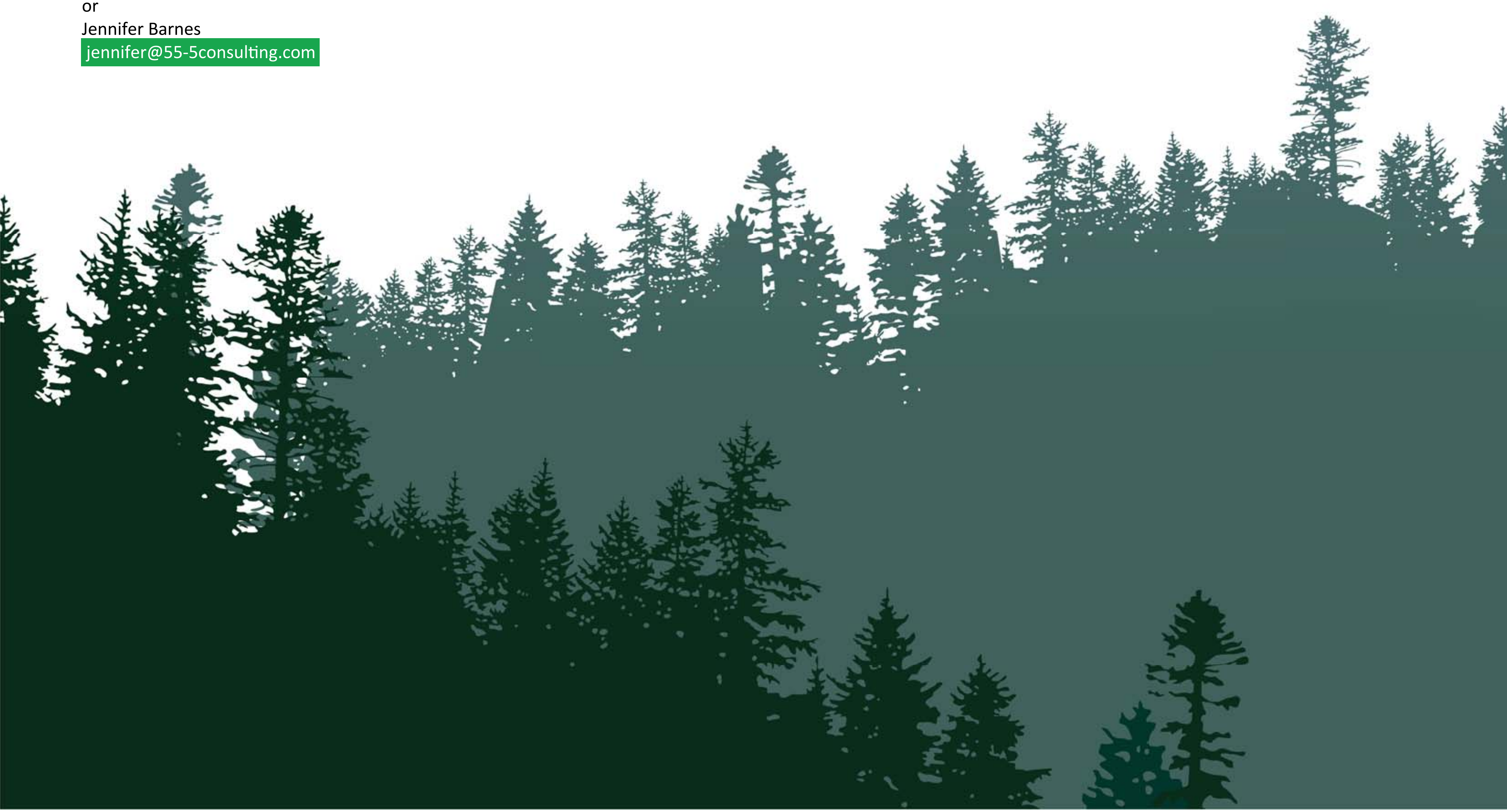
This study owes a debt of gratitude to scores of individuals and companies across the Pacific Northwest, including:

Neelima Shah, Bullitt Foundation
Brett Davies, Ecotrust
Mark Grey, Stephen C. Grey & Associates
Rachael Meyer, Weber Thompson
Meyer Harrell, Weber Thomspon
Weber Thompson Architects
Matthew Combe, Seattle 2030 District
Amy Waterman, Seattle 2030 District
Joel Sisolak, Capitol Hill Housing
Jeff Speert, JRS ENGINEERING
Steve Moddemeyer, Collins Woerman
Chris Webb, Herrera Inc.
Jason King, Mithun
Tim McGee, Liko Lab
Patti Southard, King County
Matthew Jones, Magnusson Klemencic Associates
Steven D. Haluschak, Magnusson Klemencic Associates
Stefanie Young, Rushing Co
Jonathan Morely, Berger Partnership
Todd Bronk, Berger Partnership
Living Future Institute
Biomimicry Oregon

Thank you, also, to the many individuals who have attended Urban Greenprint workshops and contributed so much to the conversation as well as to the firms that have supported our research and events.

For additional information,
Please contact

Alexandra Ramsden
alexandrar@rushingco.com
or
Jennifer Barnes
jennifer@55-5consulting.com



www.urbangreenprint.org