Compendium of Scientific and Practical Findings Supporting Eco-Restoration to Address Global Warming

Volume 2, Number 2, January 2019, r.1

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NOTE: Citations in our text are in brackets. The format is [lead-author year: page number (if a specific quote is referenced)]. In text quoted within a referenced paper the citation format may be different; we have preserved the original.

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About Biodiversity for a Livable Climate

Biodiversity for a Livable Climate, bio4climate.org, is a 501(c)(3) non-profit founded in 2013 whose mission is to support the restoration of ecosystems to reverse global warming. We are:

- ***A think tank***, creating research and reports (such as this Compendium), and presenting conferences on the science and practice of eco-restoration with speakers from around the world.
- ***An educational organization***, offering presentations, courses and materials, including over 200 videos of speakers (with over 125,000 views on YouTube) from our 12 conferences since November 2014 (bio4climate.org/conferences), with many restoration and climate-positive examples from both scientists and practitioners.
- ***An advocate*** that reaches out to other organizations to encourage and facilitate the incorporation of eco-restoration as a climate solution into their own messaging and actions. We seek to connect to other groups and projects to help nourish and advance their own growth, and carry messages among groups to collaboratively learn and build on each other's efforts, and occasionally facilitate the emergence of new groups. Since climate affects everyone, every organization has to deal with it in its own way, and we strive to help with the transition.

- ***An activist group*** that engages in non-partisan political processes. For example, we helped shepherd a bill through the legislative process in 2017 to establish a Maryland Healthy Soils Program.

We are a small 501(c)(3) non-profit with a major impact in addressing climate, and we rely on your generous contributions! Please go to www.Bio4Climate.org/Donate to join our monthly donor program, or to make a one-time donation, all tax deductible. Many thanks!

Suggested Citation

Compendium of Scientific and Practical Findings Supporting Eco-Restoration to Address Global Warming, Vol 2 No 2, January 2019 , https://bio4climate.org/resources/compendium/. This is a collection of article summaries and commentary that will grow as new literature becomes available and as older literature is re-discovered.

Acknowledgements

Current contributors to this collection are co-editors Hannah Lewis and Adam Sacks, writers Hannah Lewis and Charlie Shore, and reviewers Philip Bogdonoff, Fred Jennings and Robert Larabee. The value of the contributions from our many speakers and collaborators cannot be overstated. We invite our readers to review our collection of conference videos on the program page of each of our twelve conferences (https://bio4climate.org/conferences/) as of November 2018.

We are most appreciative of the support from our sponsors over the past four years. In particular, the 11th Hour Project provided significant funding for our first two years, and the new and important institution that it helped create, the Regenerative Agriculture Foundation, is continuing its strong moral and financial support. We are also pleased to acknowledge generous conference sponsorship from the Organic Consumers Association, Regeneration International, the Virgin Earth Challenge, Bristol Community College, the Tufts Institute of the Environment, Margaret Roswell, the Overbrook Foundation and Foundation Earth. Additional important support has been kindly provided by the Nutiva Foundation, the Rockefeller Family Fund, the Savory Institute, Irving House and the Bionutrient Food Association. We also gratefully acknowledge support from several institutions, including Tufts University, Harvard University, Bristol Community College, and the University of the District of Columbia.

Conversion table

hectares vs. acres	1 ha ≈ 2.5 ac
megagrams vs. tons	1 Mg = 1 metric ton
teragrams vs. tons	1 Tg = 1 million metric tons
petagrams vs. gigatons	1 Pg = 1 billion metric tons (1 Gt)

weight[1] carbon vs. weight CO_2	12/44
parts per million CO_2 vs. weight of carbon[2]	1 ppm CO_2 ≈ 2 Gt carbon

Introduction

While previous issues of the Compendium have addressed ecosystem strategies to reverse global warming, here we discuss ecosystem restoration to adapt to the consequences of climate change. From drought in Cape Town and wildfire in California and Greece to flooding in Beijing, Paris, Houston and North Carolina, each new report of catastrophe makes climate change more real and more frightening. And while taking the giant steps required within the next 12 years to avert climate catastrophe as the IPCC advises[3] may seem out of reach for everyday people, anyone can act locally and regionally to restore the ecosystems that protect our homes and communities. Happily, healthy ecosystems contribute both to mitigation and resilience.

Slowing down water and the art of survival

Managing rainwater within a landscape so that neither heavy storms nor long dry spells devastate human endeavors and constructions is referred by Yu Kongjian as the "art of survival" [Yu 2012]. This Chinese landscape architect with an ecological mindset learned the art of survival by studying the ways of ancient peasant farmers. He contrasts the wisdom embodied in their simple structures, such as terraced crop fields on sloping land designed to capture and hold storm water for later use with the modern "art of pleasure making and ornament."

Modern urban design tends to favor non-functional decorative features – "monumental architecture" like a grand stadium, manicured lawns, or fruit trees grown for their blossoms rather than their fruit, for example. Such investments are pretty, but expensive and "easily superseded," according to Yu. Equally beautiful urban designs such as green rooftops and boardwalk-accessible urban wetland parks, on the other hand, can be affordable, high-performing features designed to withstand environmental extremes.

> World cities, and especially those in China, face deepening environmental problems: flood, drought, pollution, aquifer drop, loss of natural habitat and cultural heritage. A low-culture approach using what I term 'adaptive design' provides a technique for solving problems in an economical and ecological way [Yu 2012: 72].

[1] We refer to carbon in soils and biomass, etc. by weight of carbon; atmospheric carbon may be referred to by weight of carbon *or* by weight of CO_2, a frequent source of confusion
[2] Ppm is a *volume* measurement, 1 ppm is approximately equal to 2 gigatons carbon by *weight* - and yes, this can be confusing too. Moving 1 ppm CO_2 from the atmosphere results in 2 Gt carbon added to soils or other carbon sink.
[3] "We have 12 years to limit climate change catastrophe, warns UN":
https://www.theguardian.com/environment/2018/oct/08/global-warming-must-not-exceed-15c-warns-landmark-un-report

For Yu, design is adaptive “when it responds elegantly and efficiently to its environmental setting so that new uses can endure” [Yu 2012: 72], meaning a design for urban resilience in the face of ever more severe weather.

It’s not only Chinese peasants who understood water cycles and how to manage them. Ancient peoples of the Middle East actually depended on seasonal flooding. Like we do today, these ancient farmers grew crops on river floodplains. Yet unlike today’s practices of diking off the river to keep croplands dry, they allowed annual flood pulses onto their fields.

> Annual flood pulses are so predictable and long-lasting that plants, animals, and even human societies have adapted to take advantage of them. In ancient Egypt and Mesopotamia, the fertility of the soils was renewed each year by the annual overflow of the rivers, thereby sustaining large populations in one place for millennia and permitting the development of great civilizations [Sparks 1995: 168].

In India’s Rajasthan region, where the monsoon cycle brings torrents of rain all at once, after which begins a long dry season, rural farming communities built johads. These are small earthen dams on sloping land that create ponds or wetlands by harvesting stormwater during the rainy season. This water reserve then becomes a vital resource during the dry season. However, johads were abandoned in favor of more modern borehole wells, which are deep, not wide like a basin, and therefore not able to catch rainwater, which instead simply ran off the landscape. By the 1980s the johads were gone, wells were dry, people walked 9km in search of drinking water, and farmers left town in search of other employment. But then communities throughout the region started to rebuild johads, which raised the water table enough to refill wells, support agriculture and wildlife, and for streams to flow again [Singh 2015, SIWI 2015].

Similarly, severe drought in Burkina Faso in the Sahel region bordering the Sahara Desert presented farmers with a simple choice: find a way to restore the land and farm again, or migrate. As in Rajasthan, these farmers were prompted in desperation to rediscover their region’s own traditional techniques for water conservation. They dug rows of small pits in their fields to capture rainfall, which they filled with compost and manure, and into which they planted crops. Other farmers built stone terraces along the contours in their fields to capture rainfall and prevent runoff; some farmers did both. Over time, at least 140,000 farming households over 200,000 hectares or more were practicing these techniques, resulting in the revival of crop production, reestablishment of trees, shrubs and grasses, and the recharging of the area’s water table by a depth of five meters [Reij 2009].

Land management and hydrology

The concept of hydrological drought (as distinct from meteorological drought) helps explain the success of these age-old techniques to enhance surface and groundwater supply. Meteorological drought is the occurence of abnormally low rainfall for a given region.

Hydrological drought is a consequence of meteorological drought – it happens when surface and ground waters run low thanks to a prolonged rainfall shortage compared to historical conditions for a region. Human water consumption for irrigation, industry and household use intensifies hydrological drought [Wada 2013].

Yet, as seen in the examples above, proper land management can raise the water table in an area in spite of occasional episodes of meteorological drought. In other words, while we cannot directly control when and how much rain falls, we can manage what happens to water once it reaches the ground.

Rain falling on much of our modern built environment is managed with ditches, gutters, drains and sewers designed to whisk it away as quickly as possible, rather than absorbing it in place. Farmland too is sometimes fitted with underground “tiles” (pipes) to drain fields, or with dikes to keep water out. Moreover, by the very absence of design, nearly all conventional farmland is so lacking in organic matter that it can barely absorb rainfall, which instead runs off the soil surface carrying soil with it.

In short, water hitting the ground in today’s world moves quickly. Stormwater moves in torrents over land seeking an outlet. That is until the outlet is full, at which point the water stagnates, rising like a bathtub, soaking and rotting property.

Ironically, the water we seek to drain away when there’s plenty becomes desperately lacking after the rain has stopped. Two sides of the same coin, flooding and drought often go hand in hand. By the same token, because a surfeit of impervious surfaces is at the root of these twin challenges, the solution of turning more land into a spongy surface helps resolve both problems at once. Spongy surfaces slow down water, allowing it to percolate into groundwater reserves.

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Ecosystem restoration creates a spongy land surface by protecting soil with vegetation, thus allowing the soil to repair itself with biodiversity and organic matter, key ingredients of a good soil sponge. And beyond fostering drought and flood resilience, healthy ecosystems serve a myriad of protective functions, including cooling their surroundings, cleaning polluted water, drawing down CO_2, and harboring the biodiversity that is the magic making ecosystems perform so many vital functions.

However, because the services rendered by nature go widely unrecognized or taken for granted, nature's power as an ally is often shackled.

> Human societies tend to value the potential benefits that a landscape might provide in a limited way, adjusting management practices towards desired outputs by maximizing the benefits gained from one or some of the services (often the provision of goods) leading to the loss of multifunctionality and the degradation of natural capital at the expense of human welfare [Schindler 2014: 230].

An example of a landscape with undervalued ecosystem function is a river floodplain. Because floodplains are often favored for agricultural, industrial, commercial or residential uses, rivers are constrained to their channels and their banks leveed, despite that a river and its floodplains are members of a single interdependent ecosystem. Through seasonal pulses of floodwater over the banks, like a heart pumping blood through a body, a river replenishes groundwater and nutrients throughout its floodplains, making these areas some of the planet's most productive and biodiverse ecosystems [Sparks 1995]. Consider, for example, that the Amazon Basin is a floodplain, where fish biodiversity actually depends on riparian forest cover [Arantes 2017]. Fish swim into flooded forests during flood pulses and directly consume terrestrial floodplain vegetation (seeds, fruits, detritus).

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In addition to supporting robust biodiversity, floodplain ecosystems give water somewhere to go during severe flooding events rather than damaging cropland, houses or other properties. By allowing water time to infiltrate into the ground, floodplains recharge groundwater, thus alleviating future droughts [Opperman 2009]. Riparian ecosystems also serve as a migration corridor for birds and fish especially, and also as a refuge from the heat of more exposed areas.

In other words, intact river-floodplain ecosystems perform multiple ecosystem services and thus help us manage some of our most pressing societal problems if only we acknowledge the value of floodplains in these terms.

Making space for water

Given competing interests for floodplain property, some have argued for strategic partial reconnection of floodplains to the river by allowing portions of floodplain to flood, so that pressure elsewhere along the river during a flood may be alleviated [Opperman 2009].

For example, California's Yolo Bypass was created in the early 1900s after the Sacramento River flooded several times and levees proved inadequate to protect the city [Sommer 2001]. The site of the bypass was historically the vast wetland floodplain of the Sacramento River and other nearby rivers and streams that had since been converted to agriculture. Today, the bypass reconnects the river to its floodplains.

Since 1997, Yolo Bypass also features more than 16,000 acres of wildlife area, including seasonal and perennial wetlands, riparian forest, pasture, and seasonal crop production where fields are allowed to flood during winter. This solution has not only kept Sacramento dry during numerous high water events, it has also restored diverse populations of fish, bird, snake, mammal and other species to the area, while providing recreational and educational opportunities to nearby communities.

While the Yolo Bypass Wilderness Area exemplifies the large-scale engineered reconnection of a major river to its floodplain, many smaller stream floodplains benefit from the work of non-human engineers. Long considered the nemesis of ranchers and farmers alike, beavers caught damming irrigation ditches or flooding fields are often summarily trapped and killed. Yet in Elko, Nevada, beavers and altered livestock grazing regimes have brought stream beds back to life [Goldfarb 2018, Evans & Griggs 2015].

One rancher's management change began by excluding cattle from grazing along Elko's Suzie Creek – just during the hot season when plants are vulnerable. This allowed rushes, sedges and other vegetation to grow back, slowing water down enough for sediment to fill in the gouged out gully and raise the streambed back up to the level of its floodplain. Once beavers discovered their favorite food - willow - growing again at Suzie Creek, they moved in and have since built 139 dams there. These dams, in turn, raised the water table by about two feet, becoming the natural irrigation system for the ranch's now lush riparian pastureland. The beaver dams proved vital in 2012-2015 when Suzie Creek kept flowing despite several summers of drought that left the rest of the region parched.

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At around the same time as Suzie Creek's revitalization, across the Atlantic in Devon, England, a pair of Eurasian beavers were introduced to a wooded stream at the headwaters of the Tamar River [Puttock 2016]. A few years and 13 dams later, the beavers' activity was filtering pollutants out of water passing through the dam sites and slowing the flow so as to minimize downstream flooding during storms. As in North America, beavers were once abundant in Europe, but by the 16th Century were wiped out in the UK. In recognition of beavers' beneficial effects on hydrological systems, multiple reintroduction programs have begun establishing colonies across Europe and North America.

"Because of their abilities to modify streams and floodplains, beavers have the potential to play a critical role in shaping how riparian and stream ecosystems respond to climate change," explain the authors of a recent study of potentially suitable beaver reintroduction sites [Dittbrenner 2018: 2]. The authors continue:

> By damming streams, beavers create pond and wetland complexes that increase … species and habitat diversity, and therefore ecosystem resilience to climate-induced environmental change. Beaver impoundments slow stream velocity allowing sediment suspended in the water column to settle, aggrading incised stream systems, and reconnecting streams with their floodplains. The increase in surface water promotes groundwater recharge, storage, and supplementation during base flows. The increased geomorphic complexity also promotes higher thermal variability and cold-water refugia in deeper waters and in areas of downstream upwelling [Dittbrenner 2018: 2].

Furthermore, by repairing hydrological functioning and increasing a landscape's overall level of moisture, beaver populations could literally dampen conditions for wildfire, which is intensified by drought [Maughan 2013].

Such vital ecosystem services provided by a keystone species like beaver in the era of climate change are nothing to scoff at. And while beavers are still trapped and killed for sport and by hunters or land managers who consider them a nuisance [Goldfarb 2018], *castor canadensis* is also increasingly accepted, as evidenced by more pro-beaver attitudes within the fish and wildlife departments of western states that had previously considered them mainly as pests. Beavers are discussed on state wildlife agency websites in terms of "living with wildlife,"[4] where

[4] https://wdfw.wa.gov/living/beavers.html, https://www.dfw.state.or.us/wildlife/living_with/beaver.asp, https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=114087&inline

beaver life histories are described, along with explanations of the benefits of beaver dams for landowners and for the landscape overall.

Similarly, Holland is learning new ways to live with water. In the Netherlands, literally “low country” due to much of its land area being at or below sea level, there is an age-old struggle with water and flooding, notably through the use of dikes. However, alarmed by recent flooding and the prospects of sea-level rise from climate change, the nation is undergoing a paradigm shift wherein the guiding principle for water management has become “make room for the river” [Pahl-Wostl 2006]. Among other tactics, certain areas are being “depoldered,” meaning dikes removed from low-lying areas and the land returned to wetland; people living in those areas are assisted in relocating [Bentley 2016].

Similarly, several cities in China are striving to “make friends with water” through adoption of the concept of “sponge cities” that aim to “retain, adapt, slow down and reuse” stormwater by increasing the porosity of urban surfaces, including increasing the amount of ecologically functional urban green space [Guardian 2018].

In our panic over increasing numbers of extreme weather events, we may grasp at familiar solutions – extra air-conditioning to shelter from the heat, higher levees to hold back floodwaters, more irrigation to combat drought, or logging forests to reduce wildfire fuel. While these measures may (or may not) temporarily bandage the situation, they increase the fragility of our built environment and usher us further down the path of climate chaos though unrelenting energy consumption and increasingly hobbled ecosystems. For our own sake, it’s time to make friends with nature and to acknowledge her superior power by partnering with instead of continuously fighting her.

Restoration in action

We know how to enhance resilience to extreme weather where we live and work. Communities throughout the world are utilizing these approaches, and here we highlight several initiatives in a variety of habitats to illustrate potential paths forward. More information is included just below each project description. Following this section is a collection of summaries of scientific articles that provide evidence for eco-restoration to enhance resilience to a chaotic climate.

Sponge cities, China

“In the past, humans have taken the land away from the water; now we need to give the land back.” – Professor Hui Li [Guardian 2017]

Faced with severe flooding in many cities across China, such as a major 2012 Beijing flood, the Chinese government announced the Sponge Cities Initiative in 2014 as a remedy. The national government identified 16 cities as pilot sites, soon adding another 14 cities, including Beijing. The sponge city concept represents a paradigm shift in flood management away from impervious surfaces and chutes meant to swiftly drain a city after a storm. By contrast, a sponge city aims to manage stormwaters by vastly increasing the amount of soft, permeable surfaces that can absorb water where it falls, filter it, and store it in vegetation, ponds and aquifers.

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> According to the "Guideline of Sponge City Construction", the target of the approach is to increase the area of urban land able to absorb surface water discharges by approximately 20%, and to retain or reuse approximately 70% of urban stormwater by 2020; and further reuse up to 80% of stormwater by 2030s. This means that the ideology of the Sponge City concept is not only addressing urban flood risk, but also taking a proactive approach to collection, purification and reuse of urban stormwater in Chinese cities to address future climatic extremes (floods and droughts) [Chan 2018: 3-4].

One of China's new sponge cities, the Lingang/Nanhui district of Shanghai, is buildIng streets with permeable pavement, which allows water to percolate into the ground beneath, and planting rain gardens between lanes of traffic as well as some 400,000 square meters of rooftop gardens. In another city, the 84-acre Qunli Stormwater Park consists of a wetland surrounded by newly constructed filtering ponds that collect and filter the city's stormwater runoff before slowly releasing it into the wetland, which in turn recharges groundwater. Earthen mounds are planted in cottonwood trees, and a system of elevated pathways through the park allows people to enjoy the space.

Inspiration for Qunli Stormwater Park and several other sponge city landscape design features comes from the ancient water management practices of Chinese peasants. According to landscape architect and sponge city advocate Yu Kongjian, peasants constructed simple terraces in combination with ponds to regulate flood and drought. "On sloping ground in monsoon regions these water catchments are critical," Yu explains in an essay explaining the sponge city concept [Yu 2017: 29]. "Peasants also employed crop rotation to maximize yield, beautifully sustaining humanity for thousands of years" [Yu 2017: 29]. He continues :

> Ironically, these centuries-old productive landscapes have given way to urbanization. Fine terraces are leveled into … planes called developable land; small ponds are drained and replaced with underground drainage systems; ponds and dikes give way to mechanical farming. The centuries-old ecosystem balance is broken, leading to flood, drought and habitat loss. Grey infrastructure haunts Chinese cities, while high maintenance landscapes with ornamental planting make broad scale landscape change unaffordable. [Yu 2017: 29]

China's 'sponge cities' are turning streets green to combat flooding:
https://www.theguardian.com/world/2017/dec/28/chinas-sponge-cities-are-turning-streets-green-to-combat-flooding
"Sponge City" in China: a breakthrough of planning and flood risk management in the urban context, Land Use Policy:
https://www.sciencedirect.com/science/article/abs/pii/S0264837717306130
Yu, Kongjian, 2017, Sponge cities: rediscovering the wisdom of the peasant, Landscapes/Paysages Spring/Printemps 2017,
https://www.csla-aapc.ca/landscapes-paysages/back-issues.

Community-based watershed stewardship programs, USA

From California to Minnesota, Pennsylvania, Maryland, and Washington DC, people are coming together in their communities to learn what river their watershed drains into, how urban stormwater management has impaired that river, and how to restore river-floodplain ecosystems through a grassroots approach.

A watershed is an area of land over which any rain that falls drains into the same river or water body. For example, all waters falling onto the eastern half of Washington DC flows into the notoriously polluted Anacostia River, while the western half of the nation's capital drains into the Potomac River. Thus, the city is split into two watersheds.

The Anacostia River was once surrounded by forests, meadows and wetlands, which absorbed, filtered and slowed water on its way downhill to the river. Over time, urban development and industrial processes paved over these natural sponges. The area of tidal wetlands surrounding the Anacostia has shrunk from 2,500 acres in the 1800s to 150 acres today.

Today's stormwater catchment made up of asphalt streets, parking lots and rooftops leaves water nowhere to go but into storm gutters, gushing out to the river, sometimes flooding over its banks. Furthermore, in many of the older parts of Washington, DC, the infrastructure uses CSOs ("combined sewer overflow") -- where storm drains share pipes with the sewer system -- and therefore the stormwater exacerbates water treatment issues. There is thus an added incentive to reduce stormwater runoff.

The Anacostia Watershed Society (AWS), a D.C. non-profit with a mission to make the river "fishable and swimmable by 2025," engages school children and other community members in wetland restoration along the river. In addition, as in several other communities around the country, AWS partners with the DC Dept of Environment to train community members to be ambassadors for the river. Over the course of a several-week training program, Watershed Stewards learn how individual houses and buildings contribute to the problem with impervious surfaces and gutter downspouts directing rain water directly into storm sewers. Then they learn about absorptive green rooftops, and the possibility of redirecting water from a downspout to a rain garden or a deep-rooted perennial bed, where the water can percolate into healthy spongy soil, ultimately recharging groundwater.

Primed with knowledge, enthusiasm, and the camaraderie of fellow stewards, participants are expected to implement a project of their own, to teach their neighbors what they've learned, and to volunteer in related community projects focusing on watershed restoration. In Minnesota, watershed steward projects redirect rainfall from gutters into gardens, where it can hydrate plants and recharge groundwater, at a rate of more than 1 million gallons per year. According to the program website, this outcome is due to the efforts initiated in 2013 which now include 141 stewards working in partnership with seven watershed districts and one municipality. An Anne Arundel, Maryland, program started in 2009 boasts having planted nearly 100,000 native plants, trees and shrubs, led by some 200 stewards in 100 communities engaging 134,000 of their neighbors in watershed restoration efforts.

Minnesota : https://masterwaterstewards.org/
Washington DC : https://www.anacostiaws.org/
Maryland : http://aawsa.org/,
https://www.mdsg.umd.edu/topics/watershed-stewards/watershed-stewards
Pennsylvania : https://extension.psu.edu/programs/watershed-stewards
California: https://ccc.ca.gov/what-we-do/conservation-programs/watershed-stewards-program/

Beavers for flood reduction, United Kingdom

To reduce the severity of flooding in Lydbrook, Gloucestershire, England, where a 2012 flood did extensive damage, the UK Ministry of Environment released a family of beavers upstream of the village in a 6.5 ha enclosure in a publicly-owned forest. Scientists who have studied the stream believe the beaver dams could hold back some 6,000 cubic meters of water, which might otherwise gush into the village during a heavy storm. If successful, this landfill-tax-funded project is intended to be replicated elsewhere in the UK. Beavers have already been successfully reintroduced elsewhere in England and Scotland, resulting in the Scottish government listing beavers as a protected native species.

Beavers released in Forest of Dean to prevent flooding:
https://www.theguardian.com/environment/2018/jul/24/beavers-forest-dean-possible-flooding-solution
Meet the latest recruit to the UK flood defence team: the beaver:
https://www.theguardian.com/environment/2017/sep/16/beavers-uk-flood-defences-forest-of-dean
Beavers could be reintroduced to Wales after centuries absence:
https://www.theguardian.com/environment/2017/jan/02/beavers-could-be-reintroduced-to-wales-after-centuries-absence
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Low-tech stream repair for drought resilience: western USA

As the hydrological benefits that beaver dams bring to streams and surrounding landscapes becomes better known, ranchers, wildlife managers and researchers are increasingly working together to repair streams by building Beaver Dam Analogs (BDAs). This method is attractive to ranchers searching for ways to manage drought and to irrigate their pastures reliably. In the spring, snowmelt or heavy rainfall can happen quickly, leaving parched landscapes where it's needed as it rushes downstream into a river and out of sight. Beaver dams slow water down. The human-made BDAs create pools and rehydrate the landscape, ultimately attracting beavers to return, recolonize the streams, and keep the dams in good repair.

"The longer that we can keep that [water] on the landscape, we increase the productivity of those plants. And [that] ultimately leads to more drought resilience, right? These sponges fill up with water. It's like putting money in the piggy bank for those lean times," said Jeremy Maestas, an ecologist with the department of agriculture's Natural Resources Conservation Service. As part of the Sage Grouse Initiative to repair sagebrush habitat, NRCS hosts training workshops throughout the region from Oregon to Montana to Utah on how build the small, porous, beaver-inspired dams in streams.

Beavers: an unlikely solution to Western drought:
http://www.wyomingpublicmedia.org/post/beavers-unlikely-solution-western-drought#stream/0
SGI workshop explores 'cheap and cheerful' riparian restoration to benefit wildlife and ranchers:
https://www.sagegrouseinitiative.com/enhancing-habitat-resilience-mimicking-beavers-cheap-cheerful-restoration/

Riparian restoration, California

The arid San Joaquin Valley of California is intensively farmed and dependent on irrigation. The San Joaquin River, once teeming with migrating fish and other wildlife, is surrounded by farmland and has become warm, muddy, and nearly devoid of aquatic life. In 2012 and 2014, River Partners, a California non-profit dedicated to restoring riparian habitat and river connectivity, partnered with state and federal agencies to buy 2,100 acres of farmland adjacent to the river. The farmers were ready to let the land go because of its proneness to flooding.

To reconnect and restore the floodplain, Dos Rios project workers are breaching berms and levees and planting native trees and shrubs tolerant of ephemeral flooding. This is one of several similar projects managed by River Partners, as well as others led by the state. Further funding for such floodplain restoration efforts is likely to continue given that California voters have passed Proposition 68 or "California Drought, Water, Parks, Climate, Coastal Protection, and Outdoor Access For All Act of 2018." This legislation to invest $4 billion in park and ecosystem conservation and restoration and climate resiliency includes $300 million for floodplain projects in the Central Valley.

Dos Rios Ranch Preserve: California's largest floodplain restoration project:
https://www.riverpartners.org/project/dos-rios-ranch/
California is preparing for extreme weather. It's time to plant some trees:
https://www.nytimes.com/2018/07/15/climate/california-is-preparing-for-extreme-weather-its-time-to-plant-some-trees.html
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Saltwater marsh restoration, Canada

The Atlantic coast of Canada has started seeing damages related to sea-level rise and storm surges, including flooding, landslides, and shoreline recession. Some communities fear dikes will fail. As a result, people are looking to restoration of native coastal ecosystems as a defense against rising waters. When flooded, coastal marshes often receive large sediment loads that raise their elevation, potentially keeping pace with higher ocean levels. A recent study [Schuerch 2018] showed that making space for inland marsh migration can allow marshes even to thrive in the face of sea-level rise, which is expected to be 1 to 2 feet by 2100 on much of the Canadian Atlantic coast.

In 2010, the Canadian government funded a project in the Bay of Fundy on the Atlantic Coast to restore 16 hectares of saltmarsh land, long ago dried for agriculture, back to its original marshy state. Ducks Unlimited Canada, who led the project, initiated the restoration process by breaching a 150 year-old dike to allow the tide to flow back onto the land. The purpose of this project was to preserve agricultural land further inland from the eroding coastline and rising seas, so a new dike was built just behind the restored marsh.[5]

[5] A similar project is being undertaken in Northern California: "HUMBOLDT BAY NWR: Living Coastline Project Will Restore Tidal Salt Marsh at Humboldt Bay" - https://www.fws.gov/fieldnotes/regmap.cfm?arskey=36946.

As noted, marshes can adapt to sea level rise by accumulating sediment. These sediment deposits also enable marshes to quickly bury (or sequester) large amounts of carbon. During the six years after the restoration process began, annual carbon accumulation at the site averaged 13.29 Mg/ha [~5.5 t/ac], mainly due to the sediment deposit that would otherwise likely have mineralized and been released as CO2.

> If not deposited in marshes, the organic C in the suspended sediments in the upper Bay of Fundy is likely to be deposited in nearby mudflats. Unlike salt marshes, which tend to be stable or accreting, mudflats are highly dynamic systems subject to frequent erosion events, with scouring to depths of 20 cm or more. … Sediment and associated organic C is also more likely to be preserved in marshes compared with mudflats due to the stabilization effect of macrophyte roots and the associated erosion protection [Wollenburg 2018: 10].

In addition to quickly burying large amounts of carbon, the restored marsh showed signs of success when vegetation (cordgrass) re-established itself in 2012. By 2016, although patches of bare mud were still present, cordgrass was covering most of the marsh area.

This success story is likely to be repeated several times over since the Canadian government announced $75 million for coastal restoration as part of a $1.5 billion Coastal Protection Plan. This includes a project to restore another 75 hectares of salt marshes in the same Bay of Fundy. The coastal restoration fund prioritizes coastal watersheds, estuaries, saltgrass marshes, eel-bed marshes, and migratory corridors for salmon and other species.

Salt marsh restoration project launched:
https://www2.gnb.ca/content/gnb/en/news/news_release.2010.10.1657.html
Coastal restoration fund backgrounder:
https://www.canada.ca/en/transport-canada/news/2017/05/coastal_restorationfund.html East Coast salt marshes to be restored to battle effects of climate change:
https://www.cbc.ca/news/canada/nova-scotia/east-coast-salt-marshes-to-be-restored-1.4721044
Future response of global coastal wetlands to sea-level rise:
https://www.nature.com/articles/s41586-018-0476-5.
Rapid carbon accumulation following managed realignment on the Bay of Fundy:
https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0193930.

Holistic planned grazing for drought relief, Zimbabwe

“You must have had a lot more rain because how else can water appear where it has not existed before?” asked Zimbabwe Minister of Water Development Sam Nkomo when he saw a clear water-lily-covered pool that had only come to exist in the upper river catchment two years prior [Savory 2009].

Two herders and their employer Allan Savory explained that “the water had come and stayed through the dry season higher up in the river system than it had ever been known [to] before” [Savory 2009]. But this was not due to more rain than usual. Rather, it was because the ranch had increased its cattle and goat numbers 400% and kept them in one herd, which they constantly moved to fresh grazing land according to the needs of the grasses and plants. Managing grazing this way meant the vegetation got quick, strong periodic treatments of trampling, urine and manure, following which it had sufficient time to recover and regrow. This stimulated thicker vegetation cover and better water absorption into the soil, thus increasing groundwater and streamflow.

Faced with drying wells and silt-filled dams nationwide, Minister Nkomo responded positively to his discovery of Savory’s “holistic planned grazing” for restoring rivers and biodiversity and combating drought. In 2009 when this article was published, plans were underway to replicate this grazing management approach in other Zimbabwe watersheds.

Dimbangombe: Success in Africa, stories and photos by Allan Savory:
http://www.rangemagazine.com/features/fall-09/fa09-what_works.pdf
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Regreening the Tigray region, Ethiopia

More than 224,000 ha of drylands in the Tigray region of northern Ethiopia that had previously succumbed to devastating cycles of drought and flood have been restored. As a result, the hillsides are green again, previously dry wells are recharged, and fruit trees now grow in the valleys. To remedy the problem of severe land degradation, locals throughout the region started in the 1990s to dig small pits and built terraces and bunds (small walls) to capture rainfall and keep it from running off slopes, while also planting millions of tree and bush seedlings. In addition, tree cutting and livestock grazing[6] were banned from degraded lands to allow natural regeneration of vegetation.

Regreening program to restore land across one sixth of Ethiopia:
https://www.theguardian.com/environment/2014/oct/30/regreening-program-to-restore-land-across-one-sixth-of-ethiopia

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[6] Livestock grazing is known to cause land degradation as it did in this Ethiopia case, or regeneration, as demonstrated in the previous article on Zimbabwe. The different outcomes depend on how the grazing is managed. However, the problem of degradation from unmanaged livestock grazing is often better recognized than is the potential for adaptively managed grazing to be part of the solution.

Loess Plateau Rehabilitation Project, China

China's Loess Plateau, roughly the size of France, lies between Tibet and Beijing just south of Mongolia, and is traversed by the Yellow River. Once covered in forest and grassland and the center of Chinese power and wealth, this area eventually became severely degraded by agriculture and unmanaged grazing. The fragile loess soils, composed of glacially deposited fine sediments, were prone to serious erosion when denuded of vegetation. By the 20th Century, the Loess Plateau's barren landscape was regularly ravaged by dust storms and cycles of flooding, drought and famine. When rain fell, it left the land as quickly as it had come. Some 95% of rainfall simply washed off into gullies, flooding the river and choking it with sediment from extreme erosion.

In the mid-1990s, the Loess Watershed Rehabilitation Project began. The Chinese government working with the World Bank assembled a team of hydrologists, agronomists, and soil and forest specialists to evaluate the problem and what it would take to regreen the region. Apparently engaging local people every step of the way, they identified ecologically destabilizing land management practices, established land management policies (banning agriculture on steep slopes, tree cutting and unmanaged grazing), and developed implementation strategies. Each village was asked to work together to determine how land would be divided fairly among households, each of which received a long-term land use contract for a particular parcel for which they were responsible. Local people were hired to implement ecosystem restoration measures, such as terracing, building small earthen dams to capture rainfall, and planting vegetation. The results have been positive overall, with vegetation and biodiversity returning to a previously desert-like landscape.

Lessons of the Loess Plateau longer version, written and edited by John D. Liu:
https://www.youtube.com/watch?v=HjNDiBCb-mE

Culture revival of livestock grazing for wildfire management, California

An old-school Italian festival celebrating the work of grazing animals and their faithful herders has taken root in Petaluma, CA. "Transhumance" is the act of moving grazing animals from one grassy site to another. The festival bearing this name takes place in the city or town centers through which the animals traverse en route to fresh paddocks. People gather there to celebrate the cultural tradition of livestock grazing, to trade, and to make merry.

A Petaluma transhumance festival was begun for practical purposes. Sweetgrass Grazing, a local contract grazing business whose client list has expanded in the wake of the recent

California wildfires, needed a practical way to move livestock from one client's site to another. A well-recognized approach for controlling the severity of wildfires is fuel reduction by means of removing vegetation. Yet, in contrast to mechanical or herbicide removal, grazing livestock herds remove vegetation in a way that builds the soil and creates conditions for healthier compositions of grassland species. Furthermore, nimble sheep, goats and herders can also access higher elevations that are inaccessible to machines.

In addition to conditioning townspeople to the idea of herding livestock through town, the festival seeks to sensitize the community at large to the wellbeing of surrounding landscape and possibilities for taking care of that land.

Transhumance: a revival of grassland culture:
https://www.fibershed.com/2018/08/28/transhumance-a-revival-of-grassland-culture/
Transhumance festival: https://www.sassyandgrassy.com/

Diverse cover crops and livestock for drought relief, Texas

The 2011 drought in Texas was the worst in recorded history and it lasted until 2015. The ground was so dry that Jonathan Cobb, a 4th generation farmer in Blackland Prairie of central Texas, couldn't even get crops planted. His 2,500-acre conventional row crop operation was already struggling financially through a treadmill of increasingly more inputs and long hours with little or no yield improvement. So he made the hard decision to leave farming and move to the city.

But before he left, he attended a workshop with renowned soil scientist Ray Archuleta, who focused Jonathan's attention for the first time on soil health. Archuleta demonstrated the water-holding capacity of healthy, biologically active aggregated soils compared to a typical compacted soil that crumbled and eroded when water was poured on it. This demonstration opened Cobb's mind to a whole new way of approaching agriculture. It gave him hope that farming even through extreme drought was possible.

> There was hope that nature actually did exist on its own before man started cultivating it … things that seem obvious, like a forest ecology that nobody fertilizes a forest … of course it works, it can be very abundant. And so there was a hope in that message, but there was still this big chasm to cross between how do we get there because nobody is doing it here [NRCS 2015: 5:20min].

Jonathan and his wife Kaylyn crossed that chasm by downsizing the farm to 450 acres, getting rid of the tillage equipment, learning about Holistic Management grazing, and replacing row crops with cover crops and multi-species grazing systems, including beef, lamb, pork and poultry. Now their focus is on building soil health, and they have lush pastures to show for it. Texas still gets hot, but cover crops cool down the soil:

> I've measured [the hot days] since I've gotten into soil health, and on a 103-degree day of ambient temperature, the surface of a bare Blackland soil gets to 155 degrees. You could cook a steak to a safe level. Obviously your soil bacteria are not going to be living at that stage, not the ones you want anyway. Where we had cover residue from no-till and cover crops, my soil surface was 77 degrees on the same day less than a mile away. It's a drastic change in the environment that you're creating out there [Acres USA 2015].

***On a 103-degree day of ambient temperature, the surface of a bare Blackland soil gets to 155 degrees. You could cook a steak to a safe level. Obviously your soil bacteria are not going to be living at that stage, not the ones you want anyway. Where we had cover residue from no-till and cover crops, my soil surface was 77 degrees on the same day less than a mile away.* - Johnathan Cobb [Acres USA 2015]**

They direct-market their products online and deliver it to designated pick-up locations in the area. And they enjoy what they do: "If we can make a living and stay here then we couldn't ask for anything more," Jonathan says [Voth 2018].

Jonathan Cobb profile: https://www.youtube.com/watch?v=fjdVQPBBqXQ
A farmer and a farm are saved by soil health:
https://onpasture.com/2018/02/19/a-farmer-and-a-farm-is-saved-by-soil-health/
Interview: Forging a better path - Texas Farmer Jonathan Cobb embraces shift from conventional to biological-based practices
http://ecofarmingdaily.com/interview-forging-better-path-texas-farmer-jonathan-cobb-embraces-shift-conventional-biological-based-practices/

Compilation of article summaries on resilience through eco-restoration

The following articles were selected and summarized by Bio4Climate's Compendium editors and writers. The purpose of this collection is to highlight the scientific evidence and argumentation showing healthy restored and protected ecosystems as a powerful (albeit under-recognized) tool for managing the weather extremes wrought by climate change.

Floodplains and wetlands: making space for water

Sustainable floodplains through large-scale reconnection to rivers, Opperman et al. 2009

> The area of floodplains allowed to perform the natural function of storing and conveying floodwaters must be expanded by strategically removing levees or setting them back from the river. Floodplain reconnection will accomplish three primary objectives: flood-risk reduction, an increase in floodplain goods and services, and resiliency to potential climate change impacts [Opperman 2009: 1487].

Floodplain reconnection reduces flood risk by: (1) replacing vulnerable land uses with flood-tolerant uses, thereby reducing damages, and (2) giving the water somewhere to go, thereby sparing downstream and other nearby communities. Furthermore, by storing and conveying water, floodplains alleviate pressure on upstream dams/reservoirs for flood control and water supply, increasing the resilience of this infrastructure. Finally, by restoring biological activity and diversity, floodplain restoration activates ecosystem services, including carbon sequestration and water quality improvement and groundwater recharge.

The authors note that agricultural lands would be less expensive than densely populated residential areas to reconnect and should be prioritized. Furthermore, agricultural land could remain as such by switching to production of flood-tolerant crops, such as timber and pasture. Furthermore, floodplain reconnection has proven popular among farmers, who requested more than ten times the amount of land be enrolled in a one-time floodplain easement program than the USDA could afford to support with American Recovery and Reinvestment Act funds.

Multifunctionality of floodplain landscapes: relating management options to ecosystem services, Schindler et al. 2014

> Human societies tend to value the potential benefits that a landscape might provide in a limited way, adjusting management practices towards desired outputs by maximizing the benefits gained from one or some of the services (often the provision of goods) leading to the loss of multifunctionality and the degradation of natural capital at the expense of human welfare. As a result of this biased valuation, the opportunity costs of biodiversity conservation have been perceived as too high [Schindler 2014: 230].

Using a lens of landscape multifunctionality, this study evaluates 38 potential interventions (ranging from mining, agriculture and residential development to dam removal, natural habitat creation and hiking trail maintenance) in European floodplain ecosystems for their potential to provide multiple ecosystem services (ESS). “Most ESS arise from living organisms and the interaction of biotic and abiotic processes, and refer specifically to the ‘final’ outputs from landscapes that provide benefits to humans” [Schindler 2014: 230].

Each intervention was evaluated to determine whether its effect on a given ecosystem service was positive, negative or neutral. The more ecosystem services an intervention was considered to positively affect (such as pollination, water purification, flood mitigation, providing for farming, fishing, drinking water, or recreation), the greater its contribution to landscape multifunctionality.

> Interventions with the most positive effects were related to the creation of natural habitat, dike relocation, lateral floodplain reconnection, creation of channels, oxbows and ponds, whereas the interventions [related to] terrestrial settlement and transportation infrastructure, navigational infrastructure, and intensive forms of agriculture, forestry and fisheries are rather problematic when preserving multifunctionality in floodplains [Schindler 2014: 238].

Thus the authors found that:

> Restoration and rehabilitation measures strongly improved the multifunctionality of the landscape and caused win-win situations for enhancing overall ESS supply for all regulation/maintenance and cultural services, but also for provisioning services [Schindler 2014: 242].

In short, a multifunctional approach allows for ecosystem services and goods that we depend on yet often take for granted, such as clean, abundant drinking water, clean air, pollination, and productive wild fish populations, for example, to be considered in economic evaluations of sites and landscapes such as floodplains.

Need for ecosystem management of large rivers and their floodplains: these phenomenally productive ecosystems produce fish and wildlife and preserve species, Sparks 1995

In their natural state, rivers are not separate or separable from surrounding lands. Rather, a river channel is just one integral part of a larger river-floodplain ecosystem. Annual flood pulses and larger flooding events connect river channels to their floodplains, driving the cycles of life for the particularly diverse ensemble of species that live in floodplain ecosystems. For example, fish use floodplain lakes and backwaters for spawning, shelter, feeding and nurseries. Plants on the floodplain depend on nutrients supplied by sediment deposited during flooding. Due to their geological age, size, habitat complexity, and variability, large river ecosystems – such as the Amazon basin - are among the more biodiverse ecosystems on Earth.

Building levees to contain river water eliminates annual flood pulses, thereby fracturing an ecosystem dependent on these processes. Therefore, for example, "in both tropical and temperate rivers, fish yield per acre is considerably greater in rivers with flood pulses and floodplains than in nearby impoundments where flood pulses are reduced or absent" [Sparks 1995: 172]. In addition,

> On land, the natural nutrient-replenishment system once provided by the flood must be replaced with commercial fertilizer. Some societies practice a flood-adapted form of agriculture or harvest both fish and a compatible crop, such as rice, but intensive, high-yield agriculture often conflicts with fisheries, particularly if pesticides are used that can contaminate fish through biomagnification [Sparks 1995: 172].

To at least partially reconnect rivers with floodplains, the author recommends modifying existing structures to divert some flow to create or maintain side channels into the floodplains and restore the annual flood pulse.

The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA, Narayan et al. 2017

The authors address the lack of high-resolution, large-scale assessments of the value of coastal wetlands for reducing property damages from flooding. In the first part of this paper, they assess Hurricane Sandy-induced damages to wetlands. The second part examines the risk reduction benefits of salt marshes in Ocean County, NJ, in terms of average annual economic flood losses. This study involved over 2000 synthetic storm events in Ocean County. The storm events were matched in frequency with actual storms that occurred between 1900 and 2011.

Wetland extent was positively correlated with damage reduction in all but one of 12 states impacted by Hurricane Sandy. The authors used a hydrodynamic model that calculated the propagation of storm surges from the coastal shelf on to land. The average amount of damage reduction was slightly over 1%; however, four states with extensive wetlands experienced flood damage reduction of 20-30%.

Losses were less for areas with salt marshes than for those without. On average, salt marshes reduced flood-related damages by 18%. Higher elevations were also correlated with damage reductions.

The authors noted that damage reduction was also apparent at locations several kilometers upstream of affected wetlands. A few areas, however, showed increased storm damage because of their proximity to wetlands. These areas often were dammed, or had their stream channel redirected. Based on their findings, the authors advocate for the increased use of flood risk models by the insurance industry and small businesses.

The second warning to humanity – providing a context for wetland management and policy, Finlayson et al. 2018

The authors of this article note that prior agreements to halt wetland degradation, such as the Ramsar Convention of 1971, have been largely unsuccessful. They advocate for both a re-emphasis on how wetlands help mitigate climate change, and how to protect existing wetlands from the damaging effects of climate change. They had previously authored the Second Warning to Humanity and Wetlands, which urged the Society for Wetland Scientists (SS) and other organizations to raise the profile of wetlands. Doing so can lead to policy changes which would attenuate the deleterious actions that humans currently apply to wetlands.

The authors then provide 11 recommendations for preserving and renewing wetlands. These recommendations include halting the conversion of wetlands to other land uses, rewilding wetlands with native species, and reducing the wastage of wetland-derived foods. Other recommendations are increasing wetland education, adopting renewable energy sources that don't impact wetlands, prioritizing the enactment of connected, well-funded and well-managed networks of protected wetland areas, and supporting ecologically sound financial investments.

Wetlands in a changing climate: science, policy and management, Moomaw et al. 2018

This article emphasizes the global importance of protecting and restoring wetlands in the context of climate change and outlines policy strategies for wetland protection and restoration.

Wetlands play a major though under-appreciated role in climate change mitigation and adaptation. Wetlands enhance local resilience to climate change by providing: “flood storage, buffering of storm damage, protecting water quality by filtering pollutants and sediment out of runoff generated by severe storm events, groundwater recharge and provision of water supply during drought, provision of wildlife refuges and corridors and maintenance of biodiversity” [Moomaw 2018: 192], as well as “direct harvests of fish, animals, and plants” [Moomaw 2018: 188]. Furthermore, wetlands/peatlands store massive amounts of carbon, drawing it out of the atmosphere.

> Peatlands and vegetated coastal wetlands are among the most carbon rich sinks on the planet sequestering approximately as much carbon as do global forest ecosystems [Moormaw 2018: 183].
>
> Wetland conditions are critical for C accumulation and storage since decomposition in these systems is limited by a lack of oxygen due to water saturation. Therefore, when plant productivity exceeds decomposition there is an accumulation of soil C. This process eventually develops deep peat deposits, which may accumulate for thousands of years [Moomaw 2018: 187].

By the same token wetlands can become major GHG sources when damaged or destroyed by land use change, fire or climate change.

> Altering wetlands can increase the vulnerability of the organic C pool by weakening the self-regulating feedbacks that exist in many peatland systems. Land use change that affects wetland hydrology has had substantial impacts on wetland structure and function. Draining wetlands decreases CO_2 uptake and increases rates of microbial decomposition and CO_2 release. Soil C is also lost by peat extraction, drainage and other disturbance. The hydrologic changes can be so large that they result in massive losses of C to the atmosphere, such as occurred during the fires in tropical peatlands in Southeast Asia [Moomaw 2018: 187].

Many land-use practices in or near wetlands reduce wetlands’ resilience to any further stress, such as hotter, drier weather wrought by climate change.

> Unfortunately, many of the world's freshwater wetlands are already stressed by increased land-use pressure, so that additional hydrological alteration can contribute to an overall decrease in resilience to climate change. Human alteration is commonplace throughout river corridors, challenging management as the impacts of upstream alterations accumulate along the waterway. As demands for river resources increase, such problems are expected to worsen. Flowing water is compromised by river re-engineering practices, even though moving water generally improves oxygenation and plant health. Also, upriver freshwater extraction in tidal freshwater wetlands coupled with sea level rise can cause the salinification of surface and ground water, with accompanying stress and even the collapse of tidal vegetation in the freshwater reaches of estuaries [Moomaw 2018: 188].

On the other hand, wetland resilience can be bolstered through proper land management.

> The effects of climate changes on wetland C storage will be determined largely by the extent to which the wetlands have been modified through land-use change [Moomaw 2018: 187].
>
> One opportunity to decrease the amount of saltmarsh loss that is likely to occur with sea level rise is to actively plan for future inland marsh migration now [Moomaw 2018: 191].

The authors express concern that wetlands are overlooked in policy discussions on climate change, noting that climate scientists tend to sideline the role of wetlands, while wetlands science and management have often failed to acknowledge the outsized role of wetlands as a carbon sink. Thus:

> To play a more effective role in climate change mitigation and adaptation/resiliency, wetland scientists need to clearly communicate the significance of wetlands to the wellbeing of society and the economy. Communicating with policy makers and the public requires aligning wetland science and specific climate mitigation and adaptation/resiliency ecosystem services with the concerns and mindset of the audience [Moomaw 2018: 198].

A handful of policy structures at international, national and subnational levels aim to better account for and protect wetlands. For example, the International Panel on Climate Change (IPCC) has since 2013 provided guidance (through the Wetlands Supplement) to countries about including wetlands in national GHG inventories, thus moving "closer to requiring countries to account for the substantial emissions from these ecosystems when they are disturbed or destroyed" [193]. The 1975 Ramsar Agreement establishes an international framework for wetland management, but lacks adequate guidance on how to best protect wetlands from the stressors of climate change. At the local level, decisions about wetlands are often made by land managers.

> Thinking globally and acting locally, wetland managers can incorporate carbon management and climate resiliency science into project-level work (including developing a body of climate-related Best Management Practices), whether or not governing policies and regulations exist. As noted earlier in this article, avoidance of impacts to wetlands, and associated carbon stocks and processes, is likely to be the most effective management practice for preventing increases in GHG emissions from wetlands, protecting climate resiliency functions, and protecting traditional wetland ecosystem services, and it is therefore important for managers to understand the underlying science [Moomaw 2018: 197].

Future response of global coastal wetlands to sea-level rise, Schuerch et al. 2018

The vulnerability of coastal wetlands to sea-level rise is disputed, with some researchers predicting most will be flooded out of existence by the end of the 21st Century. Coastal wetlands provide critical ecosystem services, including protection from storm surges, water quality improvement, fisheries habitat and carbon sequestration. By accounting for the enhancement of sediment build-up when storms are more frequent and more severe and for the possibility of "accommodation space" for coastal wetlands to move inland, however, these authors reach a more optimistic conclusion. (Sediment build-up, or accretion, allows coastal wetlands to grow vertically, potentially remaining at a higher elevation than sea-level.) They estimate that:

> Rather than losses, wetland gains of up to 60 per cent of the current area are possible, if more than 37 per cent (our upper estimate for current accommodation space) of coastal wetlands have sufficient accommodation space, and sediment supply remains at present levels [Schuerch 2018: 231].

This is an important ecosystems restoration message because it means humans can directly influence the persistence of coastal wetlands, and thus the continuation of the essential ecosystem services they provide.

This is an important ecosystems restoration message because it means humans can directly influence the persistence of coastal wetlands, and thus the continuation of the essential ecosystem services they provide.

> Our simulations suggest that the resilience of global wetlands is primarily driven by the availability of accommodation space, which is strongly influenced by the building of anthropogenic infrastructure in the coastal zone and such infrastructure is expected to change over the twenty-first century. Rather than being an inevitable consequence of global sea-level rise, our findings indicate that large-scale loss of coastal wetlands might be avoidable, if sufficient additional accommodation space can be created through careful nature-based adaptation solutions to coastal management [Schuerch 2018: 231].

The authors describe specific solutions to protect coastal wetlands, which they recommend be implemented at a large, regional or landscape scale.

> Existing nature-based adaptation solutions that allow coastal wetlands to migrate inland include the inland displacement of coastal flood defenses (typically along highly engineered coastlines) or the designation of nature reserve buffers in upland areas surrounding coastal wetlands. These schemes, however, are currently implemented as local-scale projects only; strategically upscaling such projects, for example, as suggested by the shoreline management plans in England and Wales or the coastal master plan in Louisiana, may help coastal wetlands adapt to SLR [sea level rise] at the landscape scale and protect rapidly increasing global coastal populations [Schuerch 2018: 234].

Partnering with beavers to restore ecosystems

Beaver dams and overbank floods influence groundwater–surface water interactions of a Rocky Mountain riparian area, Westbrook et al. 2006

This study provides empirical evidence that beavers influence hydrologic processes in riparian areas. Conducted at the headwaters of the Colorado River in the Rocky Mountains, the study examines patterns from two beaver dams of surface inundation, groundwater flow, and groundwater level dynamics. The authors observe that :

> Beaver dams on the Colorado River caused river water to move around them as surface runoff and groundwater seepage during both high- and low-flow periods. The beaver dams attenuated the expected water table decline in the drier summer months for 9 and 12 ha of the 58 ha study area [Westbrook 2006: 1] … by providing a constant supply of water to the riparian area via surface and subsurface flow paths [Westbrook 2006: 10].

> In both cases [both dams], water left the Colorado River, flowed across the floodplain and terrace, and then back to the river far downstream of the dams [Westbrook 2006: 11].

Noting that the current beaver population is but a small fraction of what it was before Europeans settled the west, the authors state that:

> If the results of our intensive study were extrapolated to a time of more abundant beaver then the magnitude of their hydrologic effects may have encompassed nearly the entire study area. It is easy to visualize abundant beaver as key drivers of hydrologic processes in mountain valleys and other unconfined stream valleys throughout North America [Westbrook 2006: 10].

The significance of this study is that beaver dams can maintain the water table in forests, creating resilience to drought. Beaver dams do this by causing water to overflow the banks of the river and spread over a greater surface area. More effective even than any given rain event, “overbank flood events have generally been regarded as the main hydrologic mechanism for replenishing groundwater and soil water in riparian areas” [Westbrook 2006: 8].

The significance of this study is that beaver dams can maintain the water table in forests, creating resilience to drought. Beaver dams do this by causing water to overflow the banks of the river and spread over a greater surface area.

Modeling intrinsic potential for beaver (Castor canadensis) habitat to inform restoration and climate change adaptation, Dittbrenner et al. 2018

Beavers are recognized for their ability to restore floodplain hydrology and biological function, yet finding suitable places for their reintroduction remains a conservation challenge. The goal of this study was to identify places in the Snohomish River basin of Washington state suitable for beaver reintroduction.

> Because of their abilities to modify streams and floodplains, beavers have the potential to play a critical role in shaping how riparian and stream ecosystems respond to climate change. The Pacific Northwest of the United States is experiencing increases in annual air temperature and decreases in snow pack and summer precipitation, resulting in lower

> base flows, particularly in streams that rely on late season snowmelt. Climate shifts have altered stream-temperature regimes to the detriment of cold-water fishes, including Pacific salmon. Recent increases in winter precipitation and storm magnitude have increased the potential for stream scour, channel incision, and floodplain disconnection, thereby promoting the drying of adjacent riparian areas [Dittbrenner 2018: 2].
>
> By damming streams, beavers create pond and wetland complexes that increase spatial heterogeneity and geomorphic complexity, species and habitat diversity, and therefore ecosystem resilience to climate-induced environmental change. Beaver impoundments slow stream velocity allowing sediment suspended in the water column to settle, aggrading incised stream systems, and reconnecting streams with their floodplains. The increase in surface water promotes groundwater recharge, storage, and supplementation during base flows. The increased geomorphic complexity also promotes higher thermal variability and coldwater refugia in deeper waters and in areas of downstream upwelling [Dittbrenner 2018: 2].

To qualify as a suitable site for beaver reintroduction, a site needs to be intrinsically suitable beaver habitat and clear of competing human interests.

Of 5,019 stream km assessed in this study, just 33% had moderate or high intrinsic potential for beaver habitat. “Of the riparian areas around streams with high intrinsic potential for beaver, 38% are on public lands and 17% are on large tracts of privately-owned timber land” [Dittbrenner 2018: 1], while the rest was on human-dominated landscapes (agricultural, industrial, residential, etc.). Thus, the areas available for beaver reintroduction are limited. Even so, the authors argue that beavers can play a critical role in adapting to climate change, and they propose that watersheds dominated by public ownership, “provide ample opportunities to test how beavers can be reintroduced into landscapes where they are absent or at low population levels” [Dittbrenner 2018: 11].

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Beaver restoration would reduce wildfires, Maughan 2013

Politicians often call for logging and fuel reduction to prevent future wildfires. However, it’s not good logging trees that are burning in such fires so much as cheatgrass, annual weed, dry brush and dead weeds. Reintroducing beaver to create ponds could raise the water table, increase humidity in the drainage area (thus reducing burn intensity) and provide a refuge for animals during a fire.

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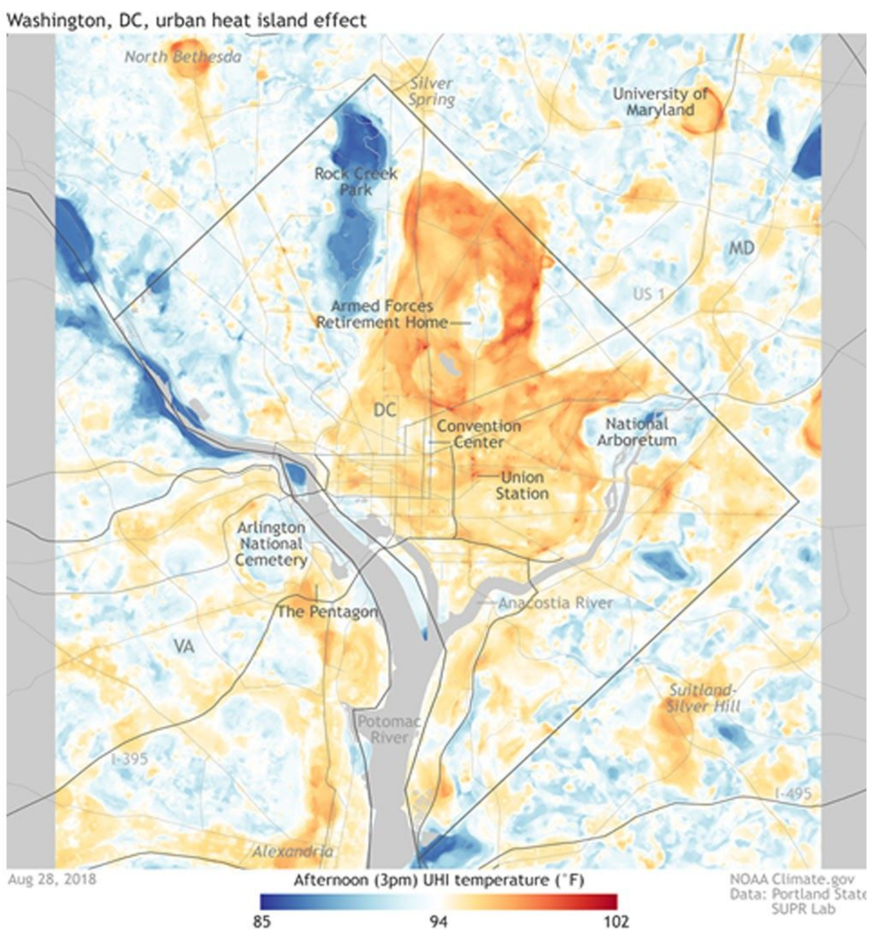
More ecosystem-oriented considerations for heat wave, drought, flood and fire resilience

Hot days in the city? It's all about location, NOAA 2018

In a project funded by National Oceanic and Atmospheric Association (NOAA), about two dozen citizen scientists measured temperatures in Baltimore and Washington DC on two of the hottest days of 2018. By measuring temperatures second by second with thermal sensors while driving prescribed routes through each city, the data collectors revealed a 17-degree temperature gap between the coolest and hottest parts of DC on the same day. The difference? Trees. The well-wooded areas of Natural Arboretum and Rock Creek Park were the coolest parts of the city. The results were similar in Baltimore, where the hottest places were neighborhoods covered in concrete and asphalt with little vegetation. These hotspots were 103 degrees, compared to areas with lots of big trees and parks, which were 16 degrees cooler on the same day.



“Major roadways and dense urban pockets are some of the warmest landscapes in both cities” [NOAA 2018], according to Jeremy Hoffman of the Science Museum of Virginia, one of the lead researchers on the study. “These are areas with little or no vegetation, more asphalt and concrete buildings, which can amplify a heat wave” [NOAA 2018].

Researchers used the data to create heat maps of both cities, which can pinpoint the neighborhoods most vulnerable to dangerous heat waves, and to help city officials identify cooling and resiliency strategies, namely bolstering the quantity and quality of green space, planting new trees and protecting existing trees.

Introduced annual grass increases regional fire activity across the arid western USA (1980–2009), Balch et al. 2013

Cheatgrass is an introduced annual grass that has spread everywhere throughout the western USA. It is among the first plants to emerge in the spring, after which it completes its life cycle, drying out in summer and thus creating a continuous, dry, fine fuel load across the landscape. This study examined the cheatgrass invasion’s effect on the fire regime of the Great Basin region of the western USA, finding that:

> Fires were more likely to start in cheatgrass than in other vegetation types and that cheatgrass is associated with increased fire frequency, size, and duration [Balch 2013: 179-180].
>
> Here, we have documented that cheatgrass-dominated areas, which currently cover ~40,000 km2, sustain increased fire probability compared with native vegetation types. As sites burn, more and more of them are likely to become cheatgrass grasslands thus increasing their future probability of burning. If future climate scenarios hold true, the combination of warmer temperatures and high water availability[7] could yield larger fire events that are carried between forested or shrubland areas by invasive grasses, thus perpetuating a novel grass-fire cycle across the western United States and ultimately reducing cover of woody species [Balch 2013: 182].
>
> In native shrub and grassland ecosystems of the arid western United States, high antecedent precipitation has been shown to be one of the strongest predictors of government-registered burned area (1977–2003), even more so than current-year temperature or drought conditions. The oscillation between wet years that enable substantial grass growth and dry years that desiccate those built-up fuels may create

[7] “In the northern Great Basin, precipitation is projected to increase during the winter and early spring months most critical for cheatgrass growth” [Balch 2013: 182].

> ideal conditions for high fire years, but this hypothesis remains untested for cheatgrass rangelands [Balch 2013: 174].
>
> Fire-driven conversion of shrubland to grassland has been linked to a loss of carbon storage and available soil water [Balch 2013: 174].

Adapt to more wildfire in western North American forests as climate changes, Schoennagel et al. 2017

Wildfires in the West have become larger and more frequent over the past three decades (globally, the length of the fire season increased by 19% from 1979 to 2013) and this trend will continue with global warming. Typical fire prevention strategy, centering on fuel reduction and fire suppression, has proved inadequate. Instead, society must accept the inevitability of fires and reorganize itself accordingly, according to this study. Specifically, an adaptive resilience approach would mean:

> (i) recognizing that fuels reduction cannot alter regional wildfire trends; (ii) targeting fuels reduction to increase adaptation by some ecosystems and residential communities to more frequent fire; (iii) actively managing more wild and prescribed fires with a range of severities; and (iv) incentivizing and planning residential development to withstand inevitable wildfire [Schoennagel 2017: 4582].
>
> Between 1990 and 2010, almost 2 million homes were added in the 11 states of the western United States, increasing the WUI [wild-urban interface] area by 24%. Currently, most homes in the WUI are in California (4.5 million), Arizona (1.4 million), and Washington (1 million). Since 1990, the average annual number of structures lost to wildfire has increased by 300%, with a significant step up since 2000. About 15% of the area burned in the western United States since 2000 was within the WUI, including a 2.4-km community protection zone, with the largest proportion of wildfires burning in the WUI zone in California (35%), Colorado (30%), and Washington (24%). Additionally, almost 900,000 residential properties in the western United States, representing a total property value more than $237 billion, are currently at high risk of wildfire damage. Because of the people and property values at risk, WUI fires fundamentally change the tactics and cost of fire suppression as compared with fighting remote fires and account for as much as 95% of suppression costs [Schoennagel 2017: 4583].
>
> There often is a lack of political will to implement policies that incur short-term costs despite their long-term value or to change long-standing policies that are ineffective. For example, few jurisdictions have the will or means to restrict further residential development in the WUI, although modifying and curtailing residential growth in

> fire-prone lands now would reduce the costs and risks from wildfire in the long term. [Schoennagel 2017: 4585].

> ***...modifying and curtailing residential growth in fire-prone lands now would reduce the costs and risks from wildfire in the long term*** **[Schoennagel 2017: 4585].**

Amplification of wildfire area burnt by hydrological drought in the humid tropics, Taufik et al. 2017

This study distinguishes between meteorological droughts (lower than average rainfall) and hydrological droughts, where rainfall shortage has eventually led to surface or groundwater levels falling, to predict area burnt from wildfires. By contrast, most studies consider only climate data when predicting wildfire, yet "these overlook subsurface processes leading to hydrological drought, an important driver" [Taufik 2017: 428].

The authors hypothesize that periods with low groundwater recharge will create conditions for a greater area burnt. They found that massive wildfires in Borneo over the past two decades coincided with years when there were large areas of hydrological drought.

> Statistical modelling evidence shows amplifying wildfires and greater area burnt in response to El Niño/Southern Oscillation (ENSO) strength, when hydrology is considered. [Taufik 2017: 428]

Hydrological drought stems from a lack of rain, but also depends on the ability of the land to store water. Thus, land use can exacerbate a hydrological drought.

> Human activities through land-use change and associated drainage and land clearing immediately following deforestation or long fallow periods create favourable conditions for the fires and amplify the hydrological drying processes in the aboveground fuels and the underlying organic soil [Taufik 2017: 428].

***Human activities through land-use change and associated drainage and land clearing immediately following deforestation or long fallow periods create favourable conditions for the fires and amplify the hydrological drying processes in the aboveground fuels and the underlying organic soil* [Taufik 2017: 428].**

Tall Amazonian forests are less sensitive to precipitation variability, Giardina et al. 2018

> Our results demonstrate that in the Amazon, forest height and age regulate photosynthesis interannual variability and are as relevant as mean precipitation. In particular, tall, old and dense forests are more resistant to precipitation variability. Tree size and age directly impact forest structure and thus the carbon cycle in the Amazon. This is especially significant given the importance of the Amazon rainforest, not only for the global carbon cycle, but also for global atmospheric circulation, which is closely connected to the evapotranspiration process of this area. Forest height, age and biomass have a role equivalent to mean precipitation in the regulation of forest photosynthesis response to interannual climate variability [Giardina 2018: 4].

Subordinate plant species enhance community resistance against drought in semi-natural grasslands, Mariotte et al. 2013

This study examines how subordinate species[8] influence community insurance against drought in semi-natural grasslands of the Swiss Jura. The insurance hypothesis proposes that an increase in community diversity corresponds to an increase in the range of potential species responses to environmental stress. The authors tested the role of subordinate species in community resistance to drought, recovery and resilience, and on productivity. They induced summer drought conditions for two months by covering the test plants with raincovers.

The drought simulation reduced soil water content by 67%, relative to comparable watered land plots. Drought, removal of subordinate species, and their interaction, all had dramatic adverse impacts on community resistance. In contrast to dominant and transient species, subordinate

[8] Among grassland plants, subordinate species, as distinguished from dominants, "are smaller, grow under the canopy of dominants and account for a low proportion of the total community biomass" [Mariotte 2013: 764].

species showed significantly stronger resistance in drought plots than in control plots. Additional findings supported the conclusion that the plant community was more resistant and produced more biomass after drought when containing high biomass of subordinate plants.

Plant community resilience was not affected by drought but was decreased by the subordinate removal treatment. Species composition was also affected by drought and removal conditions; most dominant and transient species[9] were associated with watered plots. Some transient species (such as the ox-eye daisy) were associated with plots in which subordinate removal had occurred.

The authors conclude that, in general, dominant species fared poorly in response to drought, whereas the proportion of subordinate and transient species increased under these conditions. They also noted that the decline in resistance was about 10 times higher in plots where subordinates had been removed than in plots without removal. Thus, the subordinates facilitated the regrowth of dominants and transients during drought. They proposed that the reduced competition among dominants during drought conditions afforded the subordinates the opportunity to accumulate more biomass.

The authors demonstrate that: "in species-rich grassland communities, subordinate species, a key component of plant diversity, are a main driver of community resistance to drought. Our findings show the importance of ecosystem-level impacts of these low abundant plants" [Mariotte 2013: 771]. They further speculated that the role of subordinates in resisting drought for the whole community may lie in their ability to increase water availability through greater interaction with the soil microbial community, such as mycorrhizal fungi. This article adds credence and specificity to our understanding of the key role of biodiversity in ecosystem functioning.

Worthy Miscellany

Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls, Kallenbach et al. 2016

Although the overall contribution of decaying plants, available substrate, and microbes to the buildup of soil organic matter (SOM) is well recognized, their individual contributions are not as clearly understood. Analytical shortcomings have constrained a thorough study that can distinguish the amount of SOM attributable to plants and the amount attributable to microbes.

[9] "Species that generally do not persist over time and appear only briefly as seedlings that fail to survive are defined as transient species" [Mariotte 2013: 764].

Using pyrolysis-GC/MS, the authors investigated the chemistry of carbon and microbe-depleted soils after 18 months, after inoculation by various substrates and with two clays (montmorillonite and kaolinite).

By six months, active microbial communities were present in all inocula save one, and SOM molecular diversity increased across all model soil systems. Soils treated with either sugar or syringol (a structural component of cell walls) contained substantial concentrations of lipids and proteins after 18 months. Soil organic carbon (SOC) also increased over time. Syringol-treated montmorillonite soils accumulated the most carbon, and had lower bacterial and higher fungal abundance than sugar-treated soils. Higher fungal abundance was positively correlated with carbon use efficiency (CUE) across treatments.

The authors concluded that the microbial community may be a stronger driver of SOM development than the soil's mineralogy. They also found that their sugar- and syringol-treated samples provided a chemical diversity that was as rich as natural soil. This article contributes to an expanding scientific knowledge base regarding soil ecosystems and the critical role of soil microorganisms vis a vis the carbon cycle.

Global assessment of agricultural system redesign for sustainable intensification, Pretty et al. 2018

This article highlights the relevance of the concept of "sustainable intensification" (SI), wherein farming practices are improved to produce more crops (intensification) while doing no harm to – and possibly even enhancing - the environment (sustainable).

> The combination of the two terms was an attempt to indicate that desirable outcomes, such as more food and better ecosystem services, need not be mutually exclusive. Both could be achieved by making better use of land, water, biodiversity, labour, knowledge, and technologies [Pretty 2018: 441].

Having screened hundreds of SI projects/programs worldwide and selected those implemented at a large enough scale to benefit ecosystem services and agricultural objectives across whole landscapes, the authors estimate that 29% of all farms worldwide and 9% of agricultural land have crossed a transformative threshold in their use of SI methods.

Sustainable intensification can be achieved in three non-linear stages of transition: (1) improved efficiency (such as through precision agriculture, which uses sensors to target fertilizer application, thereby wasting less), (2) substitution (such as substituting biological control agents in the place of synthetic inputs), or (3) system redesign. The authors state that of these three stages, only system redesign is capable of "maximizing co-production of both favorable agricultural and environmental outcomes at regional and continental scales" [Pretty 2018: 442].

The authors describe system redesign as follows:

> The third stage is a fundamental prerequisite for SI to achieve impact at scale. Redesign centres on the composition and structure of agro-ecosystems to deliver sustainability across all dimensions to facilitate food, fibre and fuel production at increased rates. Redesign harnesses predation, parasitism, allelopathy, herbivory, nitrogen fixation, pollination, trophic dependencies and other agro-ecological processes to develop components that deliver beneficial services for the production of crops and livestock. A prime aim is to influence the impacts of agroecosystem management on externalities (negative and positive), such as greenhouse gas emissions, clean water, carbon sequestration, biodiversity and dispersal of pests, pathogens and weeds. Whereas efficiency and substitution tend to be additive and incremental within current production systems, redesign brings the most transformative changes across systems [Pretty 2018: 442].
>
> We analysed transitions towards redesign in agricultural systems worldwide. We reviewed literature on SI, including meta-analyses and practices, to produce a typology of seven system types that we classify as redesign: (i) integrated pest management, (ii) conservation agriculture, (iii) integrated crop and biodiversity, (iv) pasture and forage, (v) trees in agricultural systems, (vi) irrigation water management and (vii) intensive small and patch systems [Pretty 2018: 443].

By showing that “the expansion of SI has begun to occur at scale across a wide range of agroecosystems” [Pretty 2018: 444], this analysis offers a roadmap for how to transition global agriculture toward systemic ecosystem and community resilience in the face of global warming. The authors emphasize the importance both of social networks and cooperation for the co-creation and sharing of agricultural knowledge, and of state policies to support or at least not undermine SI expansion. The authors suggest that agricultural management may be at a crucial tipping point, where “a further small increase in the number of farms successfully operating re-designed agricultural systems could lead rapidly to re-design of agriculture on a global scale” [Pretty 2018: 445].

Appendix A

Close up on California in the era of climate change: a verdant vision for fire-prone land

Picture California in the 1700s, around the time the first Spanish missions appeared. It must have looked like heaven on earth for the 100,000s of native people living there [Ecological Society of America 2014], cradled between forested mountains and sparkling ocean. Meandering streams and rivers teeming with salmon criss-cross the valley and are knit together by a latticework of beaver dams. These porous little dams spread water over floodplains stretching in every direction, topping off aquifers and creating diverse habitat for an abundance of life. Wildfires come and go, and some are even manipulated by native peoples to diversify the resources in the landscape. But fires burn through relatively small patches before being damped out by ample ambient moisture, while triggering new growth in their wake.

This old-time paradise lacks the cozy thrill of watching a good Hollywood movie with a box of buttery popcorn, or the sense of security from a Central Valley harvest bountiful enough to nourish a nation. Indeed, our current era boasts a different kind of paradise – one that features convenient access to entertainment, great food, elegantly decorated homes and exotic vacations. This modern paradise is only occasionally interrupted by massive wildfires or storms that level whole neighborhoods, taps that run dry or are tainted with poison, deadly heat waves, or by news reports of such events. Those without the means to live in modern paradise are often the ones featured in the disturbing news reports.

Now imagine California in 2050, after ecosystems have been restored and deployed to rehydrate the landscape and to give Mother Nature the elbowroom she needs to go about her business without doing quite as much damage to human habitats, in spite of ongoing climate chaos. While we can't and may not even want to go back to a pre-colonial natural California paradise, we can shore up our human spaces against the ravages of climate change by rehabilitating ecosystem processes in all the open space inside of and surrounding our existing cities and towns.

This means preventing any further urban sprawl into rural/wilderness areas. It means relocating people out of flood and fire prone rural/wilderness edges (as the Netherlands has done in its most low-lying areas [Bentley 2016]), and moving them into refurbished urban lots, while fully supporting them through the transition. It means thoughtfully investing in cities and towns to make them affordable and beautiful to reduce people's compulsion to move into the fringes.

It means reconnecting rivers to their floodplains so that water has somewhere to go other than surging into cities when it floods, and so that floodplains, their wild inhabitants, and the underlying aquifers can benefit from a recharge of groundwater and nutrients. It means helping farmers transition to agricultural methods that conserve water, recycle nutrients, and restore biodiversity to their fields. And it means seeking out the best in applied ecological science to restore and manage wilderness areas in a way that favors biodiversity and therefore resilience.

Like the growing global call to reduce carbon emissions to net zero by 2025, the prospect of vast and thorough ecosystems restoration sounds utopian, naïve, impossible. However, serious solutions are needed to manage ever more extreme weather. Hotter, drier conditions wrought by climate change have made the land crisp and flammable, causing wildfires to spread further and faster in recent years. A century of wildfire suppression allowing fuel build-up, urban sprawl butting up against fire-prone wilderness areas, and the spread of invasive flammable cheatgrass have further contributed to the severity of recent fires.

Moreover, the frequency of rainy seasons that are extremely dry is predicted to increase, especially in southern California, where consecutive dry years will become more common [Swain 2018]. At the same time, the frequency of major flooding events, comparable to the 1862 flood that temporarily turned the Sacramento Valley into an inland sea, is predicted to triple by the end of this century.

Water – whether too much or too little – is at the heart of California's troubles. With a Mediterranean climate defined by a winter rainy season and long dry summers, California is inherently prone to feast or famine when it comes to water. State water managers, therefore, have long been dealt the challenge of capturing and storing winter rainfall for summer use. Water storage today is achieved with reservoirs, underground aquifers and mountain snowpack, which slowly releases water from melting snow during spring and summer.

The state's water management system may be due for a redesign, though. For one thing, snowpack is no longer a reliable storage system. Not only is there less snowpack overall, but what there is bears a greater risk now of "rain on snow" events that melt it all at once in a giant gush. Furthermore, levees are not high enough for the scale of flooding that is predicted to become more common, and the water infrastructure overall is in need of repair to the tune of $34 billion [Mount 2017].

The state's aquifers are a natural storage system that contribute about one third to annual water supply, but they have been unregulated and severely overdrawn during droughts, in some cases leading to land subsidence[10] [Martin 2018]. In response, however, the government

[10] Land subsidence occurs when large amounts of water have been removed from underground aquifers causing the rock structure of the aquifer to partially collapse because the water was partially responsible for holding the ground up. This is a problems throughout the US, and can result in a permanent reduction in the storage size of the aquifer (https://water.usgs.gov/edu/earthgwlandsubside.html).

passed the Sustainable Groundwater Management Act in 2014, which makes local governments responsible for monitoring and recharging the aquifers within their jurisdictions.

Localities can fulfil their legal obligations at least in part by restoring natural processes that recharge groundwater, such as giving rivers more space to meander and restoring native vegetation. Plants protect and build soil, rendering the soil more sponge-like and able to absorb and hold water, allowing water to percolate into aquifers. Vegetation also shades soil surfaces, limiting evaporation. These principles hold true for all healthy ecosystems, which is to say biodiverse ecosystems, whether in the context of wilderness or agriculture. Biodiversity fosters ecosystem stability, productivity and resilience.

At this turning point for water management in California, what if the state were to redesign its aging system in a way that places a much higher value on hydrological functionality? Improving the land's hydrology would mean facilitating the ground's absorption of precipitation (such as the Yolo Bypass Wilderness Area has done), slowing water down rather than isolating it from the land with straight, narrow and constrained waterways ultimately emptying into the ocean.

Slowing down water would recharge aquifers and revitalize streams, rivers, wetlands, grasslands and forests. Expansive functional forested ecosystems could in turn reactivate local water cycling through transpiration and rain recycling, cooling the land in the process. Moistening and cooling the land by enhancing its absorptive capacity could create fire breaks and reduce flammability, thus mitigating the threat of out-of-control wildfires.

Moistening and cooling the land by enhancing its absorptive capacity could create fire breaks and reduce flammability, thus mitigating the threat of out-of-control wildfires.

Disturbed, dry hydrological systems are associated with more severe wildfires. In Borneo, researchers [Taufik 2017] found that massive wildfires coincided with years characterized by large areas of hydrological drought, where surface or groundwater levels had dropped due to extended rainfall deficits. Land use changes including deforestation and canalization to drain wetlands exacerbated hydrological drought, leading to more acres burned during wildfires.

How to restore ecosystems? On a small scale, Californians are already succeeding in this by removing levees to reactivate the floodplain [Fountain 2018], introducing beavers to restore streams and surrounding habitat [Goldfarb 2018],[11] and adaptively grazing livestock in wilderness areas to thin out vegetation, thus reducing fuel loads and replacing it with soil-nourishing manure and urine [Greenwood 2018]. Farmers in the Yolo Bypass Wilderness Area have adapted their practices to allow for seasonal flooding of their fields [Sommer 2001]. Farmers throughout the state participate in the department of agriculture's Healthy Soils Program by implementing conservation practices to build soil and enhance ecosystem processes, such as carbon sequestration.

Urban areas too are learning to manage water in a way that better withstands boom or bust rainfall patterns. While cities everywhere are normally designed to remove stormwater as quickly as possible, some cities are beginning to see stormwater not so much as a nuisance, but as a valuable resource [Shimabuku, Diringer, Cooley 2018]. For example, the small agricultural town of Gonzalez, CA, modified its municipal code to facilitate low-impact development measures, such as the removal of portions of curb to allow rainwater to drain into vegetated areas. Santa Monica set a city-wide goal of becoming water self-sufficient by 2022 and plans to meet this goal, in part, by capturing more than 500 million gallons of stormwater for treatment and reuse. San Francisco now requires new developments of a certain size to capture and reuse stormwater on site.

San Francisco also recently passed a bill to allow denser development near transit lines within the city, potentially alleviating the housing crisis that's driving sprawl. (A similar bill was defeated at the state level, unfortunately, due in part to a NIMBY-like resistance to sharing more spacious urban neighborhoods with lower-income newcomers.)

All these initiatives are a promising start. To stave off ever-longer fire seasons, alongside more severe flooding and drought, however, these innovations cannot remain isolated examples. They need to become the state-wide norm for water management, urban design and land stewardship. Such changes are urgently needed not only in California, profiled here as an instructive example of life in the era of climate change, but everywhere.

As in every community everywhere on Earth, California must take an honest, clear look at its choices: reimagine paradise as a place where we embrace the vibrancy of human diversity in dense, walkable urban neighborhoods, and cultivate biodiversity in all open green spaces; or tempt Mother Nature to destroy everything we love as we cling to an ideal of paradise as being the accumulation of manufactured luxuries, while ignoring the environmental and social costs.

[11] See also "California: The Rebeavering" [of the high Sierras]: http://www.climateprep.org/stories/2016/3/17/2pdgil8x3chadbzaxxam6a0xbkwhks

Appendix B

Water Isn't What You Think It Is:
The Fourth Phase of Water by Gerald Pollack

Guest author Gerald Pollack introduces a fundamental shift in how we view water. It has the potential to significantly alter our understandings of any processes that involve water, including aspects of climate, biology, and how we approach eco-restoration.

The Fourth Phase of Water: Beyond Solid, Liquid, and Vapor
Gerald H. Pollack, PhD, Professor of Bioengineering, University of Washington
http://faculty.washington.edu/ghp/

How can a Jesus Christ lizard walk on water? Why do pollen grains jitterbug in a puddle? Why do fair weather clouds form such lovely puffy white shapes? Why do your joints work without squeaking? Why do sprained ankles swell within seconds?

Answering these questions requires an understanding of water. Given water's simplicity and pervasiveness through nature, we presume that water must be completely understood, but in fact, precious little is known about how water molecules line up — until recently.

Students learn that water has three phases: solid, liquid and vapor. But there is something more: in our laboratory at the University of Washington we have uncovered a *fourth* phase. This phase occurs next to water loving (hydrophilic) surfaces. It is surprisingly extensive, projecting out from surfaces by up to millions of molecular layers. And it exists almost everywhere throughout nature, including your body.

This freshly identified phase of water has been described in a recent book: *The Fourth Phase of Water: Beyond Solid, Liquid and Vapor* www.ebnerandsons.com. The book documents the basic findings and presents many applications including the ones mentioned above. It also deals with water's many anomalies, turning those anomalies into easily explained features.

The existence of a fourth phase may seem unexpected. However, it should not be entirely so: a century ago, the physical chemist Sir William Hardy argued for the existence of a fourth phase; and many authors over the years have found evidence for some kind of "ordered" or "structured" phase of water. Fresh experimental evidence not only confirms the existence of such an ordered, liquid-crystalline phase, but also details its properties. Those properties explain everyday observations and answer questions ranging from why gelatin desserts hold their water, to why teapots whistle.

The presence of the fourth phase carries many implications. Here, I outline some basic features of this phase, and then deal with several of those implications. I will touch on atmospheric science, and then focus on some biological and health applications.

Does Water Transduce Energy?

The energy for building water structure comes from the sun. Radiant energy converts ordinary bulk water into ordered water, building this ordered zone. We found that all wavelengths ranging from UV through visible to infrared can build this ordered water. Near-infrared energy is the most capable. Water absorbs infrared energy freely from the environment; it uses that energy to convert bulk water into liquid crystalline water (fourth phase water) — which we also call "exclusion zone" or "EZ" water because it profoundly excludes solutes. Hence, buildup of EZ water occurs naturally and spontaneously from environmental energy. Additional energy input creates additional EZ buildup.

Of particular significance is the fourth phase's charge: commonly negative (Figure 1). Absorbed radiant energy splits water molecules; the negative moiety constitutes the building block of the EZ, while the positive moiety binds with water molecules to form free hydronium ions, which diffuse throughout the water. Adding additional light stimulates more charge separation.

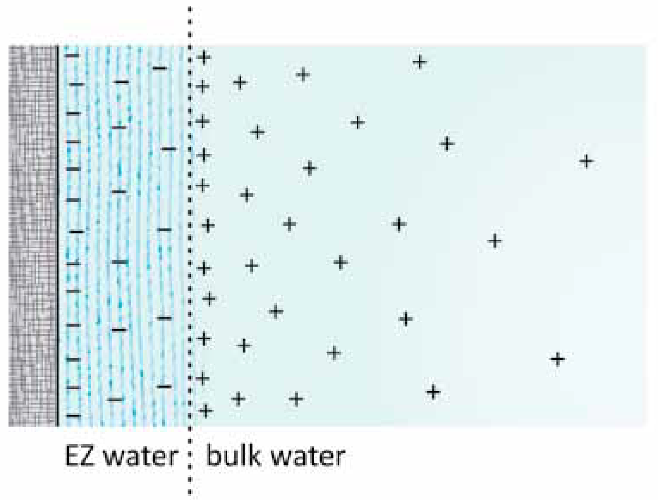


Figure 1. Diagrammatic representation of EZ water, negatively charged, and the positively charged bulk water beyond. Hydrophilic surface at left.

This process resembles the first step of photosynthesis. In that step, energy from the sun splits water molecules. Hydrophilic chromophores catalyze the splitting. The process considered here is similar but more generic: any hydrophilic surface may catalyze the splitting. Some surfaces work more effectively than others.

The separated charges resemble a battery. That battery can deliver energy in a manner similar to the way the separated charges in plants deliver energy. Plants, of course, comprise mostly water, and it is therefore no surprise that similar energy conversion takes place in water itself.

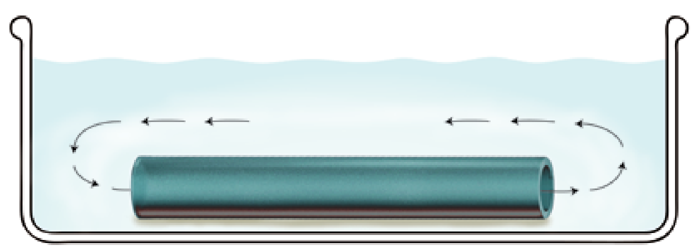


Figure 2. Practically incessant flow occurs through hydrophilic tubes immersed in water.

The stored electrical energy in water can drive various kinds of work, including flow. An example is the axial flow through tubes. We found that immersing tubes made of hydrophilic materials into water produces flow through those tubes, similar to blood flow through blood vessels (Figure 2). The driving energy comes from the radiant energy absorbed and stored in the water. Nothing more. Flow may persist undiminished for many hours, even days. Additional incident light brings faster flow. This is not a perpetual motion machine: incident radiant energy drives the flow — in much the same way that it drives vascular flow in plants. And, we have fresh evidence (see below) that it also assists the heart in driving blood in the cardiovascular system.

Applications in Biological Flow and Atmospheric Science

The water-based energy conversion framework is rich with implication for many systems involving water. These systems may range from biology and chemistry all the way to atmospheric science and engineering. The fourth phase appears nearly everywhere: all that's needed is water, radiant energy, and a hydrophilic surface. The latter can be as large as a slab of polymer and as small as a dissolved molecule. The liquid crystalline phase inevitably builds — and its presence plays some integral role in the system's behavior.

Let me provide a few representative examples.

One example is…you. Two thirds of your cells are water — by volume. In terms of the molecular fraction, that fraction translates to more than 99% because so many of those diminutive molecules are required to build that two-thirds volume fraction. Modern cell biology considers that 99% fraction of your molecules as mere background carriers of the "important" molecules of life such as proteins and nucleic acids. Conventional wisdom asserts that 99% of your molecules don't do very much.

However, EZ water envelops every macromolecule in the cell. Those macromolecules are so tightly packed that the enveloping liquid crystalline water largely fills your cells. In other words, most of your cell water is liquid crystalline, or EZ water. This water plays a central role in everything the cell does — as elaborated in my earlier book, *Cells, Gels and the Engines of Life* www.ebnerandsons.com.

What's new is the role of radiant energy: incident radiant energy powers many of those cellular functions. An example is the blood flowing through your capillaries. That blood eventually encounters high resistance: capillaries are often narrower than the red blood cells that must pass through them; to make their way through, those red cells need to bend and contort. Resistance is high. You'd anticipate the need for lots of driving pressure; yet, the pressure gradient across the capillary bed is negligible. The paradox resolves if radiant energy helps propel flow through capillaries in the same way that it propels flow through hydrophilic tubes. Radiant energy may constitute an unsuspected source of vascular drive, supplementing cardiac pressure.

Why you feel good after a sauna now seems understandable. If radiant energy drives capillary flow and ample capillary flow is important for optimal functioning, then sitting in the sauna will inevitably be a feel-good experience. The infrared energy associated with heat should help drive that flow. The same if you walk out into sunlight: we presume that the feel-good experience derives purely from the psychological realm; but the evidence above implies that sunlight may build your body's EZs. Fully built EZs around each protein seem necessary for optimal cellular functioning.

A second example of the EZ's central role is weather. Common understanding of weather derives from two principal variables: temperature and pressure. Those two variables are said to explain virtually everything we experience in terms of weather. However, the atmosphere also contains water: it is full of micrometer-scale droplets commonly known as aerosol droplets or aerosol particles. Those droplets make up atmospheric humidity. When the atmosphere is humid, the many droplets scatter considerable light, causing haze; you can't see clearly through that haze. When the atmosphere contains only few droplets, you may see clearly, over long distances.

The Fourth Phase book presents evidence for the structure of those droplets. It shows that EZ water envelops each droplet, while hydronium ions occupy the droplets' interior. Repelling one another, those internal hydronium ions create pressure, which pushes against the robust shell of EZ water. That explains why droplets tend toward roundness.

How do those aerosol droplets condense to form clouds? The droplets' EZ shells bear negative charge. Negatively charged droplets should repel one another, precluding any condensation into clouds. Those like-charged aerosol droplets should remain widely dispersed throughout the atmosphere. However, droplets *do* often condense into clouds, and the question is how that can happen.

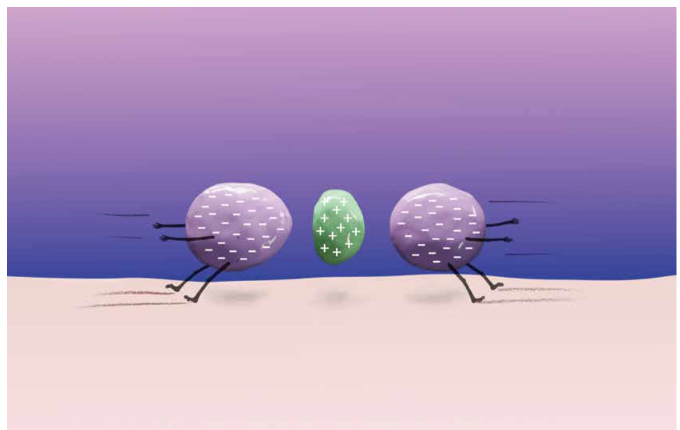


Figure 3. Like-charged entities attract because of an intermediate of opposite charge.

The reason they condense is because of the unlike charges that lie in between the droplets. Richard Feynman, the legendary Nobel Prize physicist of the late 20th century understood the principle, opining that: "like-likes-like because of an intermediate of unlikes." The like-charged droplets "like" one another, so they come together; the unlike charges lying in between those droplets constitute the attractors (Figure 3).

The like-likes-like principle has been widely appreciated, but also widely ignored: after all, how could like charges conceivably *attract*? A reason why this powerfully simple concept has been ignored is that the source of the unlike charges has been difficult to identify. We now know that the unlike charges can come from the splitting of water — the negative components building EZ shells, while the corresponding positive components provide the unlike attractors. With enough of those attractors, the negatively charged aerosol droplets may condense into clouds.

These two phenomena, radiant energy-induced biological function and like-likes-like cloud formation, provide examples of how water's energy can account for phenomena not otherwise explained. The fourth phase is the key building block that allows for construction of an edifice of understanding.

Practical Applications

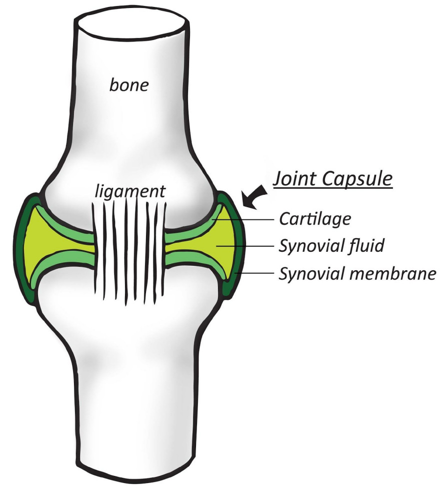


Figure 4. Enveloping the joint, the capsule ensures that the fluid's hydronium ions don't disperse. The concentrated hydronium ions repel, keeping surfaces apart and assuring low friction.

Beyond scientific, the discovery of the fourth phase has practical applications. They include flow production (already mentioned), electrical energy harvesting, and even filtration. I briefly mention the latter two applications.

Filtration occurs naturally because the liquid crystalline phase massively excludes solutes and particles in much the same way as does ice. Accordingly, fourth phase water is essentially solute free. Collecting it provides solute-free and bacteria-free water. A working prototype has confirmed this expectation. Purification by this method requires no physical filter: the fourth phase itself does the separation, and the energy comes from the sun.

Energy harvesting seems straightforward: light drives the separation of charge, and those separated charges constitute a battery. Harvesting electrical energy should be realizable with proper electrodes. This technology development is underway in our spinoff company, and has the potential to replace standard photovoltaic systems with simpler ones based on water. More detail on these practical applications can be found in the Pollack laboratory homepage: <http://faculty.washington.edu/ghp/>.

Practical applications also exist within our bodies, and I present two of them: why your joints don't squeak: and why dislocated or sprained joints will swell *within seconds*.

Joints are sites at which bones press upon one another (Figure 4). The bones may also rotate, as during deep-knee bends and push-ups. You'd think that rotation under pressure might elicit squeaky frictional resistance, but joint friction remains remarkably modest. Why so?

The ends of bones are lined with cartilage. Those cartilaginous materials do the actual pressing. Hence, the issue of joint friction reduces to the issue of the cartilaginous surfaces and the synovial fluid lying in between. How does this system behave under pressure?

Cartilage is made of classic gel materials: highly charged polymers and water; therefore, cartilage is a gel. Gel surfaces bear EZs, so cartilage surfaces should likewise bear EZs. The splitting of water associated with EZ buildup creates many hydronium ions in the synovial fluid between. Additional hydronium ions come from the molecules within that fluid, creating their own EZs and protons. Thus, many hydronium ions will lie in the area where two cartilaginous surfaces lie across from one another. The repulsive force coming from those hydronium ions should keep the cartilage surfaces apart — some investigators maintain that despite heavy loads, the cartilage surfaces never touch. That separation means that any rough spots, or asperities, will never come into contact as the respective surfaces shear past one another; and that in turn means low friction.

For such a mechanism to work, some kind of built-in restraint should be present to keep the repelling hydronium ions in place. Otherwise, they may be forced out of the local region, compromising lubrication. Nature provides that safety net: a structure known as the joint capsule envelops the joint. By constraining the dispersal of hydronium ions, that encapsulation ensures low friction. That's why your joints don't ordinarily squeak.

Figure 5. Example of post-injury swelling.

Regarding swelling, the second issue under consideration, osmosis evidently plays a role. Since the cell is packed with negatively charged proteins, the cytoplasm should generate an osmotic draw similar to the osmotic draw generated by diapers or gels. Physiologists know that it does.

A peculiar feature of cells, however, is their relatively modest water content. Compared to 20:1 or higher for many common gels, the cell's water-to-solids ratio is only about 2:1. The many negatively charged macromolecules of the cell should generate a strong osmotic draw; yet the water content in the cell remains surprisingly low. That limited water content may come as a consequence of the macromolecular network's stiffness: cellular networks typically comprise tubular or multi-stranded biopolymers tightly cross-linked to one another. The resultant stiffness prevents the network from expanding to its full osmotic potential.

If those cross-links were to disrupt, however, then the full power of osmotic draw would take effect; the tissue could then build many EZ layers and therefore hydrate massively, bringing huge expansion (Figure 5). That's what happens when body tissues are injured, especially with dislocations. The injury disrupts fibrous macromolecules and cross-links, eliminating the restraining forces that keep osmosis at bay; EZ buildup can then proceed virtually unimpeded.

The reason why swelling can be so impressive is that the cross-link disruption occurs progressively. Breaking one cross-link results in higher stress on neighboring cross-links; so disruption progresses in a zipper-like fashion. When that happens, the osmotic rush of water into the tissue can continue practically without restraint, resulting in the enormous immediate swelling that is often seen. The tissue will return to normal only when cross-links repair and the matrix returns to its normally restraining configuration.

Water and Healing

During childhood illness, grandmothers and doctors will often advise: "drink more water." In his now-classical book, sub-titled *Your Body's Many Cries for Water: You Are Not Sick, You Are Thirsty*, the Iranian physician Fereydoon Batmanghelidj confirms the wisdom of this quaint advice. The author documents years of clinical practice showing reversal of diverse pathologies simply by drinking more water. Hydration is critical.

Batmanghelidj's experience meshes with evidence of healing from special waters such as those from the Ganges and Lourdes. Those waters most often come from deep underground springs or from glacial melt. Spring waters experience pressure from above; pressure converts liquid water into EZ water because of EZ water's higher density. So, spring water's healing quality may arise not only from its mineral content but also from its relatively high EZ content.

The same for mountain water: it too should have high EZ content. Our studies have shown that ice formation requires an EZ intermediate; i.e., bulk water does not convert directly to ice; it converts to EZ, which then converts to ice. Similarly for melting: melting ice forms EZ, which subsequently converts to bulk water. Fresh ice melt contains abundant EZ water.

For spring water and fresh ice melt, then, the high EZ content may explain the recognized health benefits. EZ water should rehydrate tissues better than ordinary water because of its higher dipole moment. To appreciate this argument, picture a bean with positive charge localized at one end, negative at the other. The positive end of that dipole orients toward the negatively charged cell, which then strongly draws in that dipole. The larger the dipole, the stronger will be the draw. Since EZs contain masses of separated charges, or large dipoles, EZ water should hydrate cells better than ordinary water. That's why EZ water may particularly promote good health.

Negative Charge and Anti-Oxidants

Humans are considered neutral, but I suggest that we bear net negative charge.

Physical chemists reasonably presume that all systems tend toward neutrality because positive charge attracts negative charge. The human body being one of those "systems," we assume that the body must be neutral.

Not all systems are neutral, however. The earth bears net negative charge, while the atmosphere bears net positive charge. Water itself can bear charge: Anyone watching MIT professor Walter Lewin's stunning demonstration of the Kelvin water dropper, where separated bodies of water eventually discharge onto one another, will immediately see that bodies of water *can* bear net charge. If any doubt remains, then the experience of getting an electric shock from touching certain kinds of drinking water (which my colleagues and I have personally experienced) should eliminate that doubt.

Charges can remain separated if input energy keeps them separated — something like recharging your cell phone battery and creating separated negative and positive terminals. Since we constantly absorb external energy from the environment, the theoretical possibility exists that we may bear net charge.

Consider the arithmetic. Cells make up some 60% of your body's mass, and they are negatively charged. Extracellular tissues such as collagen and elastin are next in line, and those proteins bear negative charge and adsorb negatively charged EZ water. Only some of the smaller compartments are positively charged with protons (low pH), and they commonly *expel*: urine, gastrointestinal system; sweat, and expired air (containing hydrated CO_2 or carbonic acid). They help *rid* the body of positive charge.

So, the arithmetic shows not only that our body bears net negative charge, but also that the body makes every effort to maintain that negativity by ridding itself of protons. It is as though maintaining negativity is a "goal" of life. Plants do it easily: they connect directly to the negatively charged earth; animals need to struggle a bit more to maintain their body's charge, in exchange for greater mobility.

How does our body's negative charge relate to the benefits of anti-oxidants?

Answering this question returns us to basic chemistry. Recall that "reduction" is the *gain* of electrons, while "oxidation" means electron *loss*. Oxidation strips molecules of their negative charge, working against the body's attempt to maintain high negativity. To guard against that loss we employ *anti*-oxidants. Anti-oxidants may keep us healthy simply by maintaining proper negativity.

The Future

Water's centrality for health is nothing new, but it has been progressively forgotten. With the various sciences laying emphasis [on] molecular, atomic, and even sub-atomic approaches, we have lost sight of what happens when the pieces come together to form the larger entity. The whole may indeed exceed the sum of its parts. 99% of those parts are water molecules. To think that 99% of our molecules merely bathe the "more important" molecules of life ignores centuries of evidence to the contrary. Water plays a central role in all features of life.

Until recently, the understanding of water's properties has been constrained by the common misconception that water has three phases. We now know it has four. Taking into account this fourth phase allows many of water's "anomalies" to vanish: those anomalies turn into predictable features. Water becomes more understandable, and so do entities made largely of water, such as oceans, clouds, and human beings.

Various hour-long talks describe these fresh understandings. One of them is a University of Washington public award lecture http://www.youtube.com/watch?v=XVBEwn6iWOo [*Water, Energy and Life: Fresh Views From the Water's Edge*]. Another was delivered more recently http://www.youtube.com/watch?v=JnGCMQ8TJ_g [*Electrically Structured Water, Part 1*]. A third is a recent TEDx talk http://youtu.be/i-T7tCMUDXU [*The Fourth Phase of Water: Dr. Gerald Pollack at TEDxGuelphU*].

A much fuller, well-referenced understanding of these phenomena and more appears in the above-mentioned new book, *The Fourth Phase of Water: Beyond Solid, Liquid, and Vapor* <www.ebnerandsons.com>.

The insights described above arose out of a departure from mainstream science. They were gleaned mainly from simple observations and logical interpretations. I have purposefully ignored the "generally accepted," with some skepticism that all accepted principles are necessarily valid. I believe this skepticism has brought us a long way.

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