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

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CONTACT: Biodiversity for a Livable Climate
P.O. Box 390469
Cambridge, MA 02139, USA
compendium@bio4climate.org
(781) 674-2339

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 200 videos of speakers (with 107,000 views) from our 11 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 in a healthy direction, 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 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 and are pursuing similar efforts in the Massachusetts legislature.

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 1, July 2018, 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 editor and lead writer/researcher Hannah Lewis, writer Adam Sacks, and reviewers Paula Phipps, Charles Shore, Philip Bogdonoff, Fred Jennings and Christopher Haines. 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 eleven conferences as of March 31, 2018.

We are most appreciative of the support from our sponsors over the past 3.5 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 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

[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.

Introduction

In this third issue of the Compendium of Scientific and Practical Findings Supporting Eco-Restoration to Address Global Warming by Biodiversity for a Livable Climate ("Bio4Climate"), we focus on the pivotal roles of water cycles and soil ecology in stabilizing ecosystems and the climate.

Water, Life and Climate

Water and vegetation are climate heroes, co-starring in a story about as old as terrestrial life on Earth yet under-recognized in mainstream climate politics. Not only does the vegetation embedded in ecosystems act as a giant CO_2-absorption machine, constantly removing the greenhouse gas from the air and storing much of it in soil and biomass, but vegetation also tames the energetic flow of liquid and gaseous water around the planet, mitigating drought and flood conditions. Plants facilitate the recharge of groundwater, while also recharging the skies with moisture for rain. And through this plant-water partnership, vegetation also cools the Earth.

> Water, thanks to its high heat-carrying capacity, is able to redistribute much of the solar heat energy received by the Earth through the water cycle: through evapotranspiration and condensation. Thus the evapotranspiration and condensation of water plays an instrumental role in climate control with regard to temperature distribution in time and space. That is, it helps reduce the peaks and modulate the amplitudes of high and low temperatures on the land surface - making conditions on Earth suitable for life [Eiseltova 2012: 306].

Like all living things, plants need water to survive. Yet, the average plant uses less than 5% of the water taken up by its roots for its own cell production and growth [McElrone 2013]. The remainder is essentially a coolant in a plant's private air conditioning system. Through the process of transpiration, water absorbed by roots and transported up the stem eventually makes it to the stomatal openings on the leaves, vaporizing just below the surface and cooling the plant in a release of latent heat.

The average plant uses less than 5% of the water taken up by its roots for its own cell production and growth [McElrone 2013]. The remainder is essentially a coolant in a plant's private air conditioning system.

Latent heat is the energy absorbed by water that transforms liquid into vapor. The water in a leaf intercepting sunlight absorbs thermal energy from the sun and then releases it in vapor in a process that involves no temperature change. Thus, living plants are never hot to the touch. By contrast, solar energy alighting on a mineral surface is absorbed as sensible heat[3], raising the temperature of that surface.

An average tree can transpire hundreds of liters of water per day. Every 100 liters of water transpired equates in cooling power to the daily output of two central air-conditioning units for an average home [Ellison 2017:54]. Multiplied millions of times over a given landscape, the cooling effect of transpiration is significant.

Imagine yourself in a city, where on a hot day the asphalt is too hot even to touch, and the heat radiating from it permeates everything around it.[4] Next, imagine yourself on that same hot day walking into a city park full of trees, bushes and grasses: not only can you take your shoes off on the cool grass and park yourself in some shade, but with enough trees around you can also feel a distinct coolness in the air even out of the shade.

Similarly, vegetation cover has been shown to affect local, regional and continental climates [LeJeune 2018, Eiseltova 2012, Locatelli 2015, Alter 2018, Paul 2016, Ellison 2017, Swann 2018, Makarieva 2007]. As noted, vegetation contributes to rain through transpiration, which augments atmospheric vapor flows, and through the release of biotic aerosols, which coalesce water droplets in clouds into drops of rain [Hassett 2017, Ellison 2017]. Furthermore, by increasing groundwater retention, vegetation mitigates local flood and drought conditions and filters/cleans drinking water [EEA 2015]. The cooling action of forests also creates sanctuary from the intensifying heat of climate change for animals [Betts 2018] and people alike.

Less obvious perhaps, though equally significant, is that vegetation cover also regulates temperatures and climate on a global scale [Ellison 2017, Lemordant 2018, Gordon 2005, Kleidon 2000, Locatelli 2015], thus influencing weather patterns on Earth. For example, Gordon [2005] notes that deforestation has reduced global vapor flows by more than 4%, changing rainfall distribution patterns. Kleidon [2000] shows an average global temperature difference of 1.2C between hypothetical conditions of maximum and minimum global vegetation, regardless of any greenhouse gas effect. (For comparison, 1.2C is roughly the level of global warming since the start of the Industrial Revolution due to land use change and the greenhouse gas effect.) Ellison [2017: 52] notes that land cover change accounts for some 18% of global warming trends.

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[3] In contrast to latent heat, sensible heat can be felt and directly affects the temperatures on the body where it resides, such as when sunlight touches a mineral surface and heats it up.

[4] Interestingly, Spike Lee's movie "Do the Right Thing" builds a whole plot around the intensity of an urban heat pocket. His characters struggle to keep their "cool" – literally and figuratively - on a hot summer day on an asphalt street surrounded by concrete.

Further evidence of vegetation's significant effect on the global climate is Lemordant's [2018] finding that the physiological response of plants to increased atmospheric CO_2 affects the global hydrological cycle even more than do the greenhouse effect and changes in precipitation. That's because plants shrink their stomata to limit CO_2 intake and consequently limit the release of water vapor from those same stomata. Stomatal shrinkage results in more water left in the soil and less water entering the atmosphere through transpiration.

In summary, Ellison et al [2017] state that,

> The substantial body of research we review reveals that forest, water and energy interactions provide the foundations for carbon storage, for cooling terrestrial surfaces and for distributing water resources. Forests and trees must be recognized as prime regulators within the water, energy and carbon cycles [Ellison 2017: 51].

In their prescriptions for land management policies, both Locatelli [2015] and Eiseltova [2012] embrace the concept that vegetation (and forests in particular) exert control in diverse and dynamic ways on local, regional and global climate systems. Locatelli argues for "climate-smart" tropical reforestation that not only enhances the carbon sequestration process, but also helps local communities adapt to climate change by recharging stream flow in the dry season, reducing the severity of floods, protecting slopes against landslides and, through mangrove reforestation, reducing the impact of coastal storms and waves.

Similarly, Eiseltova et al [2012: 324] argue that "there is an urgent need that agricultural research focuses on how to close water cycles in the landscape and the development of farming systems with a more vertically-layered vegetation structure keeping water and lower temperatures during a sunny day." These authors propose "two criteria for assessing sustainable land management":

> These criteria are: the efficiency of an ecosystem to recycle water and matter; and its efficiency to dissipate solar energy. It is land managers that can substantially contribute to the restoration of the water cycle, climate amelioration and reduction of irreversible matter losses with river water flows to the sea [Eiseltova 2012: 325].

The collection of article summaries that follow reveals a cascade of recent discoveries about the relevance of forests and other vegetative ecosystems, vis a vis regional and global water cycles, in discussions of climate mitigation and adaptation. What is both fascinating and critical here is, as Locatelli et al allude to, the multi-functionality of extensive, integral vegetative ecosystems with respect to climate change. This multifunctionality is due to the roles vegetation plays both locally, in adapting to temperature and weather extremes and contributing to forestry/farming-related livelihood opportunities, and globally, through CO2 sequestration, global average temperature reduction, and evenness of rainfall distribution.

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Water Article Summaries

Evapotranspiration – A Driving Force in Landscape Sustainability, Eiseltová 2012

Vegetation cover cools Earth when it intercepts the sun's energy. This is not just by providing shade, but also through evapotranspiration, which is how plants regulate their own internal temperatures.

> For a plant … transpiration[5] is a necessity by which a plant maintains its inner environment within the limit of optimal temperatures. And at the level of landscape, evapotranspiration is the most efficient air conditioning system developed by nature [Eiseltova 2012:10].

The water in plant tissues contains the sun's energy in the form of latent heat, which is released from plants through evapotranspiration. In the absence of water, solar energy reaching Earth becomes sensible heat - the heat we can feel and measure in rising temperatures.

> Without water, the energy of the incoming radiation is transformed into sensible heat and the local area becomes overheated during the day and likewise far cooler at night (as is well known from desert areas, with differences between day and night temperatures typically exceeding 50°C). Water-saturated landscapes provide much more stable environments than do dry terrestrial systems. In landscapes with water - abundant aquatic ecosystems, wetlands and soils with high water retention capacity - about 80% of incoming solar energy is stored as latent heat of water vapour via evapotranspiration, whilst in de-watered landscapes (with a low-water retention capacity) the vast majority of solar energy is transformed into sensible heat (Pokorný et al. 2010b) [Eiseltova 2012: 307].

[5] Transpiration is the movement of water from plant roots up through the stem into the leaves, where it is vaporized and released through leaves' stomatal openings.

With respect to landscape management for sustainability, the authors introduce the idea of a "dissipative-ecological-unit," meaning "the smallest functional unit that is capable of forming internalized cycles of matter and water while dissipating energy" [Eiseltova 2012: 312]. This term emphasizes the importance of small, local water cycles, which occur naturally in undisturbed ecosystems, resulting in "an efficient local resource economy and … relatively even temperatures and moisture conditions" [Eiseltova 2012: 312].

> In catchments with a well-developed vegetation cover, water and matter are bound to short-circuited cycles and losses are minimal. In contrast, the increased clearance of forest, exposure of bare land, and drainage of agricultural land have accelerated matter losses from catchments [Eiseltova 2012: 11].
>
> There is an urgent need that agricultural research focuses on how to close water cycles[6] in the landscape and the development of farming systems with a more vertically-layered vegetation structure keeping water and lower temperatures during a sunny day[7] [Eiseltova 2012: 324].
>
> The water cycle is akin to the 'bloodstream' of the biosphere. Returning water to the landscape and restoring more natural vegetation cover is the only way to restore landscape sustainability. More attention in present-day science needs to be devoted to the study of the role of vegetation in the water cycle and climate amelioration. Restoration of a more natural vegetation cover over the landscape seems to be the only way forward.
>
> Based on our current scientific knowledge, we can propose two criteria for assessing sustainable land management. These criteria are: the efficiency of an ecosystem to recycle water and matter, and its efficiency to dissipate solar energy. Land managers can substantially contribute to the restoration of the water cycle, climate amelioration and reduction of irreversible matter [soil and nutrient] losses with river water flows to the sea.
>
> It is in the interest of society as a whole that land managers (farmers, foresters) be rewarded for their actions towards sustainable management of their land. Suitable tools to assess the achievements of individual land managers with respect to sustainable management of their land are: (1) continuous monitoring of conductivity – a measure of dissolved load - and flow rates in streams in order to estimate matter losses; and (2) the regular evaluation of satellite thermal channel images to assess temperature damping,

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[6] The water cycle is the constant movement of water through land and atmosphere via evapotranspiration and condensation. To close a water cycle within a landscape is to enhance water recycling and limit water loss through vegetative cover.
[7] There are also productivity reasons for layering vegetation structure. See, for example, Mark Shepard 2013, *Restoration Agriculture*, Acres USA.

> i.e., the effectiveness of land use to dissipate solar energy. Restoration of natural 'cooling structures' – vegetation with its evapotranspiration and condensation-induced water circulation – is essential to renew landscape sustainability [Eiseltova 2012: 325].

New climate solutions, water cycles and the soil carbon sponge, Jehne 2018

Regenerating the soil carbon sponge is our greatest point of leverage for salvaging the planet from the point of existential climate crisis. "Sponge" refers to the quality of a biologically active soil with high organic matter content to have lots of pore space for water absorption. Jehne states that every additional gram of soil carbon allows the soil to hold 8 additional grams of water. He emphasizes the soil sponge concept because it is the driver of healthy ecosystems, and also within our control to repair and regenerate.

Jehne explains that an average of 342 W/m^2 of incident solar radiation enters the troposphere while just 339 W/m^2 is reflected back into space due to the greenhouse effect [Jehne 2018: 19:00 min]. This leaves a continuous energy balance of 3 W/m^2 heating up the planet. Of the solar radiation returning to space, 24% is released through latent heat fluxes from evapotranspiration [Jehne 2018: 1:34:15]. However, due to land use change, there is 50% less transpiration on Earth than there was some 8,000 years ago. Jehne estimates that increasing transpiration by only 5% would be enough to offset the 3 W/m^2 surplus solar energy [Jehne 2018: 1:34:50].

Increasing transpiration is achieved by increasing vegetation cover, which in turn is achieved by regenerating the soil sponge. Jehne explains that conventional agriculture has employed techniques (such as burning, cultivating/tilling, applying fertilizer and pesticides, and use of irrigation and fallow) that quickly oxidize the carbon fixed by plants through photosynthesis. By contrast, regenerative agriculture builds up the soil carbon sponge by facilitating the ecological processes that create stable soil carbon and limit organic matter breakdown.

In addition to the cooling effect from the latent heat flux, transpiration also provides the moisture needed for cloud formation. Jehne states that a 2% increase in cloud cover, given its high albedo, is also enough to reflect the excess 3 W/m^2 solar radiation that is otherwise absorbed on Earth [Jehne 2018: 1:39:25]. Furthermore, bacteria released from ecosystems serve as the most effective precipitation nuclei[8] for making rain.

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[8] Precipitation nuclei are tiny particles (including ice crystals, salts and bacteria) upon which micro-droplets of water in clouds coalesce into raindrops [Jehne 2018: 1:40:00].

Continental-scale consequences of tree die-offs in North America: identifying where forest loss matters most, Swann 2018

Vegetation cover affects the amount of solar energy a land area absorbs and/or releases, thus altering local temperatures and precipitation. Plants regulate local temperatures through shading, albedo and evapotranspiration, which releases latent[9] heat.

> The ability of a surface to shed energy through latent or sensible heat is key to determining that surface's temperature - shifts in the relative balance between the two can lead to increases in surface temperatures (where sensible heat is relatively higher) or decreases (where latent heat is relatively higher) [Swann 2018: 2].

This study shows that changes in vegetation cover in a given place affect not only the local climate, but also the climate system at a continental scale. The results are temperature and precipitation changes in remote parts of the continent relative to where the tree loss occurred, leading to changes in ecosystem productivity in those remote parts. This phenomenon is called 'ecoclimate teleconnections.'

> Plants profoundly influence local climate by controlling the exchange of energy and water with the atmosphere. Changes in and/or losses of plant type or plant functioning can alter the local climate, but also potentially large scale climate by modifying atmospheric circulation. … the potentially global impact of plant cover change on other ecosystems as communicated by the atmosphere has been under-appreciated and is only beginning to be evaluated [Swann 2018: 2].

Researchers simulated tree die-offs in their model by replacing all trees in a given domain[10] with grass.

> Domain-scale tree loss led to changes in local (within same domain) surface properties and fluxes including albedo and evapotranspiration. These changes in surface properties modified local surface climate (e.g., precipitation and temperature), as well as impacted atmospheric circulation. The atmospheric circulation response connects the direct forcing of tree loss on the local atmosphere to other regions, impacting climate and thus resulting in altered Gross Primary Productivity (GPP) across North America [Swann 2018: 3-4].

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[9] Latent heat is energy released or absorbed in a constant-temperature process. For example, evaporation releases latent heat from a surface through the transformation of water into vapor, where the vapor carries energy off the surface. By contrast, sensible heat can be felt and directly affects the temperatures on the body where it resides.
[10] 'Domain' refers here to each of the 13 most densely forested bioclimatic regions in the US, as identified by the US National Ecological Observatory Network [Swann 2018: 2].

Furthermore, the severity of the remote effects of tree loss depends not only on the scale of the tree loss, but also on the location of the tree loss. The study found, for example, that tree loss in an area covering most of California had greater effect on GPP in other parts of the continent than did tree loss of a similar scale elsewhere.

> Thus, in addition to the magnitude of forest loss, the location of forest loss plays an outsized role in determining the continental scale impact [Swann 2018: 6].

Trees, forests and water: cool insights for a hot world, Ellison 2016[11]

This paper takes the innovative and paradigm-shifting position that carbon is not the primary consideration in climate; rather, water should be the central focus, integrated with carbon and energy cycles:

> Forest-driven water and energy cycles are poorly integrated into regional, national, continental and global decision-making on climate change adaptation, mitigation, land use and water management. This constrains humanity's ability to protect our planet's climate and life-sustaining functions. The substantial body of research we review reveals that forest, water and energy interactions provide the foundations for carbon storage, for cooling terrestrial surfaces and for distributing water resources. Forests and trees must be recognized as prime regulators within the water, energy and carbon cycles. If these functions are ignored, planners will be unable to assess, adapt to or mitigate the impacts of changing land cover and climate. Our call to action targets a reversal of paradigms, from a carbon-centric model to one that treats the hydrologic and climate-cooling effects of trees and forests as the first order of priority. For reasons of sustainability, carbon storage must remain a secondary, though valuable, by-product. The effects of tree cover on climate at local, regional and continental scales offer benefits that demand wider recognition. The forest- and tree-centered research insights we review and analyze provide a knowledge-base for improving plans, policies and actions. Our understanding of how trees and forests influence water, energy and carbon cycles has important implications, both for the structure of planning, management and governance institutions, as well as for how trees and forests might be used to improve sustainability, adaptation and mitigation efforts [Ellison 2016: Abstract].

[11] Excerpted from Bio4Climate Compendium Vol 1 No 1.

> Our call to action targets a reversal of paradigms, from a carbon-centric model to one that treats the hydrologic and climate-cooling effects of trees and forests as the first order of priority. [Ellison 2016: Abstract].

Biotic pump of atmospheric moisture as driver of the hydrological cycle on land, Makarieva and Gorshkov 2007[12]

The authors examine ecological and geophysical principles to explain how land far inland away from the ocean can remain moist, given that gravity continuously pulls surface and groundwater into the ocean over time.

All freshwater on land originates in the ocean from which it has evaporated, is carried on air flux, and precipitates over the land. Coastal regions benefit from this cycle by their proximity to the ocean, yet in the absence of natural forests in coastal regions precipitation weakens as distance from the ocean increases, leaving inland areas arid. The authors propose the concept of a biotic pump to explain how large continents can be sufficiently moist deep into the interior, and abundant with rivers and lakes.

Air and moisture are pulled horizontally by evapotranspiration over coastal forests. When water vapor from plants condenses, it creates a partial vacuum that pulls water evaporating from the ocean into the continental interior which results in forest rains. By contrast, deserts are unable to pull in ocean evaporation because they lack evaporative force.

Therefore, ongoing deforestation, especially coastal deforestation on a large scale, threatens to cut off rain to the interiors of Earth's continents, thereby creating new deserts. The Amazonian rainforest is the prime example: Deforestation of the eastern coast of South America has led to changes in the rainforest that is resulting in drying and desertification of the interior, with unprecedented fires and loss of rivers. Historically, Australia's interior became a desert around the time the first humans arrived on the continent, and the authors speculate that early coastal deforestation was the cause. On the other hand, restoring natural coastal forests can also restore inland water cycles and reverse desertification.

This article illustrates the importance of biological relationships that are ecologically complex and poorly understood. It highlights the significance of the precautionary principle in assessing

[12] Ibid.

what we don't know when altering ecological processes, and taking preventive action in the face of uncertainty.

How Forests Attract Rain: An Examination of a New Hypothesis, Sheil and Murdiyarso 2009

Highlighting the significance of Makarieva and Gorshkov's "biotic pump" hypothesis (above), Sheil and Murdiyarso explain it in layman's terms in this article for the benefit of a broader public, and examine its validity. They point out that the biotic pump hypothesis offers an explanation for a question not otherwise resolved in conventional climate theory.

> Conventional theory offers no clear explanation for how flat lowlands in continental interiors maintain wet climates. Makarieva and Gorshkov show that if only "conventional mechanisms" (including [rain] recycling) apply, then precipitation should decrease exponentially with distance from the oceans. Researchers have previously puzzled over a missing mechanism to account for observed precipitation patterns (Eltahir 1998) [Sheil & Murdiyarso 2009: 342].

They explain the biotic pump hypothesis and how it resolves the puzzle:

> Air currents near Earth's surface flow to where pressure is lowest. According to Makarieva and Gorshkov, these are the areas that possess the highest evaporation rates. In equatorial climates, forests maintain higher evaporation rates than other cover types, including open water. Thus, forests draw in moist air from elsewhere; the larger the forest area, the greater the volumes of moist air drawn in. This additional moisture rises and condenses in turn, generating a positive feedback in which a large proportion of the water condensing as clouds over wet areas is drawn in from elsewhere. The drivers (solar radiation) and basic thermodynamic concepts and relationships are the same as in conventional models, thus most behaviors are identical— the difference lies in how condensation is incorporated.
>
> Makarieva and Gorshkov's estimates, incorporating volume changes from condensation, imply that when forest cover is sufficient, enough moist air is drawn in to maintain high rainfall inside continents. The numbers now add up: thus, condensation offers a mechanism to explain why continental precipitation does not invariably decline with distance from the ocean [Sheil & Murdiyarso 2009: 342].

Commenting on the relevance of the hypothesis, the authors conclude:

> Acceptance of the biotic pump would add to the values that society places on forest cover. By raising regional concerns about water, acceptance of Makarieva and Gorshkov's biotic pump demands attention from diverse local actors, including many who may otherwise care little for maintaining forest cover [Sheil & Murdiyarso 2009: 346].

Human modification of global water vapor flows from the land surface, Gordon 2005

Human modification of the hydrological cycle has profoundly affected the flow of liquid water across the Earth's land surface. Compared to changes to liquid water flow, alteration of water vapor flows through land-use changes has received comparatively less attention, despite compelling evidence that such alteration can influence the functioning of the Earth System.

> We show that deforestation is as large a driving force as irrigation in terms of changes in the hydrological cycle. Deforestation has decreased global vapor flows from land by 4% (3,000 km3/yr), a decrease that is quantitatively as large as the increased vapor flow caused by irrigation (2,600 km3/yr). Although the net change in global vapor flows is close to zero, the spatial distributions of deforestation and irrigation are different, leading to major regional transformations of vapor-flow patterns [Gordon 2015: 7612].

A green planet versus a desert world: estimating the maximum effect of vegetation on the land surface climate, Kleidon 2000

This climate model simulation illustrates how the biosphere affects the climate system. With "maximum vegetation," more water is absorbed in the ground, allowing for evaporation to cool the land surface while also recycling more rain. This simulation resulted in an average temperature reduction over land of 1.2C.

The authors describe their approach:

> We quantify the maximum possible influence of vegetation on the global climate by conducting two extreme climate model simulations: in a first simulation ('desert world'), values representative of a desert are used for the land surface parameters for all non-glaciated land regions. At the other extreme, a second simulation is performed ('green planet') in which values are used which are most beneficial for the biosphere's productivity [Kleidon 2000: 471].

They describe the effects of maximum vegetation on the water cycle, stating that over land:

> …the hydrological cycle is more active, with precipitation roughly increasing by 100%, evapotranspiration by more than 200% and the mean moisture content of the atmosphere (or precipitable water) increasing by 30%. These increases can be understood by enhanced recycling of soil water as a response of both, (i) more absorbed radiation at the surface so that more energy is available for evapotranspiration and (ii) larger soil water storage capacities (SWCs) which enhance water availability during dry periods. This increased recycling also leads to an overall decrease in continental runoff by about 25% [Kleidon 2000: 476].

Changes in the water cycle result in land surface temperature changes:

> The substantial increase in evapotranspiration is associated with differences in the surface energy balance, primarily concerning the partitioning between sensible and latent heat. The latent heat flux increases by the same amount (more than 200%) as evapotranspiration and the sensible heat flux decreases to 30% of its original value. … Subsequently, the increased latent heat flux leads to more efficient cooling of the surface, resulting in temperatures reduced by 1.2 K[13] [Kleidon 2000: 477-478].

Historical deforestation locally increased the intensity of hot days in northern mid-latitudes, LeJeune 2018

Deforestation contributes to climate change on a global scale through carbon emissions (biogeochemical effects), and on a local/regional scale through biogeophysical effects related to albedo, evapotranspiration and roughness, affecting surface energy budgets.

> Here, we show that historical deforestation has led to a substantial local warming of hot days over the northern mid-latitudes - a finding that contrasts with most previous model results. Based on observation-constrained state-of-the-art climate-model experiments, we estimate that moderate reductions in tree cover in these regions have contributed at least one-third of the local present-day warming of the hottest day of the year since pre-industrial time, and were responsible for most of this warming before 1980 [LeJeune 2018: 1].

The study uses observational data to constrain the outcome of a climate model simulating the effects of deforestation on regional temperatures. The authors found that during most of the 20th century, the biogeophysical effects of deforestation were the main cause of regional

[13] A temperature change of 1.2 K (Kelvin) is equivalent to a temperature change of 1.2 C (Celsius).

temperature increases, and that by 1980 deforestation in northern mid-latitudes had declined. By that time other forcings began to take on a proportionally greater role in regional temperature increases.

Twentieth Century regional climate change during the summer in the central United States attributed to agricultural intensification, Alter 2018

Noting that “major increases in crop productivity and changes in regional climate are generally collocated in time and space over the central United States” [Alter 2018: 1587], the study tested the hypothesis that there is a causal relationship - that historical agricultural intensification has affected regional summer climate in this area.

> … from 1950 to 2010, the amount of corn harvested annually in the Corn Belt increased by 400%, from 2 billion to 10 billion bushels (National Agricultural Statistics Service, 2016) [Alter 2018: 1586].

and

> From 1910 to 1949 (pre-agricultural development, pre-DEV) to 1970–2009 (full agricultural development, full-DEV), the central United States experienced large-scale increases in rainfall of up to 35% and decreases in surface air temperature of up to 1°C during the boreal summer months of July and August, when crop water use in the Corn Belt is at its peak [Alter 2018: 1586].

The authors used a regional climate model to test their hypothesis by comparing a set of simulations where “enhanced photosynthesis over cropland [serves] as a proxy for agricultural intensification” [Alter 2018: 1589] to a control simulation with no agricultural intensification. They found that:

> Over the region that has experienced significant increases in observed rainfall (region of significant change—ROSC), the mean rainfall increase is ~7% (0.20mm/d) for the simulations and ~15% (0.37mm/d) for the observations. Thus, it seems that agricultural intensification has been a major contributor to the observed increase in summer rainfall in the central United States [Alter 2018: 1589].
>
> Strikingly, these increases in rainfall are also very consistent: Agricultural intensification enhances simulated rainfall across the aforementioned swath in the central United States during at least 62% of the 150 ensemble years (significant at the 5% level using the chi-square test). In the observational data, a similar consistency in precipitation enhancement is evident when comparing the pre-DEV and full-DEV time periods. This

> suggests that the changes in rainfall due to agricultural intensification are not the result of occasional increases but instead are indicative of a more systematic change in the summer rainfall regime of the central United States [Alter 2018: 1589].

This study usefully contributes evidence that vegetation cover affects local and regional climates, while drawing conclusions, however, that are not necessarily helpful to understanding how to mitigate and adapt to climate change. The study's findings suggest that agricultural intensification can potentially mitigate local climate change effects in the future, but it is unlikely that the methods that drove agricultural intensification in the 20th Century will continue to work in a changing climate. The reason that these methods are now obsolete is that they strip the soils of the organic material and living organisms necessary for the resilience of plants, and their ability to cope with droughts, floods, heat and other challenging conditions.

The model here uses "enhanced photosynthesis" as a proxy for agricultural intensification. While the increase in yield between early and late 20th Century Corn Belt production represents an increase in photosynthesis, high-input agriculture is but one pathway to enhanced photosynthesis. Moreover, it is an extremely problematic one with respect to climate change, given the high energy costs of fertilizer, pesticides and fuel, and the damage to the soils from these practices.

Instead, a useful lesson to draw from this study is simply that enhanced photosynthesis itself can mitigate climate change regionally. In the context of agricultural production in the era of climate change, enhanced photosynthesis might best be accomplished through ecological intensification, a strategy for improving resilience within an agro-ecosystem, and thereby greater photosynthesis and more reliable crop production.

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Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics, Ilstedt 2016

Responding to a common belief that trees lower groundwater infiltration due to transpiration, and a contrasting view that trees increase groundwater infiltration by increasing organic matter and soil porosity, these authors test an "optimum tree cover theory."

They find that "intermediate" tree cover maximizes groundwater recharge in the tropics, resulting in a 2-14% increase in total annual water input from rainfall. However, the tree species used in this study consume more water compared to many other tree species in the semi-arid tropics. Therefore, the results here may be conservative in terms of the potential of trees to increase groundwater recharge. Furthermore, the study doesn't consider the potential effects of greater transpiration from increased tree cover on local rainfall patterns.

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Critical impact of vegetation physiology on the continental hydrologic cycle in response to increasing CO_2, Lemordant 2018

This study finds that the physiological response of plants to increased atmospheric CO_2 affects the global hydrological cycle even more than does the greenhouse effect and changes in precipitation. The authors conclude:

> This highlights the key role of vegetation in controlling future terrestrial hydrologic response and emphasizes that the carbon and water cycles are intimately coupled over land [LeMordant 2018: 1].
>
> With increasing [CO_2] at the leaf surface, the density of stomata at the leaf surface is decreased and their individual opening is reduced and therefore less water is transpired per unit leaf area. In other words, leaf-level water use efficiency increases, potentially increasing surface soil moisture and runoff. On the other hand, leaf biomass tends to also increase with increasing [CO_2] … generating a larger evaporative surface that can partly offset the reduction in stomatal conductance and negate the soil water savings. Our objective is therefore to quantify how such plant [CO_2] effects influence future hydrological variable responses compared with radiative effects —the atmospheric impact of the “greenhouse effect.” Radiative effects impact precipitation, i.e., water supply, and evaporative demand, through increase in radiation, temperature, and atmospheric dryness as estimated by the vapor pressure deficit (VPD), i.e., saturation minus actual vapor pressure [LeMordant 2018: 1].
>
> Our study illustrates how deeply the physiological effects [on vegetation] due to increasing atmospheric [CO_2] impact the continental water cycle. Contrary to previous wisdom, changes in precipitation and radiation [greenhouse effect] do not play the primary role in future drying and moistening in most regions. Rather, biosphere physiological effects and related biosphere–atmosphere interactions are key for predicting future continental water stress as represented by ET [evapotranspiration], long-term runoff, EF, or leaf area index. In turn, vegetation water stress largely regulates land carbon uptake, further emphasizing how tightly the future carbon and water cycles are coupled so that they cannot be evaluated in isolation [LeMordant 2018: 5].

Weakening of Indian summer monsoon rainfall due to changes in land use land cover, Paul 2016

The Indian summer monsoon rainfall has decreased since 1950, and several hypotheses have been proposed to explain why. Most of these hypotheses involving weakening temperature gradients over the continent. This study explores the potential link between a weakening monsoon and widespread land use land cover (LULC) change from woody savanna to cropland in recent decades. Citing earlier studies, the authors note that:

> Precipitation resulting from local land surface Evapotranspiration (ET) is known as recycled precipitation. Pathak et al. found that evapotranspiration from land surface vegetation plays a major role during the end of a monsoon. They observed that, during the initial phase of a monsoon, oceanic sources play a major role, and the soil is recharged with moisture. However, during the latter half of a summer monsoon (August and September), land surface ET increases as recycled precipitation increases, a pattern that is more prominent in the Ganga Basin and Northeast India. This recycled precipitation accounts for approximately 20–25% of the rainfall in North India (Ganga Basin) and Northeast India during August and September. Hence, deforestation associated with changes in LULC may affect ET and may significantly affect monsoon rainfall [Paul 2016: 1-2].

Summarizing their own study, the authors conclude:

> Here, we performed a sensitivity analysis to quantify the impacts of large-scale conversion from woody savannah to crop land in India on monsoon precipitation. We found such a change results in decreased ET and subsequently a decrease in recycled precipitation leading to a decline in monsoon precipitation. This decline is similar in extent to the observed recent decadal weakening of monsoon precipitation. However, other reasons may account for this observed weakening, such as the warming of Indian Ocean SST [sea surface temperature] [Paul 2016: 5-6].

To better clarify causality of the weakening monsoon, given other potential factors, the authors propose that:

> The future scope of this present work is to perform detection and attribution studies for potential declines of Indian monsoons with model runs forced with SST warming only, aerosol forcing only, LULC changes only and all controlling factors together [Paul 2016: 6].

Tropical reforestation and climate change: beyond carbon, Locatelli 2015

When managed with both climate adaptation and mitigation in mind, tropical reforestation (TR) can serve multiple synergistic functions. TR *mitigates* regional and global climate change, not only by sequestering carbon but also through biophysical cooling (via evapotranspiration), by recycling rainfall regionally, and by reducing pressure on old growth forests.

Furthermore, TR helps local communities *adapt* to climate change by recharging stream flow in the dry season, reducing the severity of floods, protecting slopes against landslides and, through mangrove reforestation, reducing the impact of coastal storms and waves. Reforestation also creates livelihood opportunities through the sustainable harvest of forest products, and creates shelter and habitat for species vulnerable to climate change. However, to achieve this broad range of benefits, "reforestation practices should be designed to avoid the implementation of one strategy (mitigation or adaptation) to the detriment of the other." Arguing for the application of what they term "climate-smart reforestation," the authors recommend the following:

> The challenge for climate-smart reforestation is to implement an effective combination of approaches to meet all three objectives: societal adaptation, climate mitigation, and ecological resilience [Locatelli 2015: 4].
>
> However, as most policies consider the three objectives of climate-smart reforestation separately, they often overlook possible trade-offs and synergies. For example, reforestation projects managed with a carbon purpose could have detrimental consequences on water availability in the semi-arid tropics (Trabucco et al. 2008) or on biodiversity (O'Connor 2008). By contrast, reforestation that is explicitly climate-smart uses a multi-objective planning focus that enables different objectives to reinforce each other so that their interactions produce synergies rather than trade-offs. For example, tree regeneration in Tanzania under the Ngitili resource management system achieves carbon storage together with improved watershed conservation and greater provision of natural resources (water, food, and fodder) for livelihoods (Duguma et al. 2014). A proposed adaptation project in Colombia aims to reforest with flood-resistant native tree species to reduce flood impacts on downstream communities (UNDP 2012). A project in Costa Rica is testing different mixes of species and silvicultural practices to reduce vulnerability to storms and fires while also achieving carbon storage (Locatelli et al. 2011) [Locatelli 2015: 4-5].

This article underscores a key concept of this compendium – that functioning ecosystems (whether old growth or restored forests, for example) provide multiple, interwoven functions that support human and biodiverse life by regulating local, regional and global climate conditions.

Water-retention potential of Europe's forests: A European overview to support natural water-retention measures, European Environment Agency (EEA) 2015

The importance of water retention (the rainfall absorbed or used within an ecosystem) for mitigating flood and drought conditions and contributing to clean drinking water, for example, has been increasingly recognized in Europe in the past decade. Along with wetland preservation, better agriculture practices and other measures, preserving and re-growing forests are seen as key to enhanced natural water retention. Forests cover a third of Europe, and:

> can soak up excess rainwater, preventing run-offs and damage from flooding. By releasing water in the dry season, forests can help to provide clean water and mitigate the effects of droughts [EEA 2015: 6].

In recognition of the important water management role of forests and other natural ecosystems, new policy instruments have proposed Natural Water-Retention Measures (NWRMs).

> Natural Water-Retention Measures (NWRMs) are defined as 'measures to protect and manage water resources and to address water-related challenges by restoring or maintaining ecosystems, natural features and characteristics of water bodies using natural means and processes' (European Commission and Directorate-General for the Environment 2014). … The main focus is to enhance and preserve the water retention capacity of aquifers, soil and ecosystems and improve their status [EEA 2015: 9].

This EEA study found that:

> In water-basins where the forest cover is 30%, water retention is 25% higher than in basins where the forest cover is only 10%. In basins where the forest cover is 70%, water retention is 50% higher than in basins where the forest cover is only 10%. … Coniferous forests in general retain 10% more water than broadleaved forests or mixed forests [EEA 2015: 5].

Why Climate Change Makes Riparian Restoration More Important than Ever: Recommendations for Practice and Research, Seavy 2009

> Riparian[14] ecosystems are naturally resilient, provide linear habitat connectivity, link aquatic and terrestrial ecosystems, and create thermal refugia for wildlife: all characteristics that can contribute to ecological adaptation to climate change [Seavy 2009: 330].

Arguing for the restoration of riparian areas because of their ecological significance and inherent resilience, these authors articulate the importance of both surface and groundwater - protected within a biodiverse ecosystem - for its cooling effect.

> Because riparian areas have higher water content than surrounding upland areas, they absorb heat and buffer organisms against extreme temperatures (Naiman et al. 2000). During previous periods of climate change, riparian areas served as refugia because they provided microclimates that protected plant biodiversity (Bakker 1984, Meave and Kellman 1994). Riparian vegetation can maintain cooler water temperatures by shading water from sunlight (Sridhar et al. 2004, Cassie 2006) and the infusion of cold groundwater into warmer surface waters creates and maintains pockets of cool water (Chu et al. 2008). Thus, riparian areas provide thermal refugia for animals with thermoregulatory limitations [Seavy 2009: 332].

Fertilizer vs. Fungi

> Agrochemical companies argue that crops can't be grown without their products. And in a sense, they are right, as long as we accept as inevitable a dysfunctional soil food web [LSP 2018: 16].

The importance of synthetic fertilizer for global crop production and the environmental consequences of its excessive use is often presented as a dilemma [Steward & Lal 2017, Mulvaney 2009].

Indeed, many problems arise from our dependence on fertilizers, including the energy-intensiveness of nitrogen fertilizer production, the increasing scarcity of global

[14] 'Riparian' refers to the vegetated area running along both sides of a river.

phosphorus reserves, and the leaching of both nutrients from farm fields, polluting surface waters.

To remedy this, some advocate for a more judicious use of fertilizers and better ways to recapture and recycle it. Only a quarter of mined phosphorus is recycled back on to cropland [Childers 2011] while the rest is lost, becoming a pollutant. Even phosphorus that has made it into our bodies as food eventually becomes human waste, which could be though is often not recaptured and recycled.

While the idea of recycling phosphorus is relevant and timely, it presumes the continuation of conventional high-input agriculture. It assumes ongoing dependence on synthetic fertilizers. It presumes this ‘dilemma.’

Yet there may be a simpler, more elegant solution. Soil microbes provide benefits comparable to chemical inputs in terms of crop yield, but without the negative side-effects. Indeed, healthy soil is teeming with diversity, where billions of mostly microscopic “willing workers” in microbiologist Elaine Ingham’s words [LSP 2018: 16] make nutrients available to plants in the process of breaking down organic material and mining soil particles.

In a sample of conifer forest soil, for example, tiny tunnels can be seen in mineral particles [Jongmans 1997]. Scientists believe that mycorrhizal fungi penetrate these particles by excreting organic acids in order to mine nutrients for their plant hosts. An estimated 150 meters of pores are bored by fungi into grains of feldspar sand per year per liter of soil.

Dr. David Johnson of New Mexico State University has found that the most productive plants are not those grown with fertilizer, nor even with the most organic matter per se [Johnson 2017]. Rather, plant productivity stems from the robustness of the soil microbial community. He discovered this in an experiment that compared the growth rate of chili peppers in different soils, including a fungi-rich compost on one hand and a bacterial-dominant soil typical of most croplands on the other.

Johnson [2017] found that only 3% of carbon flow went into plant biomass production when the soil’s fungi to bacteria (F:B) ratio was low (0.04). The remainder of the carbon produced by these plants was going into other functions, including nitrogen fixation, exudates to the soil, and respiration. At a higher F:B ratio (3.68), by contrast, plant growth was more efficient with 56% of carbon flow going to the development of the plants’ roots, stems, leaves and fruit, resulting in bigger plants. Similarly, in a cover crop experiment where a desert soil was inoculated with a robust compost-derived microbial community, Johnson produced biomass comparable to the most productive (tropical rainforest) ecosystems on Earth.

“Diversity is the currency of survival, and that’s what’s making this system work so well” [Johnson 2017: 28:08 min]. Johnson explains that the key to plant productivity is microbial diversity, where multiple populations of organisms are serving vital ecosystem functions, including fixing nitrogen, solubilizing phosphorus, and secreting plant growth hormones, for example. Mycorrhizal fungi, in particular, play a key role in connecting plants to the soil ecosystems that nourish them. These fungi colonize the surface of plant roots and branch out into the soil, effectively extending the roots further to collect nutrients otherwise out of reach. In short, fertilizer inputs are not needed when microorganisms in the soil are there to pull the requisite nitrogen from the air and minerals from the ground on behalf of plants.

In return for their services, bacteria and fungi are nourished by carbon from plant litter and root exudates. For the whole system to function, Johnson explains, a constant input of energy is needed in the form of carbon compounds manufactured by plants through photosynthesis. Therefore, bare fallow fields are deadly for the soil ecosystem, and in turn less hospitable to crops later grown there.

Taking an ecosystem-wide view, Stevens [2018] found that arbuscular mycorrhizal fungi, though "they account for less than 1% of the total modelled biomass … increased the biomass of macro-organisms in the Serengeti by 48%." In other words, absent fungi, plants would be only half as productive, resulting in less food for herbivores, and half the biomass growth all the way up the food chain. While plants differ in their relative dependence on fungi, warm season grasses derive as much as 90% of their phosphorus from mycorrhizal symbioses [Stevens 2018: 537].

We don't fertilize nature and yet it can achieve some triple the productivity of the world's best crop plots [Johnson 2017]. Why, then, do we rely almost exclusively on fertilizers, and why have most of us never heard about the power of soil microorganisms for improving crop productivity? In part, our ignorance stems from the difficulty of studying the soil and its microscopic inhabitants.

> Progress in understanding the nature, extent, functioning, and identity of mycorrhizal fungal networks has been seriously hampered by the difficulties inherent in observing and studying mycelial systems without disturbing and destroying them [Leake 2004: 1017].

Further blocking our collective awareness of soil microbes' role in plant productivity is their erasure by tillage, fertilizer and pesticides. There is a physical erasure in terms of the damage these practices do to the soil ecosystem. And there's a cognitive erasure in terms of our general acceptance that yield goals are attainable only with chemical inputs.

Ironically, at the same time that chemical inputs and tillage replace soil microbes' work by supplying nutrients to plants and defending against pests, these practices also disrupt the soil microbial community. Tillage disturbs mycorrhizal fungi by breaking their hyphal networks. Fertilizer application disrupts the exchange between plants and microorganisms. When plants can absorb nitrogen “for free” (without providing carbon in exchange), explains soil ecologist Christine Jones [2014], this reduces the flow of carbon into the soil resulting in carbon-depleted soils and diminishing fungal networks and their delivery of micronutrients to plant hosts.

> Reduced carbon flows impact a vast network of microbial communities, restricting the availability of essential minerals, trace elements, vitamins and hormones required for plant tolerance to environmental stresses such as frost and drought and resistance to insects and disease. Lowered micronutrient densities in plants also translate to reduced nutritional value of food [Jones 2014: 2-3].

Fertilizer application has also been shown to lower fungal diversity [Zhao 2016] and to favor fungal genera with known pathogenic traits [Paungfoo-Lonhienne 2015]. Furthermore, chronic fertilizer use diminishes soil fertility [Russell 2009, Khan 2007, Clemmenson 2013, Shahbaz 2016, Mulvaney 2009]. This finding contradicts the commonly held view that fertilizer use over time builds up soil fertility by increasing plant biomass, and thus plant residue input to the soil. In fact, fertilizer speeds up the breakdown and loss of soil organic carbon and soil nitrogen.

> Overwhelmingly, the evidence is diametrically opposed to the buildup concept and instead corroborates a view elaborated long ago by White (1927) and Albrecht (1938) that fertilizer N depletes soil organic matter by promoting microbial C utilization and N mineralization. An inexorable conclusion can be drawn: The scientific basis for input-intensive cereal production is seriously flawed. The long-term consequences of continued reliance on current production practices will be a decline in soil productivity that increases the need for synthetic N fertilization, threatens food security, and exacerbates environmental degradation [Mulvaney 2009: 2308].

An inexorable conclusion can be drawn: The scientific basis for input-intensive cereal production is seriously flawed. The long-term consequences of continued reliance on current production practices will be a decline in soil productivity that increases the need for synthetic N fertilization, threatens food security, and exacerbates environmental degradation [Mulvaney 2009: 2308].

Indeed, due to carbon-diminishing management practices, agricultural soils contain 25% to 75% less SOC than soils in undisturbed, natural ecosystems [Lal 2010]. Consequently, scientists and farmers alike are beginning to look beyond fertilizer for a solution to poorly functioning soils. For instance, in hot, dry Western Australia farmers are experimenting with inoculating seeds with beneficial fungi.

> Finding themselves confronted with an unsustainable spiral of ever-increasing commercial fertiliser costs and uneconomic or diminishing crop yields, it was realised that a different approach needed to be taken. In recent growing seasons, seed has been inoculated with commercial fungi spores just prior to planting. While it is still too early to provide statistically robust outcomes and, bearing in mind that there are no “silver bullets” in agricultural production, the indications are that mycorrhizal fungi is promoting improvements in crop vitality, yield and soil condition [Johns 2014].

A recent meta-analysis [Schutz 2018] suggests that these Australian farmers are on the right track. Researchers analyzed a couple hundred studies of various microbial inoculants used as “biofertilizers,” grouping them by their functional traits: nitrogen fixation, solubilizing phosphorus, or mycorrhizal fungi. Corroborating David Johnson’s findings, they concluded that microbial inoculants, especially mycorrhizal fungi, are a promising option for sustainable agriculture, especially in dry climates.

Christine Jones [2014] expands on this idea, saying that in addition to promoting plant and microbial diversity, farmers wanting to build soil health should maintain year-round living ground cover, limit nitrogen and phosphorus fertilizer input, and integrate livestock into crop production systems. And here we have the core practices of agroecology, variously referred to as regenerative, organic, “biologique” in French, or sustainable agriculture – each name emphasizing a different aspect of a shared philosophy.

In chemistry, the word “organic” refers to almost any molecule that contains carbon. Carbon is made available to the biosphere primarily by plants through photosynthesis. Carbon is the basis for all living tissue and is thus also present in the remnants of dead organisms, otherwise known as organic material, which is plentiful in healthy soil. “Biologique” suggests the favoring of biological processes and symbioses to support plant growth. “Agroecological” emphasizes the idea that all species (including crops) present in an ecosystem rely on one another for food, shelter and immune defense, and cannot be isolated without harm being done (such as pest outbreaks and nutrient deficiencies). “Sustainable,” of course, means that the crops we grow today will not diminish the land’s ability to grow as many or more crops again tomorrow.

All these labels make reference to the importance of a living soil. Anyone who marvels at the wonder of life writ large is already at least halfway to the point of accepting that the same magic buzzes underground even though we can’t see it. Billions of microscopic “willing workers” are getting the job done – helping plants grow and thus supporting everything else up the food chain. Up here at the top of the food chain, it’s our job is to complete the circle and support those guys at the bottom.

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Fertilizer vs. Fungi Article Summaries

The nitrogen dilemma: food or the environment, Stewart & Lal 2017

> Nitrogen (N) is the most important essential element for crop production because it is required in large amounts and is nearly always the first nutrient that becomes limiting after an ecosystem is converted to cropland. Cereal grains provide about 50% of the world's calories, and their production has become largely dependent on the use of synthetic N fertilizer. However, fertilizer N not used by plants can degrade the environment and negatively impact both people and ecosystems. In addition, efficient use of N fertilizer generally requires phosphorus (P) fertilizer which is made from rock phosphate derived from mines. Therefore, huge amounts of N and P from outside sources are being added to the environment each successive year leading to additional environmental concerns [Stewart & Lal 2017: 124A].

This article articulates a presumed "nitrogen dilemma," as described above, that, on the one hand, agriculture requires increasing amounts of nitrogen and phosphorus fertilizer, especially as the population surges toward 10 billion. On the other hand, ongoing fertilizer application will lead to increasingly polluted and impaired fresh waters around the world, increased greenhouse gas emissions, and over-reliance on limited supplies of mined phosphorus.

The difficulty of reducing nitrogen inputs is twofold according to the article: First, farmers cannot know exactly how much nitrogen their crops will need because yield depends on water supply and respiration rates, and only indirectly on nitrogen availability. Therefore, farmers are reluctant to limit fertilizer input for fear it could in turn limit water utilization. "Because N is usually the first limiting factor other than water, most farmers want to make sure they have enough N available to fully utilize the water" [p.126A]. Second, nutrient-polluted waters is a local problem, and therefore most likely requires a local political solution, rather than being manageable through national regulations. Local policy solutions will happen only when enough people feel the direct effects of the problem locally and demand action.

Curiously, the article fails to mention the farming practices that reduce the need for fertilizers, maximize the soil's water-holding capacity, and cool the soil through continuous vegetative cover. Practices designed to enhance soil organic matter, such as cover-cropping and replacing synthetic fertilizer input with compost, manure and crop residues, can achieve the same goals that nitrogen fertilizer is supposed to address.

> …it is water that determines yield, and the amount of water available for a crop is beyond control of the farmer, even if the crop is irrigated. This is because it is only the

> amount of water transpired by the growing crop that determines the amount of biomass produced by photosynthesis, and this is affected not only by the amount of water available but on other climatic factors such as temperature, radiation, humidity, and wind [Steward & Lal 2017: 126A].

We argue that there is no nitrogen dilemma unless we cling to the idea that industrial agriculture is the only way forward despite its increasingly apparent fragility, while rejecting the potential of multifunctional, regenerative agriculture to broadly achieve our production and environmental goals.

Sustainability challenges of phosphorus and food: solutions from closing the human phosphorus cycle, Childers 2011

> Our review of estimates of P recycling in the human P cycle show considerable variability and uncertainty, but today it appears that only about one-quarter of the fertilizer P used in agriculture is recycled back to fields. The rest is lost to the cycle, and much of this loss ends up in waterways, causing expensive eutrophication problems. As with other nonrenewable natural resources, a sustainable P supply is not assured, and some projections show economically viable mineral reserves being depleted within decades. In addition to our review of human effects on the global P cycle, we present a number of sustainable solutions that involve closing the loop on the human P cycle. Some of these solutions are relatively straightforward but many involve overcoming considerable infrastructural or institutional inertia [Childers 2011: 123].

Economically viable mineral phosphorus reserves may become depleted within decades, threatening global crop production for a growing world population. The authors discuss this problem in relation to human P cycle, where the vast majority of mined phosphorus is not recycled back onto farm fields, but is released more or less irretrievably into the environment, polluting water bodies. “There are considerable social and environmental costs of P being lost from the currently ‘open’ human P cycle” [Childers 2011: 120].

The authors present several options for closing the human P cycle at the points of agricultural production, distribution and consumption, and human waste treatment. These options include reducing fertilizer application rates to better match plant needs, reducing erosion rates, reducing food waste, and recycling human urine, which is rich in phosphorus and nitrogen. The authors state that their list of solutions is not exhaustive, but rather is meant to stimulate others to think about the sustainability challenges of the human P cycle. Indeed, missing in this paper’s list of solutions is a discussion of the role of fungi, which can access otherwise inaccessible soil phosphorus through symbiosis with plants.

A broken biogeochemical cycle, Elser & Bennett 2011

> Consider the fate of the approximately 17.5 million tonnes of phosphorus mined in 2005, analysed in the paper by Cordell et al. About 14 million tonnes of this were used in fertilizer (much of the rest went into cattle-feed supplements, food preservatives, and the production of detergents and industrial cleaning agents) but only about 3 million tonnes made it to the fork (or chopstick). The largest loss — around 8 million tonnes — was directly from farms through soil leaching and erosion" [Elser & Bennett 2011: 30].

To handle the twin problems of phosphorus pollution and scarcity, strategies for phosphorus conservation and recycling are urgently needed.

> The solutions to these problems lie in recapturing and recycling phosphorus, moving it from where there is too much to where there is too little, and developing ways to use it more efficiently. Many strategies are simple and readily available, even for poor farmers and developing economies [Elser & Bennett 2011: 30].

The authors' solutions include: widespread adoption of agricultural conservation practices, reduction of food waste (at least in part by producing food within or closer to cities), recycling human waste, reducing meat consumption, recovering nutrients from confined livestock facilities (such as through bioreactors), and genetically engineering plants and animals to require lower phosphorus inputs. No mention in this article of the role of plant-fungi symbiosis in accessing phosphorus in the soil.

Networks of power and influence: the role of mycorrhizal mycelium in controlling plant communities and agroecosystem functioning, Leake 2004

Two major groups of mycorrhizal fungi are arbuscular mycorrhiza (AM) and ectomycorrrhiza (EM). Both form a symbiosis with plants by colonizing their roots and creating an interface where carbon from the plant can be exchanged for phosphorus, nitrogen and other nutrients from the soil and transferred to the plant by the fungi. The extraradical[15] mycorrhizal mycelium (ERMM), which are the vast portion of the fungal network that branches out into the soil, is difficult to study and has therefore been considered the "hidden half" of the symbiosis.

> Progress in understanding the nature, extent, functioning, and identity of mycorrhizal fungal networks has been seriously hampered by the difficulties inherent in observing and studying mycelial systems without disturbing and destroying them.… As a

[15] "Extraradical" refers to a fungal network extending beyond the plant roots.

> consequence, the external mycelium, which is the fungal structure of mycorrhiza that is most intimately associated with the soil and furthest from the roots, and by implication the most critical for nutrient uptake, is normally overlooked and has been rarely recorded. Only in the past decade have studies started to focus specifically on the extent and functioning of ERMM in the field [Leake 2004: 1017].

This article highlights the significant yet overlooked role of mycorrhizal fungi in ecosystem functioning and reviews some advances in the techniques used to study these hidden powerhouses.

> ERMM is the hidden power behind plant community composition and ecosystem functioning through the major processes it carries out, such as nutrient uptake, weathering of minerals, soil aggregate stability, and the way in which it alters competition between plants [Leake 2004: 1039].

The symbiosis with plants is the source of power for these fungi, given that the carbon received from plant hosts is practically inexhaustible and costs the plants little.

> Despite the substantial biomass and associated C drain on their hosts, the actual “cost” of mycorrhiza to plants may be negligible because mycorrhizal colonization can increase the rate of photosynthesis (Wright et al. 1998), alleviate shoot N and P limitation, and cause a substantial increase in leaf area arising from improved nutrition (Read and Perez-Moreno 2003) [Leake 2004: 1021].

Thus,

> The empowerment of mycorrhizal networks with substantial amounts of host-derived C allows them to play central roles in major biogeochemical cycles [Leake 2004: 1030].

The article concludes by emphasizing the importance for sustainable agriculture of a broader public understanding of the role of mycorrhiza for improving soil health and crop yields.

> AM [arbuscular mycorrhizal] hyphal lengths in soil show strong positive correlations with soil-aggregate stability (Rillig et al. 2002; Kabir and Koide 2002), P uptake efficiency (Schweiger and Jakobsen 2000), and crop-yield improvements (Kabir and Koide 2002). Interest in the development of less intensive management systems is presenting new opportunities for adapting agricultural production systems to enhance these benefits that can be gained from AM networks. Substantial improvements in “soil health” and AM functioning in field crops are gained by the doubling of lengths of AM hyphae in soil when tillage is reduced (Kabir et al. 1998a, 1998b). Similar gains are achieved by growth of AM-compatible cover crops in place of winter fallow (Kabir and Koide 2002) [Leake 2004: 1038].

> ERMM [extraradical mycorrhizal mycelium, or fungi] is the hidden power behind plant community composition and ecosystem functioning through the major processes it carries out, such as nutrient uptake, weathering of minerals, soil aggregate stability, and the way in which it alters competition between plants [Leake 2004: 1039].

Mycorrhizal symbioses influence the trophic structure of the Serengeti, Stevens 2018

> Our analysis shows that inputs of phosphorus through arbuscular mycorrhizal symbioses substantially increase the ability of plants to grow and maintain nutritional quality, cascading through the biomass of consumers and predators in the ecosystem. Although they account for less than 1% of the total modelled biomass, the predicted nutritional benefit provided by arbuscular mycorrhizal fungi increased the biomass of macro-organisms in the Serengeti by 48%. When considering the management of biodiversity, future ecosystem models should account for the influence of arbuscular mycorrhizal fungi on all trophic levels [Stevens 2018: 536].
>
> More than 70% of all angiosperm families form AM symbioses (Brundrett, 2009), and these symbioses are often essential for plant nutrition (Marschner & Dell, 1994). Mycorrhizal symbioses also improve plant tolerance to drought (Augé, 2001) and resistance to pathogens (Cameron, Neal, van Wees, & Ton, 2013) [Stevens 2018: 537].
>
> Plant taxa vary in the degree to which they depend upon mycorrhizas; but in general, AM symbioses are essential for the nutrition of tropical plants, and warm season grasses are often highly dependent on mycorrhizas, acquiring up to 90% of their phosphorus requirements from AM fungi [Stevens 2018: 537].
>
> Thirty years ago, McNaughton, Ruess, and Seagle (1988) concluded that large mammals have a major organising effect in the Serengeti ecosystem. From our analysis, we can conclude that AM fungi also play a critical role in the trophic structure of the Serengeti. Our model simulations suggest that although AM fungi account for less than 1% of the total biomass, phosphorus supplied by AM symbioses sustains half the vegetation biomass, and accordingly, half of the biomass of iconic migratory herbivores and one-third of the carnivore biomass [Stevens 2018: 542].

The distribution of soil phosphorus in the Serengeti, transported through AM symbioses and accelerated by migratory ungulates, may be a significant driver of plant diversity and ultimately mammalian carrying capacity (Anderson et al., 2007; McNaughton, Zuniga, McNaughton, & Banyikwa, 1997). Without AM fungal inputs of phosphorus, these nutrient diffusion gradients would undoubtedly decline [Stevens 2018: 543].

Rock-eating fungi, Jongmans 1997

Under a microscope, tiny tunnels can be seen in mineral particles from conifer forest soil. Scientists believe it is mycorrhizal fungi penetrating these particles by excreting organic acids in order to mine nutrients for their plant hosts. An estimated 150 meters of pores are bored by fungi per year per liter of E-horizon (layer that has been leached of mineral and/or organic content, leaving silicate) soil.

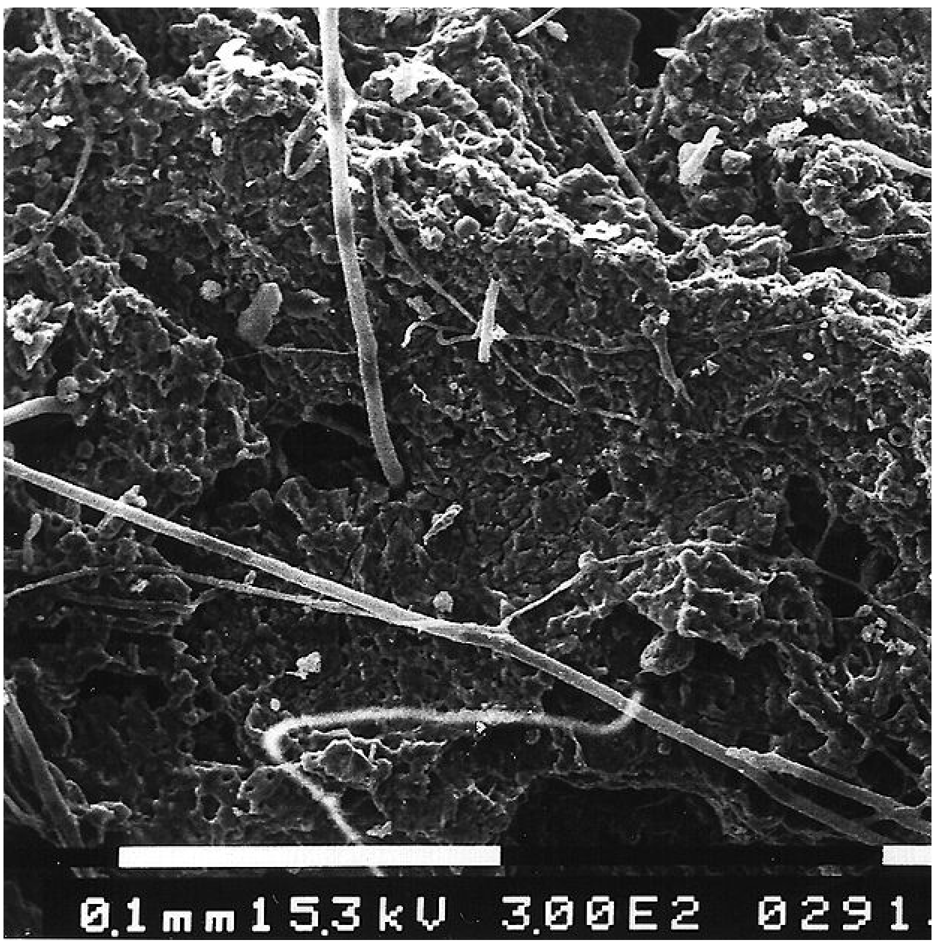

Photo credit: Jongmans 1997. "Scanning electron micrograph, showing 4–6-mm-thick hyphae entering a calcium feldspar at a granite surface near Lunsen, Sweden" [Jongman 1997].

The role of community and population ecology in applying mycorrhizal fungi for improved food security, Rodriguez & Sanders 2015

Given that nitrogen and phosphorus are the most limiting nutrients for crop growth, that global phosphorus supplies are becoming exhausted while the human population rapidly expands, and that arbuscular mycorrhizal fungi (AMF) symbioses improve crop phosphorus acquisition, AMF symbioses have a major role to play in current and future crop production.

> The potential of AMF to help increase global food security lies in the fact that all globally important food crops naturally form this symbiosis and the fungi help plants more efficiently obtain phosphate from the soil (Smith and Read, 2008). Stocks of phosphate fertilizer are rapidly being depleted (Gross, 2010). There is a simultaneous increase in demand for phosphate to help feed the growing population (Gilbert, 2009). These two combined factors represent a major threat to global food security; a threat that can potentially be reduced by better phosphate acquisition through the AM[F] symbiosis. The potential of AMF to contribute to improved crop yields has been known for decades [Rodriquez & Sanders 2015: 1054].

However, for the widespread adoption of AMF inoculation to be effective and safe, a better understanding is needed of ecological principles related to soil fungi. The authors note that few studies have linked crop yield increases with successful colonization by an introduced AMF, and they outline several challenges and questions that should be resolved to pursue this promising technique more broadly. For example, they ask whether introduced AMF establish well, and how they affect native AMF populations, and how genetic diversity in AMF populations variously affects different crops.

> Stocks of phosphate fertilizer are rapidly being depleted (Gross, 2010). There is a simultaneous increase in demand for phosphate to help feed the growing population (Gilbert, 2009). These two combined factors represent a major threat to global food security; a threat that can potentially be reduced by better phosphate acquisition through the [arbuscular mycorrhizal fungi] symbiosis [Rodriquez & Sanders 2015: 1054].

Bacteria and fungi can contribute to nutrients bioavailability and aggregate formation in degraded soils, Rashid 2016

The paper argues for the use of bacterial and fungal inoculants in combination with organic amendments and cover crops to regenerate degraded soils. In order to produce enough food for a growing global population on ubiquitously degraded soils, synthetic fertilizers will be in increasingly high demand. However, these fertilizers require copious amounts of non-renewable energy to manufacture, and become pollutants when used. Here, the authors explain how bacteria and fungi make nutrients available to plants and how facilitate soil aggregation.

Meta-analysis of biofertilizer application in agriculture, Schutz 2018

Given the global decline of reserves of both rock phosphate and fossil fuel, this study poses the question – to what extent can microbial inoculants replace/reduce the use of synthetic fertilizer? The authors find that "dryland agriculture can benefit most from biofertilizers [microbial inoculants used as fertilizers]. Due to climate change, in the future there will be even more dryland areas globally. Biofertilizers are thus a promising option for sustainable agriculture" [Schutz 2018: 11]. More specifically:

> Our comprehensive meta-analysis with studies from all over the world revealed that biofertilizers were found to be most effective in dry climates. Biofertilizer also improved PUE [phosphorus use efficiency] and NUE [nitrogen use efficiency] greatly. Furthermore, we found that biofertilizers possessing both N fixing and P solubilizing traits have the highest potential to improve the crop yields. Interestingly, AMFs, known for facilitating P nutrient uptake in plants, were on par with applications of biofertilizers with the combined traits of N fixation and P solubilization, indicating the big potential of AMFs as sole biofertilizer for most crops and climatic situations [Schutz 2018: 5].

Future Directions International Strategic Directions Paper: Agricultural Application of Mycorrhizal Fungi to Increase Crop Yields, Promote Soil Health and Combat Climate Change, Johns 2014

> There are a number of agricultural practices that will enhance fungi colonisation. Wherever possible, of course, the full range of critical soil health processes that govern productivity should be allowed to regenerate agricultural ecologies naturally. It may, however, be necessary or more practical to inoculate seed with fungi spores in order to

> recover degraded soils. A number of farmers in the Great Southern agricultural region of Western Australia are undertaking this course of action. Finding themselves confronted with an unsustainable spiral of ever-increasing commercial fertiliser costs and uneconomic or diminishing crop yields, it was realised that a different approach needed to be taken. In recent growing seasons, seed has been inoculated with commercial fungi spores just prior to planting. While it is still too early to provide statistically robust outcomes and, bearing in mind that there are no “silver bullets” in agricultural production, the indications are that mycorrhizal fungi are promoting improvements in crop vitality, yield and soil condition [Johns 2014: 4].

Nitrogen: the double-edged sword, Jones 2014

The symbiosis between mycorrhizal fungi and plants drive carbon and nitrogen cycles. Fungi demand carbon exudate from plants in exchange for nitrogen and other nutrients retrieved and transported from the soil. The “liquid carbon” exuded from plant roots feeds mycorrhizal fungi and many other soil microbes, while also becoming stabilized in soil aggregates and humus. Jones explains that when this mycorrhizal exchange is inhibited by N fertilizer, which allows plants to absorb nitrogen “for free” (without providing liquid carbon in exchange), this reduces the flow of carbon into the soils, which in turn diminishes fungal networks and their delivery of micronutrients to plant hosts, and results in carbon-depleted soils.

> Despite its abundance in the atmosphere, nitrogen is frequently the most limiting element for plants. There is a reason for this. Carbon, essential to photosynthesis and soil function, occurs as a trace gas, carbon dioxide, currently comprising 0.04% of the atmosphere. The most efficient way to transform CO2 to stable organic soil complexes (containing both C and N) is via the liquid carbon pathway. The requirement for biologically-fixed nitrogen drives this process.
>
> If plants were able to access nitrogen directly from the atmosphere, their growth would be impeded by the absence of carbon-rich topsoil. We are witnessing an analogous situation in agriculture today. When inorganic nitrogen is provided, the supply of carbon to associative nitrogen fixing microbes is inhibited, resulting in carbon-depleted soils.
>
> Reduced carbon flows impact a vast network of microbial communities, restricting the availability of essential minerals, trace elements, vitamins and hormones required for plant tolerance to environmental stresses such as frost and drought and resistance to insects and disease. Lowered micronutrient densities in plants also translate to reduced nutritional value of food [Jones 2014: 2-3].

Jones further explains how to modify agricultural practices to protect and build the soil: maintain year-round living ground cover, limit nitrogen and phosphorus fertilizer input, promote plant and microbial diversity, and integrate livestock into crop production systems.

Synthetic nitrogen fertilizers deplete soil nitrogen: a global dilemma for sustainable cereal production, Mulvaney 2009

> There is a prevailing view that global food and fiber production will continue to expand because of modern agricultural management systems with improved cultivars and intensive chemical inputs dominated by synthetic ammoniacal fertilizers. The use of these fertilizers has led to concerns regarding water and air pollution but is generally perceived to play an essential role for sustaining agricultural productivity, not only by supplying the most important nutrient for cereal production but also by increasing the input of crop residues for building soil organic matter. The scientific soundness of the buildup concept has yet to be substantiated empirically using baseline data sets from long-term cropping experiments. The present paper and a companion study by Khan et al. (2007) provide many such data sets that encompass a variety of cereal cropping and management systems in different parts of the world. Overwhelmingly, the evidence is diametrically opposed to the buildup concept and instead corroborates a view elaborated long ago by White (1927) and Albrecht (1938) that fertilizer N depletes soil organic matter by promoting microbial C utilization and N mineralization. An inexorable conclusion can be drawn: The scientific basis for input-intensive cereal production is seriously flawed. The long-term consequences of continued reliance on current production practices will be a decline in soil productivity that increases the need for synthetic N fertilization, threatens food security, and exacerbates environmental degradation [Mulvaney 2009: 2308].

Nitrogen fertilizer dose alters fungal communities in sugarcane soil and rhizosphere, Paungfoo-Lonhienne 2015

In this study, nitrogen fertilization altered the relative abundance of fungal taxa in the rhizosphere, increasing fungal genera with known pathogenic traits, and decreasing a fungal phyla (Basidiomycetes) known to break down lignin, thus important for carbon cycling in the soil.

> Fungi play important roles as decomposers, plant symbionts and pathogens in soils. The structure of fungal communities in the rhizosphere is the result of complex interactions among selection factors that may favour beneficial or detrimental relationships. Using culture-independent fungal community profiling, we have investigated the effects of

> nitrogen fertilizer dosage on fungal communities in soil and rhizosphere of field-grown sugarcane.The results show that the concentration of nitrogen fertilizer strongly modifies the composition but not the taxon richness of fungal communities in soil and rhizosphere. Increased nitrogen fertilizer dosage has a potential negative impact on carbon cycling in soil and promotes fungal genera with known pathogenic traits, uncovering a negative effect of intensive fertilization [Paungfoo-Lonhienne 2015:just 1].

Nitrogen fertilizer effects on soil carbon balances in Midwestern U.S. agricultural systems, Russell 2009

Despite increasing residue input in annual crop production systems, N fertilization does not increase soil organic carbon (SOC) over time because N fertilization also increases organic carbon (OC) decay. This study also shows that belowground OC inputs contribute to soil carbon sequestration more than aboveground OC inputs to the soil.

> When all phases of the crop rotations were evaluated over the long term, OC decay rates increased concomitantly with OC input rates in several systems. Increases in decay rates with N fertilization apparently offset gains in carbon inputs to the soil in such a way that soil C sequestration was virtually nil in 78% of the systems studied, despite up to 48 years of N additions [Russell 2009: 1102].
>
> Across all systems, SOC storage was significantly correlated with the quantity of belowground OM [organic matter] inputs ($P < 0.01$, both sites). In contrast, SOC was not correlated with the quantity of aboveground inputs ($P = 0.45$, Nashua; $P = 0.55$, Kanawha) [Russell 2009: 1111].
>
> This study highlights the importance of incorporating both production and decomposition processes, as well as the location (above- or below-ground) of detrital inputs into models of N-fertilization effects on soil C dynamics in agroecosystems. These results are highly relevant for evaluating the potential of N fertilization to mitigate the effects of removal of organic-matter ‘‘residue’’ from the system for bioenergy production. Our data suggest that the stimulation of OC decomposition by the addition of fertilizer N would likely counteract the positive effects of N fertilization on inputs of OC to the soil, at least for annual crops. Given the current quantity of N that is applied over such a large area, management strategies that can maintain high yields and also reduce N-fertilizer use would also have beneficial environmental consequences. Our study indicates that selection of crops for higher belowground NPP [net primary production], in rotation with crops that fix N, could maximize both yields and soil C sequestration without excessive N-fertilizer additions [Russell 2009: 1111].

Community proteogenomics reveals the systemic impact of phosphorus availability on microbial functions in tropical soil, Yao 2018

In this study, long-term phosphorus fertilization limited the extent to which the genes and proteins of microbial communities were allocated to degrading recalcitrant soil phytate to acquire phosphorus. In phosphorus-deficient soil, on the other hand, the genes responsible for breaking down recalcitrant substrate to acquire phosphorus were more prevalent in microbial communities. In other words, microbial communities can adapt genetically to different levels of nutrients in the soil in order to continue meeting their nutritional requirements. This adds to the body of evidence that fertilizer use impairs the inherent qualities of a living soil to nourish the plants growing there.

> A greater than fourfold increase in the gene abundance of 3-phytase was the strongest response of soil communities to phosphorus deficiency. Phytase catalyses the release of phosphate from phytate, the most recalcitrant phosphorus-containing compound in soil organic matter. Genes and proteins for the degradation of phosphorus-containing nucleic acids and phospholipids, as well as the decomposition of labile carbon and nitrogen, were also enhanced in the phosphorus-deficient soils. In contrast, microbial communities in the phosphorus-rich soils showed increased gene abundances for the degradation of recalcitrant aromatic compounds, transformation of nitrogenous compounds and assimilation of sulfur. Overall, these results demonstrate the adaptive allocation of genes and proteins in soil microbial communities in response to shifting nutrient constraints [Yao 2018: 499].
>
> In conclusion, our proteogenomics results provide systems biology insights into the adaptation of soil microbial communities to different levels of phosphorus availability in a humid tropical forest environment. Phosphorus deficiency significantly enhanced the genetic capabilities of microbial communities to extract phosphorus from phytate and, to a lesser extent, from nucleic acids and phospholipids. Long-term phosphorus fertilization altered the allocation of genes and proteins by microbial communities to acquire carbon, nitrogen and sulfur from a variety of substrates. The results suggest that the selective degradation of recalcitrant substrates, including phytate in phosphorus-deficient soils and aromatic compounds in phosphorus-rich soils, is an important means for microbial communities to balance their elemental requirements. The adaptive allocation of genes and proteins for acquisition of these nutrients in different soils can be explained as an optimal foraging strategy by which microbial communities maintain efficient growth under resource limitation [Yao 2018: 505].

Appendix A: Scenario 300

Scenario 300: Reducing Atmospheric CO_2 to 300 ppm by 2061

by Jim Laurie, Staff Scientist
Biodiversity for a Livable Climate
bio4climate.org
jimlaurie7@gmailcom
March 20, 2018

Danger in the Arctic: The Urgency of the Climate Situation

Atmospheric carbon dioxide levels have increased from 315 ppm in 1958 to 410 ppm in 2018. This is the first time in at least 2 million years that these levels have been reached on planet Earth. In the last five years, the yearly rise is accelerating and is now about a 2.5 ppm increase per year. At that rate, CO_2 will exceed 500 ppm before 2060.

Evidence of the impact of rising greenhouse gases includes the rapid loss of mountain glacier ice and the accelerating loss of the Arctic ice cap. As the Arctic Ocean loses its ice cover in the summers, solar insolation is warming the seawater and releasing methane gas to the atmosphere, particularly from the shallow East Siberian Shelf.

Even remaining at 400 ppm will continue to warm and further acidify all the oceans. The possibility of a runaway greenhouse spike from the release of trapped methane in methane hydrates and permafrost might appear to be slight at the present time, but it will increase as the oceans warm. A “Business as Usual” increase to 500 ppm will increase that possibility significantly to a very dangerous level. As well, oceans have absorbed 93% of of the planet’s heat increase due to the absorption of CO_2.

Figure 1, below, summarizes the present situation. Fossil fuel burning is adding 10 gigatons (billion tons) of carbon to the atmosphere each year. About half of that is being absorbed by processes on the land and its soils, or in the oceans. That increase in CO_2 is acidifying the ocean and ocean warming is slowing the ocean’s ability to absorb more. (It’s like warming your soda drink, which releases the carbon dioxide because gases are less soluble in warmer water.)

Reducing the stress of acidification on the oceans by burping out excess CO_2 is important.. Eliminating fossil fuel emissions will help, but not nearly enough to return to 300 ppm within a safe time frame. **Managing the land in better ways appears to be the only option to draw down enough carbon within a few decades. Is this a reasonable possibility?**

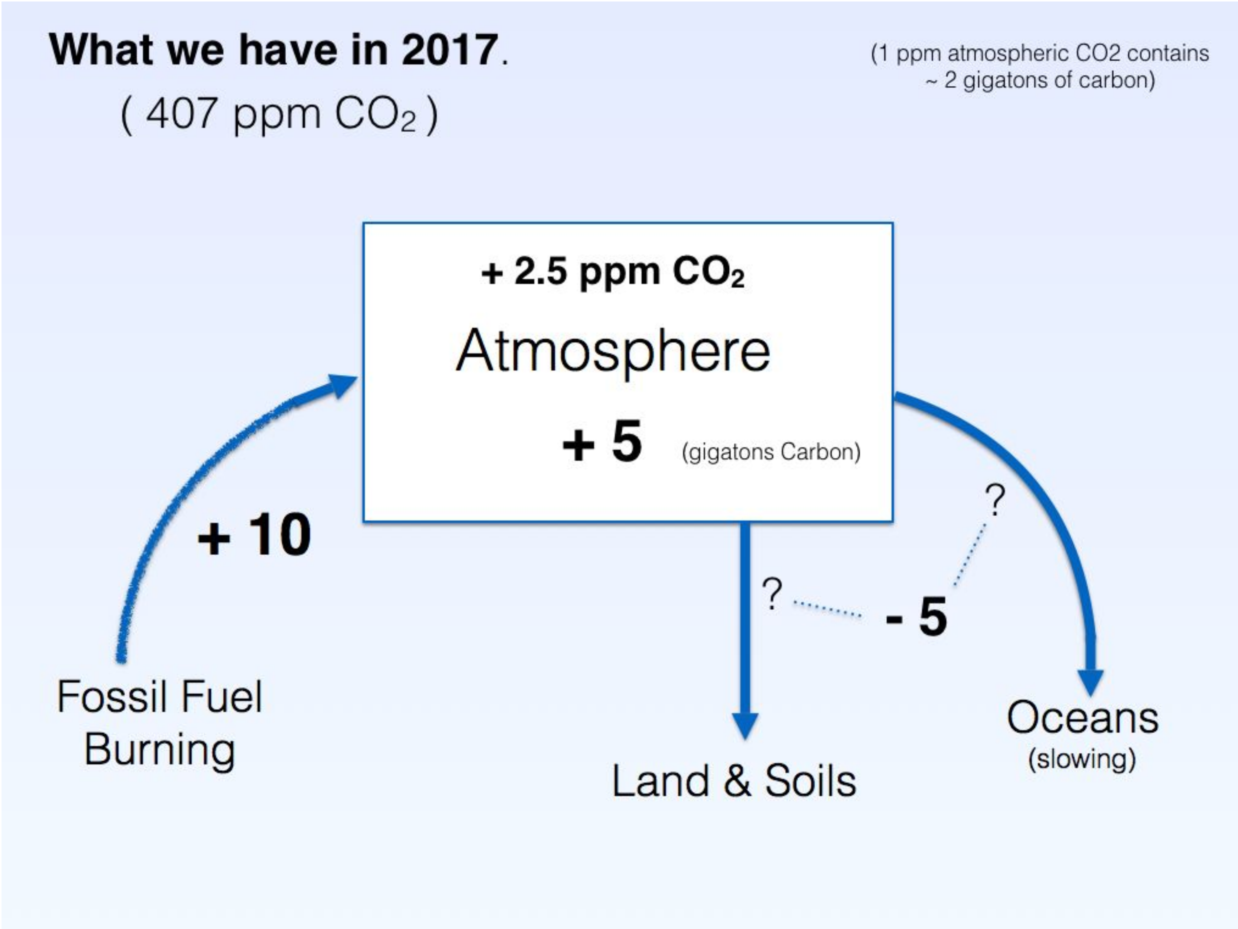

Figure 1. Scenario 300: Land ecosystems must eventually draw down 20 gigatons (Gt) of carbon from the atmosphere on a yearly basis to reach 300 ppm by 2061. In 2017 10 Gt of CO_2 were added to the atmosphere from burning fossil fuels, 5 Gt were removed from the atmosphere by the oceans, with an uncertain amount sequestered in soils. This leads to a net 5 Gt increase in atmospheric burdens. Numbers are approximate. Note that 2 Gt is approximately equal to one ppm (parts per million).

Scenario 300 proposes that restoration of degraded ecosystems of several types could capture enough carbon in soils to reduce the atmospheric CO_2 concentration from about 410 ppm in 2018 to 300 ppm before Halley's Comet returns in 2061. Youth born at the beginning of the 21st Century will be reaching their retirement years and it is hoped that they will have a future to look forward to. Seeing this famous Comet return for their first viewing could be a time of celebration for the many tough choices they had to face and a time of reflection at their successes and failures. How can older generations, from baby boomers on, help prepare them for what is coming?

To reach this monumental goal of 300 ppm of atmospheric CO_2 within a timeframe of about four decades would require good management on about half of the available lands. If the net soil carbon increase reached 20 billion tons, it would be possible to rapidly draw down atmospheric CO_2 levels by several ppm every year. Is there enough land to do this? Does nature have the capacity when there is good human management?

Figure 2 below proposes that we could achieve a 4 ppm yearly drawdown if the land ecosystems captured 20 Gt of carbon each year. As the CO_2 levels begin to drop, the reduced partial pressure of CO_2 in the atmosphere will eventually allow the oceans to “burp” out some CO_2 to the atmosphere. How much of the CO_2 reduction in the atmosphere will be neutralized by CO_2 coming out of the oceans? For our purposes I have estimated one third of the net difference between carbon captured by the soils and the fossil fuels being burned.

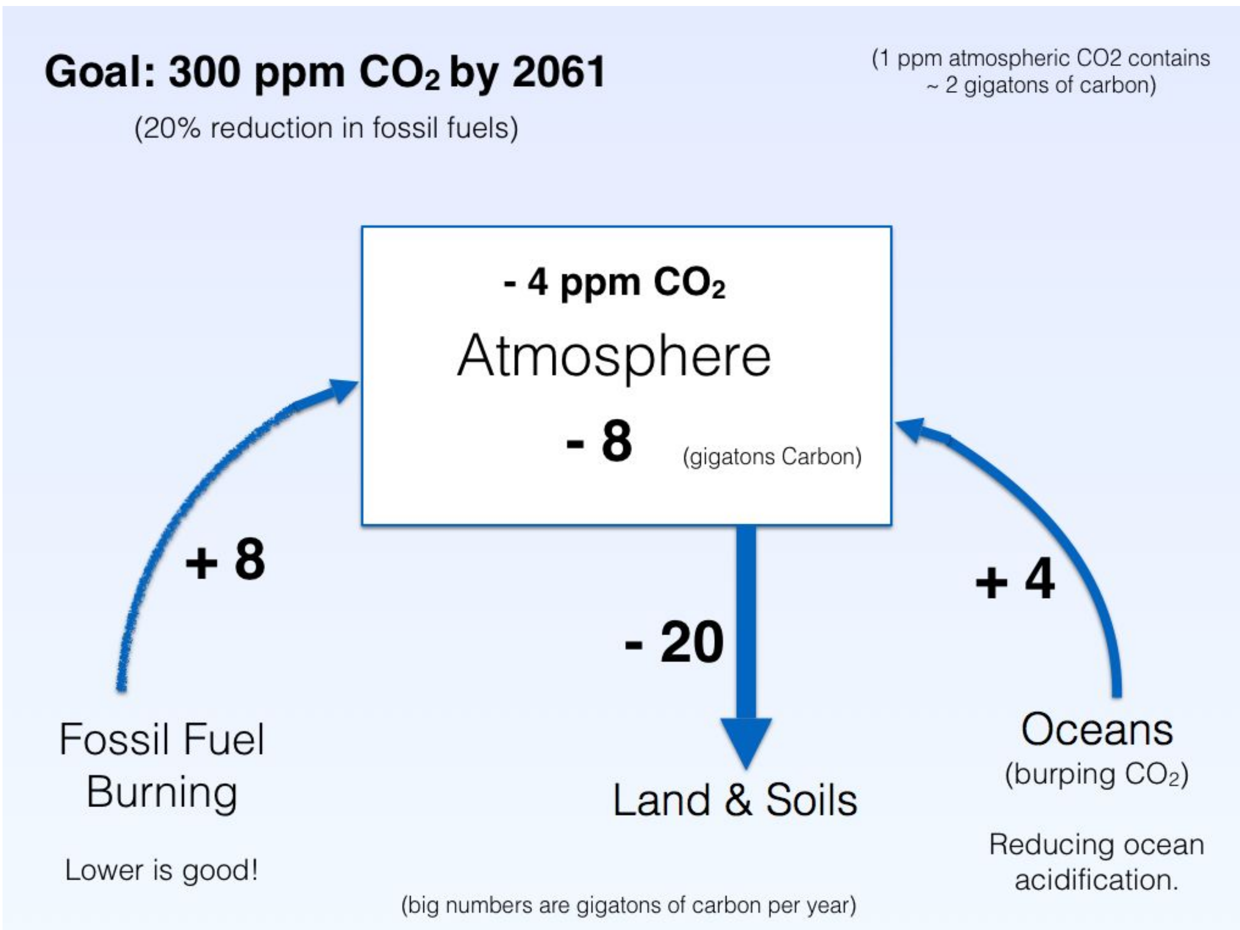

Figure 2. Calculation of net atmospheric drawdown of 4 ppm CO_2 (8 Gt carbon) annually, accounting for 8 Gt of fossil fuel emissions and 4 Gt of carbon released .oceans, offset by 20 Gt sequestered in soils.

This number will vary depending on factors like water temperatures that may slow down the return to 300 ppm. The good news is that ocean acidification will gradually be reversed. Figure 2 shows a 20% reduction in fossil fuel burning, down from 10 Gt to 8 Gt. One third of the difference between land and fossil fuels is 4 Gt coming out of the oceans. If this estimate is too low, then the return to 300 ppm will take longer and ocean acidification will reduce faster. If the estimate is too high, the reverse is true. Figure 2 also shows that CO_2 can come down by 40 ppm in a decade *if we can learn how to capture 20 Gt of carbon in the land ecosystems and soils yearly.*

Do Earth's ecosystems have the capacity to capture 20 Gt of carbon yearly?

Figure 3, below, the "Road Map to 300," gives several pathways to achieve this goal. While there are potentially 29 billion acres to work with (see table), this scenario uses only about half of this potential. If half of the available land is managed well in a holistic way, the Earth has plenty of capacity to store gigatons of carbon. In the Road Map, there are 13.5 billion acres in the "Half-Earth" column.

Road Map to 300 - Several Pathways

(Half Earth Plan - 5% to 10% wetlands is essential in grasslands, farms and forests.)

Ecosystem Land Type	Potential Billions of Acres	"Half Earth" Billions of Acres	Yearly Carbon Capture (tons/acre)	Billion Tons (per year)
Grasslands & Semi-Deserts (degraded but restorable)	13	6	x 1	6
Regenerative Farms Permaculture	6.3	3	x 2	6
Forests	7.1	3	x 2	6
Wetlands	2	1	x 6	6
Living Shorelines (Rising Sea Levels)	1	0.5	x 4	2
Arctic Permafrost (Azolla and Grazing Herds)	→	→	→	Part of Grasslands Total
Total	~ 29	13.5		26 GT C

Potential Billions of Acres Source: Robin White et al, *Pilot Analysis of Global Ecosystems: Grasslands*, WRI, p.51

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Figure 3. The Half-Earth Plan.

The final column shows that these 13.5 billion acres could capture 26 Gt of carbon annually. To do this requires 6 billion acres of grasslands to capture 6 Gt of carbon per year, averaging 1 ton

/ acre. 3 billion acres of farmlands and croplands can capture another 6 Gt by averaging 2 tons per acre per year. Forests are similar with 3 billion acres capturing 6 Gt of carbon and also averaging 2 tons C per acre per year.

Wetlands are extremely valuable and should be included to rehydrate all the other ecosystems. If 5% to 10% of the restored land were wetlands, the task of capturing carbon would be so much easier because they capture so much sediment and nutrients. A billion acres of wetlands can capture 6 GT of carbon annually.

The fifth row is called “Living Shorelines.” As the oceans continue to rise until after the continents begin to cool, we have the choice to “build a wall” and fight the rising tides …or… we can restore much of the coast to what it once was, a biodiverse area with salt marshes, seagrasses, kelp forests, mangroves and coral beds. I estimate that 0.5 billion acres of living shorelines would sequester 4 tons C per acre. Human civilization will have to move “uphill” for a while, but restoring living coastlines and populations of forage fish can bring back a fishing industry that has been largely depleted.

Humans will have to make huge changes in the ways we interact with nature and with each other. Our actions must become less competitive as we work together to enable symbiosis in the recovery of massively degraded ecosystems. It will be the greatest challenge in human history and will require several decades to accomplish.

It can be inspiring too, as vast areas of land come back to life. As these ecosystems restore the water cycle and build deep carbon rich soils, there can be sufficient food and water for the human population as well as the many other organisms we depend on. As CO_2 levels fall and small water cycle processes like infiltration and transpiration increase, the continents will begin to cool. Eventually continental cooling and ice formation at higher altitudes will begin to cool the oceans. Soil formation on the land will reduce erosion and ocean “dead zones” will diminish. As ocean acidity begins to drop, shellfish will also be less stressed and more productive.

Figure 4 below shows some possibilities in the next four decades. Also in Figure 4, we see that it takes two decades to “ramp up” restoration processes. In the 2020’s CO_2 levels only drop by 10 ppm (1 ppm / year). As more people get involved and land restoration accelerates, we see a 25 ppm drop in the 2030’s. By 2030 the amount of carbon being captured by soil processes reaches 20 Gt / year as shown in Figure 2. In the 2040’s and 2050’s we have reached the “Half-Earth” plan of restoring 13 billion acres on the planet. CO_2 levels in the atmosphere are now dropping by 4 ppm per year or 40 ppm per decade. We can reach 340 ppm by 2049 and 300 ppm by 2059 according to this scenario.

Scenario 300 Step Up - 4 Decades

(Events)

Decade	Fossil Fuels (gt / yr)	Land Use (gt / yr)	Oceans (gt / yr)	Net Total (gt /yr)	Decade Total (gigatons)	Decade Total (ppm CO_2)	Atmospheric CO_2 - End of Decade
2019	Methane Spike declared imminent. A global biodiversity restoration plan begins with support from many nations, many US states & Native American tribes.						415 ppm
2020's	By 2029 - 40% Fire Reduction - 40% Ag Chemical Reduction 40% Trawling Reduction - 10 million in Global Restoration Corps						405 ppm
2030's	By 2039 - 1 billion grazing animals reversing desertification (half are wild herds) - 30 million beaver in North America & 20 million in Asia						380 ppm
2040's	By 2049 - Living Shorelines & Permafrost Restoration Programs are in full gear. Oceans still rising but ice forming in higher altitudes.						340 ppm
2050's	By 2059 - Rising Water tables refill Aral Sea & Great Salt Lake. 200 million Beaver on 4 continents. Fungi help restore deep soils to 20 billion acres						300 ppm
2061	World Celebrations Watching Halley's Comet in July 2061					Goal >>	300 ppm

Slide #4

Figure 4. Steps in the progress of Scenario 300.

Is this a practical plan? Will humanity be able to change this rapidly? Many cannot imagine such a complete turnaround of our management of the planet's lands and biodiversity. Do we have a choice? As the news and evidence from the Arctic and Antarctic continues to shock us with the possibility of a runaway greenhouse gas scenario and rapidly increasing methane levels, we will continue to maintain "Business as Usual" at our own peril. This plan may not be "practical" in the present cultural context, but there are serious consequences already evident in abundance if we do not embark on a plan like this.

Human extinction is possible as we proceed to 500 ppm. Human extinction may even be probable, but it is not necessary. We can turn this around by using what we already know about restoring the land and becoming a symbiotic catalyst to rehydrating and cooling the planet. We can do this. …so let's get started.

Figure 5 below shows a Strategy Map for the "Lower 48 States" in the USA. This map should be considered a brainstorming tool and not a proposal. It does give a general plan for the 2 billion acres in this area. This area now burns enough fossil fuel to put about 2 billion tons of carbon into the atmosphere every year.

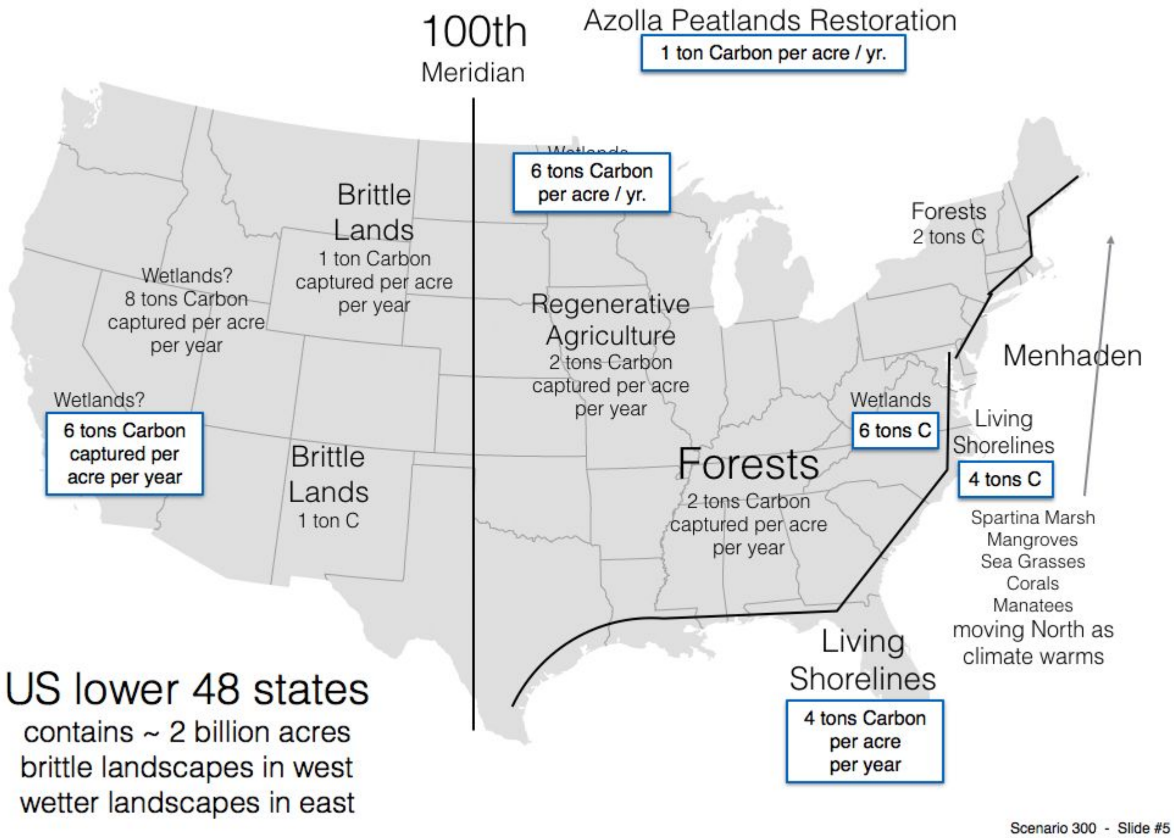

Figure 5. Strategy map in the U.S. Note: Brittle landscapes are drier lands that experience periodic dry seasons annually.

How could these lands capture 3 or even 4 billion tons of carbon and make the USA a net carbon sink? As we learn to capture carbon on the national level, we can also learn how to make North America and other continents net carbon sinks. *Remember, the goal is to restore ecosystems capable of capturing 20 billion tons of carbon per year. When that level is reached, carbon dioxide will be falling out of the sky, dropping by several ppm every year.*

Resources - Building a Case for Scenario 300

Pilot Analysis of Global Ecosystems: Grassland Ecosystems, by Robin White, Siobhan Murray, Mark Rohweder, World Resources Institute, 2000. This PAGE report is the source of my “Potential Billions of Acres” column in Figure 3. The “Half-Earth” column is the area needed to achieve the scenario's goal of 300 ppm by 2061. Thus, with our estimates based on using only 50% of available land in various ecosystems, there is a good deal of latitude in each instance.

Wetlands are a special case. The goal of restoring 1 billion acres of wetlands can be done if wetlands are incorporated into the plans for restoration of other systems. Wetlands can raise the water tables several feet in dry areas as we have seen in Zimbabwe and in Nevada, improving grazing opportunities there. Wetlands established in areas with higher rainfall can also improve resiliency of forests and farms. If 5% to 10% of these lands were managed as wetlands, the benefits would be enormous and a lot of carbon would be captured, too. This percentage represents about 1 billion acres.

Bio4climate Videos: Biodiversity for a Livable Climate (bio4climate.org) is a non-profit in Massachusetts dedicated to restoring the lands, waters, and biodiversity of the planet. We have produced eleven conferences in our four years exploring how to do this and continue to learn at a rapid rate. Our website has documented these conferences and their diverse range of speakers and participants. All of our speaker presentations have been video recorded and are available free online (see an introductory playlist at https://www.youtube.com/playlist?list=PLsWWRqCX9eSYwxFIgBDGMMQXFvK2mwR06). There are now almost 200 videos on the main page or program page of each conference with over 108,000 views on YouTube (see https://bio4climate.org/conferences). Many of these will be highlighted as resources below.

Walter Jehne is an Australian microbiologist and climate scientist. He has outlined a global strategy for ecosystem restoration in response to the Virgin Earth Challenge. His plan also shows that 20 billion tons of annual carbon sequestration by ecological restoration is possible if humans have the will to make it happen.

Two Links to Walter's work:

https://irp-cdn.multiscreensite.com/d6b81fb6/files/uploaded/2017%20-%20Regenerating%20Earth%27s%20Soil%20Carbon%20Sponge.pdf

http://www.globalcoolingearth.org/regenerate-earth/

Rangelands, Grasslands, and Deserts (see discussion of Allan Savory's work in Compendium, Vol. 1 No. 1, pp. 59 ff.): The goal is 6 billion tons carbon capture per year (13 billion acres available - Half-Earth Plan > 6 billion acres x 1 ton C / acre per year).

Much of world's rangelands are degraded and some are severely degraded. Allan Savory describes areas of seasonal rainfall as "brittle" environments. Areas that receive less than 20 inches of rainfall a year tend to be more brittle, but seasonality is important. In the "lower 48" United States lands west of the 100th meridian generally receive less than 20 inches of rain and are more brittle than lands east of this line. Most of these areas globally were once thriving biodiverse grasslands, but many are now growing “deserts” with vast areas of bare ground. Grasslands require grazing, hoof disturbance, and nutrients in the form of dung and urine from dense animal herds. The herds are not allowed to return to the impacted area until it has adequately recovered. Depending on brittleness, this might range from a few weeks to two years. While many rangelands have not been very productive, Allan Savory has demonstrated that these lands can come back within three or four years if managed holistically.

Many of these lands are now bare ground most of the year. Either they are devoid of animals, subjected to continuous grazing, or used as monoculture croplands for grains, cotton, etc. These croplands are usually high input operations using chemical fertilizers (NPK), pesticides, and irrigation water. Another problem in these brittle landscapes can be fire: both wildfires and intentional burns add much CO_2 to the atmosphere.

The Africa Centre for Holistic Management in Zimbabwe**.** Allan Savory’s contributions continue in Zimbabwe working with the Africa Centre. He is most impressed by the rising water tables and the return of wildlife to the areas being grazed by communities using movable kraals (corrals). Water cycle improvements in infiltration ensure that a considerable amount of carbon is going into the ground: the raised water tables enable more vegetation and soil biota to grow.

The “Road Map to 300” table shows Grasslands and Deserts covering 13 billion acres (Fig. 3). If only half of this land were managed in a way that captured 1 ton of carbon per acre each year, 6 billion tons of carbon per year would be added to the soil. Is 1 ton of carbon captured per acre possible with good management? We are learning that it is not only possible but can also be very profitable.

Richard Teague from Texas A&M found many examples using multi-paddock grazing where carbon capture was between 1 and 2 tons per acre per year. Dr. Teague spoke at the first Bio4climate conference at Tufts University in 2014. Link is below: https://www.youtube.com/watch?v=rhDq_VBhMWg&list=PLsWWRqCX9eSakMuHMosBKzdhb_NAtn2cB&index=4

Teague also gave a more detailed presentation at the Quivira conference in 2015. See https://www.youtube.com/watch?v=crG4L4J-OEg His summary at Quivira [37:30 to 39:53 minutes] emphasized that academics must work with leading ranchers and farmers to document how effective holistic management can be. He estimates that these ranchers and farmers are 20 to 30 years ahead of the academics in their ability to restore the land.

Christine Jones’ work on the Colin Seis ranch in Australia has involved the study of pasture cropping (grazing mixed with cover crops and crops sown into pastures). She is also measuring accumulated carbon levels down to two feet. Most studies don’t look past six inches of soil. The Seis Ranch has been getting about 1.8 tons carbon per acre per year over ten years, but in the

last two years it has risen to 3.6 tons C per acre per year. It is important to note that no fertilizers are being used and mineral density in the crops is improving as carbon levels rise. Note that fungi "mine" rocks in the soil for minerals.[16] See
http://www.amazingcarbon.com/PDF/JONES%27CarbonThatCounts%27.pdf
and http://www.soilsforlife.org.au/cs-winona

Gabe Brown in North Dakota has had even better results when he finally began mixing grazing with cover crops and crops sown into pasture. On some pastures Gabe is now capturing carbon at about 7 tons per acre per year. This area only receives 16 inches of annual rain and has a short growing season. The importance of mycorrhizal fungi is to be emphasized in both the Seis and Brown studies. By refusing to use chemical fertilizers, pesticides, and antibiotics, Gabe Brown's lands are rich in mycorrhizal fungi and soil insects and costs of production are far lower.

Gabe's TED talk link: https://www.youtube.com/watch?v=QfTZ0rnowcc [11:15 - 15:30 minutes]. By integrating cover crops and multi-species grazing, he has seen organic matter rise from 4.2% to 11.1% from 2006 to 2013. This change represents a 6.9% increase in organic matter in seven years. I calculate that to be about 7 tons of carbon captured per acre per year. Gabe's farm is in an area with 16 inches of rainfall and a 5-month growing season.

David C. Johnson from New Mexico State, speaking at the "Climate Reckoning" conference produced by Bio4climate in November 2017, amplified the message about fungi. In his research, his results show a capture rate of 10.7 tons C per hectare per year (4.33 tons C per acre per year). His method was no-till, no-chemicals, but he does not use grazing animals. In his presentation, he referred to Gabe Brown's work. David's calculation for carbon capture (adding his BEAM fungal/bacterial balancing technique) at the Brown Ranch is 20.63 tons C per hectare per year or 8.25 tons C per acre per year! See
https://www.youtube.com/watch?v=neIIPRRnXQQ&feature=youtu.be [28:10 - 36:15 min.]

"Make Soil - End Global Warming," Figure 6, shows how important biodiversity is to stabilizing the climate. Look for the key players: grazing herds, perennial grasses, dung beetles, mycorrhizal fungi, carbon farmers … and more.

[16] Using Acid and Physical Force, Fungi Burrow Through Rock - Eos --
https://eos.org/articles/using-acid-and-physical-force-fungi-burrow-through-rock

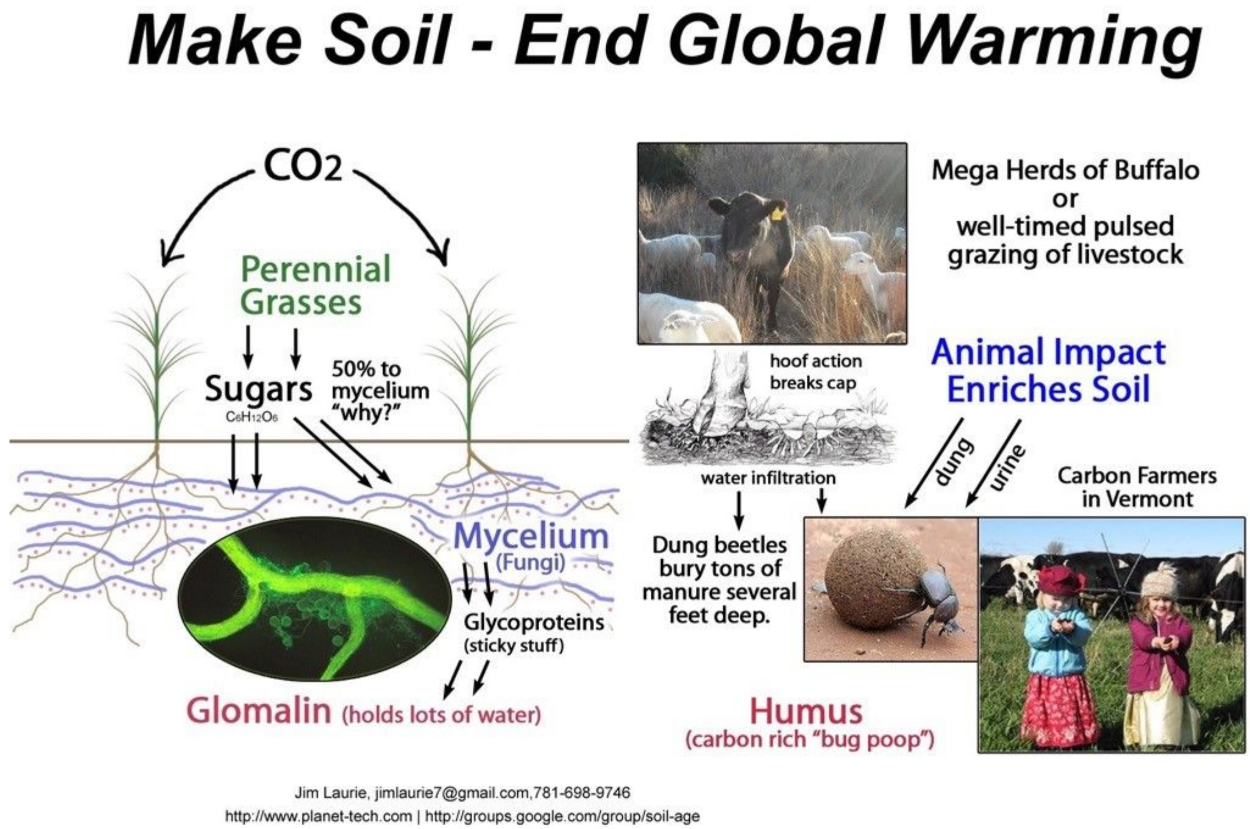

Figure 6. The importance of biodiversity.

Grasslands Summary: We are finding many examples of grasslands *exceeding the 1 ton of carbon per acre yearly capture rate*. If we can bring one half of the land in these brittle environments under good management within two decades, we should exceed the 6 billion tons annual carbon capture that is our goal for these lands. Integrating wetlands and wet meadows with these grasslands is another way to increase the carbon capture rates, which we will explore below. We are discovering that good management can work even in very brittle lands and has been demonstrated on tens of millions of acres on five continents. We know how to do this.

The overarching issue is that billions of acres of degraded land are still being overwhelmed by chemicals, pesticides, tillage, and/or continuous grazing, often at a financial loss to the landowner. The challenge is to bring these restorative possibilities to range managers everywhere.

Regenerative Farms and Permaculture. Goal is 6 billion tons carbon capture per year. (6.3 billion acres available - Half-Earth Plan > 3 billion acres x 2 tons C / acre per year)

Agricultural lands are generally less brittle and receive more rainfall than rangelands. Because of this there is greater opportunity to capture carbon. Using regenerative techniques with the goal of building soil with healthy mycorrhizal networks should yield 2 tons of carbon sequestered per acre per year. *If we are able to reach this goal on 3 billion acres (half of these lands) that would capture another 6 billion tons of carbon annually.*

Most agricultural lands have been the victim of severe erosion due to tillage and synthetic chemical use. They have lost over half of their organic matter, which makes it difficult to hold water in these soils. There is a huge opportunity to reverse this process. It would require far less dependence on chemical fertilizers and pesticides.

Fungal networks are essential to bring nutrients to the plants. Feed lots must be ended: the animals are needed out on the land (both rangelands and croplands) as a nutrient pump distributing manure, urine, and saliva, as well as a food source for humans. Raising 100% grass-fed beef and ending ethanol subsidies would reduce incentives for grain production and lead to a more nutrient-dense diet.

Providing funding to ranchers and farmers on the land for ecosystem services would accelerate this conversion. Providing $20 per acre for good management on 12 billion acres described in this scenario would require $240 billion dollars. This is about a quarter of the world's military budget. Because climate change is the greatest threat to global security, this is a relatively small price to pay.

Greg Judy is a grazier in central Missouri. He has seen an increase of as much as three inches of topsoil created in four years. An inch of this rich soil contains 8 tons or more of carbon per acre. *Three inches over 4 years yields 6 tons C per acre per year.*

Judy counts earthworms on the land he manages and finds as many as 17 piles of earthworm castings per square foot, or 700,000 casting piles per acre. His grazing plan includes a very dense herd in an area for a short duration (1 day) and 2 to 3 months recovery time. The manure deposited is significant and the trampling of the grass brings a great deal of biomass in contact with the soil to feed the earthworms. Dung beetles are also at work, drying out the dung and burying most of it in balls several feet deep. While the beetles are deepening carbon rich soils, the earthworms are mixing the same soil through many levels.

Greg Judy has written two books explaining his methods and includes his financial planning. These books are great sources for land managers, farmers, and ranchers:

No Risk Ranching: Custom Grazing on Leased Land
Comeback Farms: Regenerating Soils, Pastures and Profits with Livestock Grazing

Greg discusses biodiversity restoration in his lecture at the Virginia Association for Biological Farming Conference. See https://www.youtube.com/watch?v=W6HGKSvjk5Q. Some good clips from this talk include [10:00 to 20:00 minutes] and [49:50 to 62:30].

Joel Salatin is a farmer in the Shenandoah Valley of Virginia. He has written many books on farming. He describes how 8 inches of topsoil have accumulated over bedrock in a decade (2000 to 2010). *At 8 tons per acre per inch of topsoil, that's 64 tons C in ten years. Five tons C per acre per year is a conservative estimate.* (Remember, Scenario 300 only requires 2 tons per acre on half of the agricultural lands worldwide to see a major drawdown of atmospheric CO_2.) Salatin's description can be found in his book titled, *The Sheer Ecstasy of a Lunatic Farmer* [Ch. 1, pp. 2-15]**.**

Mark Shepard is a farmer and grazier in Wisconsin. He is planting a diverse blend of nut and fruit trees mixed with perennial crops, mushrooms, and grazing. He is rebuilding soils using ideas like the permaculture techniques described by Bill Mollison[17] years ago. Shepard's book, *Restoration Agriculture: Real World Permaculture for Farmers*, is very detailed and shows farmers how to grow nutrient dense food. This approach builds extensive mycorrhizal fungi in the soil which is a good sign of carbon rich soils. The perennial plants feed much carbon in the form of sugars and enzymes to the soil microbes and fungi.

Shepard also writes about his financial plan and shows how it is more profitable than the corn system most farmers now use in his area. If we subsidized "carbon farming" methods like Shepard, Salatin, Judy, and others are using, the transition to these methods could happen within the two decades required in Scenario 300. This is especially true if we stopped subsidizing soil-killing chemical agriculture.

Lands managed using permaculture, perennials, and holistic planned grazing would be amazing sites for long-term academic study over the time span of a decade or two. Farmers can rarely afford to do these studies; furthermore, they should be rewarded for ecosystem services, not charged for expensive lab work. Understanding the value of these systems should be a national priority. We are now subsidizing the "death of soils" by encouraging more chemical use. Using some of these funds for restoration studies would certainly be a step in the right direction.

Forests: Goal is 6 billion tons carbon capture per year. (7.1 billion acres of forest available - Half-Earth Plan > 3 billion acre x 2 tons C / acre per year.)

The "Half-Earth Plan" for forests has numbers similar to regenerative agriculture. If three billion acres were managed "holistically" to improve water and nutrient cycles, then 2 tons carbon capture per acre each year would achieve the goal.

[17] https://en.wikipedia.org/wiki/Bill_Mollison

Our understanding of how a healthy forest works is still very sketchy, but we are discovering that old-growth forests can capture more carbon and nitrogen than younger forests. Clearcutting every 40 years and burning the debris before replanting has been devastating to forest soils, but it was considered the best way to manage forests and remained largely unchallenged until the 1980s. What we have learned since gives hope that restoring forests can be a big part of Scenario 300.

Replanting clearcuts and selectively cutting in standing forests would be a good start. Allowing many mature forests to advance into "old-growth" stage is another possibility. Trees can feed mycorrhizal fungi and microbial networks. Grazing insects and nematodes release nitrogen for the trees slowly and their "bug poop" contains progressively more stable carbon compounds like humus and lignin. As soils in older forests mature, the amount of stable carbon in the ground continues to increase. Selectively cut wood products can hold their carbon for decades. Holistically managed forests that demonstrate the value of ecosystem services should qualify for subsidies mentioned above for well-managed ranches and farms.

Jon Luoma wrote *The Hidden Forest: Biography of an Ecosystem (1999)*. This excellent work describes research at the Andrews Forest in Oregon, where many discoveries have been made since its protection in 1948. Soil processes are described in great detail in Chapters 5 and 6.

Joan Maloof**,** writing in her book, *Nature's Temples: The Complex World of Old-Growth Forests* (2016), has focused on old-growth forests and finds that "increasing the time between logging events for managed forests and preserving old-growth forests, the carbon stored in forests and kept out of the atmosphere could theoretically double (pp. 36- 37).

Paul Stamets has done amazing research on fungi for decades and gives us many insights about forest restoration from his knowledge of mycorrhizal fungi in his book, *Mycelium Running: How Mushrooms Can Help Save the World* (2005).

If forests contained 10% beaver meadows and other wetlands, the average carbon capture rates and biodiversity would rise. Rising water tables would also reduce fires, a major source of greenhouse gases. This theme of integrating up to 10% wetlands into our restoration plans for improving carbon sinks keeps coming up in this document. Let's look at wetlands more closely.

Wetlands. 1 billion acres restored globally is essential: (Goal is 6 billion tons carbon capture per year - 1 billion acres x 6 tons C / acre per year.)

The loss of wetlands is a big part of the climate crisis. If we are serious about reversing climate change we must learn how restore these wetlands. It is estimated that the continental United States was once 10% wetlands due largely to beaver activity (see Alice Outwater, *Water: A Natural History* 1996). Extending the 10% figure to the rest of the globe, 2 B acres of wetlands are a real possibility. If we make our goal half of that over the next 40 years, it would require a billion acres of new wetlands. The scenario uses a carbon capture rate of 6 tons per acre per year, which is much higher than other ecosystems but justified by the following examples.

Steven Apfelbaum has created wetlands which sequester 7 to 12 tons per acre in North Carolina and Illinois. He also stresses the importance of covering peatlands that have been exposed to the air by dropping water tables. Drying out these carbon rich soils can lead to huge fires. He agrees with Walter Jehne about the importance of reducing landscape scale fires, a huge source of atmospheric CO_2. Apfelbaum spoke at the first Bio4climate conference at Tufts in 2014. See https://www.youtube.com/watch?v=gYq8WsLyPlg [9:58 - 20:04 minutes].

Carol Evans & Jon Griggs have encouraged beaver activity on Maggie and Susie Creeks in Nevada. The wet meadows now have 2 to 3 feet of mucky black soil and the water table in the area is 3 feet higher than 15 years ago. This muck contains significant carbon, at least 100 to 150 tons C per acre increase in 15 years. (This is what our climate scientists should be focused on.)

My estimate for Susie Creek is a yearly increase of 6 to 10 tons C per acre. Carol Evans is a fisheries biologist who has been studying these streams for several decades. Jon Griggs is the manager of Maggie Creek Ranch and is thrilled to see how the the vegetation can come back even in an area averaging less than 10 inches of precipitation per year. Link to their talk at our 2015 Tufts Conference: https://www.youtube.com/watch?v=IR7w9Tritj8&t=67s

While creating wetlands in populated areas – beavers often have different priorities than humans – we are learning how to work with them. The larger opportunity is in the desiccating and abandoned brittle landscapes. These lands need animal activity. Wild herds would help but rebuilding them will take awhile. Ranchers can bring in cattle, but they are often worried about water availability.

The Nevada case mentioned above is a great example of a regeneration strategy. Ranchers had a good management plan and kept the animals moving. As the creeks began to hold water longer, the beaver appeared. Without wood in those first years, they used rocks and mud and built deep channels to create permanent pools so they could survive the hot summers. The land holds much more water and the small, local water cycle is being enhanced (see reference below re Small Water Cycle). Trout and freshwater mussels are making a comeback in many of these streams.

Chernobyl - Restoration after Human Evacuation. The area around Chernobyl was a huge grain operation until the nuclear accident in 1986. Over 1000 square miles were evacuated and the area has become a curiosity for scientists who are doing research with strict exposure limits. This Exclusion Zone is now a biodiverse ecosystem with abundant wetlands and wet meadows due to beaver activity. Many threatened species have returned and are doing well including otters, moose, wild horses, and a diverse mix of water bird species. The wolf populations are doing well here approaching a hundred animals.

Because of radiation, most humans will avoid this area for a long time. Consequently, there is a great opportunity to observe how nature rehydrates the land and captures a great deal of carbon. Beaver once roamed most of central Asia all the way from France to China and Mongolia before they were trapped out in the 1300's. Imagine rehydrating most of Asia's degraded grasslands by nurturing beaver activity to raise water tables while restoring wild herds along with local grazing herds. Asia would become a net carbon sink. Check out this amazing Nature Documentary, *Radioactive Wolves Of Chernobyl*: https://www.youtube.com/watch?v=yzza7Aouzn8 [Historical wetlands summary at 13:25 to 17:30 minutes].

Michal Kravčík, an engineer from Slovakia, has been restoring landscapes and educating communities on several continents. He wants to restart what he calls the "small water cycle" in as many areas as possible. Kravcik asserts that water is now flowing off the continents faster than it is returning from the oceans as rain. This would explain why the continents have been slowly desiccating (drying out) for centuries. By his calculation, the runoff exceeds the rainfall coming from the ocean, and the difference exceeds the volume of Lake Erie, *every year*. Michal and others have been helping to slow the water down, increasing infiltration and transpiration, and cooling the planet.

The Kravčík team's vision for the future is a book titled *Water for the Recovery of the Climate - A New Water Paradigm.* This 94-page book is free and may be downloaded at http://www.waterparadigm.org/download/Water_for_the_Recovery_of_the_Climate_A_New_Water_Paradigm.pdf. See particularly the explanation of the "Small Water Cycle", pp. 17-18.

Wetlands Summary: Wetlands are also a must in other landscapes. If California returned 10% of its agricultural lands to wetlands and beaver meadows, it would have far fewer drought problems. If forest management required slowing of water and wetlands to raise water tables, the forests would have better immunity to pests, and wildfires would be reduced. Fire is not a very good tool if our aim to to reduce greenhouse gases. Keeping water at higher altitudes longer and having it go through many transpiration cycles (Kravčík's Small Water Cycles) before it reaches the sea will cool the system while building many water storage "bank accounts" for the inevitable dry periods.

Living Shorelines. Potential is 2 billion tons carbon capture per year (0.5 billion acres needed x 4 tons per acre per year)

The coastlines are very developed in many areas with large cities and little biodiversity. The sub-surface continental shelves have been plagued with dead zones from soil runoff and frequent trawling of the bottom by large fishing fleets. We are also already experiencing the impact of rising oceans and can expect sea level rise to accelerate for the next few decades.

Our goal of restoring ecosystems, building soils, and rehydrating continents will eventually reduce greenhouse gas levels and cool the continents, but oceans still contain most of the heat energy that the 'greenhouse blanket' has captured in the last century. Until much of this energy can escape through an atmosphere with reduced levels of carbon dioxide, methane, and other GHGs, we will be faced with continuing melting ice in Antarctica, Greenland, and high altitude glaciers. In Scenario 300, it will still take about four decades before we attain an atmospheric CO_2 level of 300 ppm. Hopefully at that 300 ppm level, we will begin to see some glaciers reforming in the higher altitudes and latitudes. It will be a big day when the Arctic Ocean begins to build up ice again, but the lag time might take many decades longer.

We expect at least a 5 or 6 foot sea level rise before the year 2100 even with the swift implementation of Scenario 300. However, without Scenario 300 the situation would be far worse. We could build walls to keep the ocean out, but the expense of this will exhaust resources needed for other challenges. Could we allow the ocean to rise and create large areas of saltwater ecosystems to supplement our carbon capture? Restoring these ecosystems and bringing back the plankton-eating forage fish could reinvigorate the coastal food webs. Strategically limiting coastal development and learning how to help cities thrive in a more aquatic environment is needed, now.

There are already many groups working on this possibility. Restoring salt marshes, sea grasses, mangroves, and corals is possible. Strategic thinking many decades into a rapidly changing future is already being done. In November 2016, Bio4climate organized an oceans conference at Harvard with the title: "Restoring Oceans, Restoring Climate," see https://bio4climate.org/conferences/oceans-2016-program/

This conference had over 20 presentations. The videos are available at the above link. A small sample of speakers includes Tom Goreau from the Global Coral Reef Alliance giving examples of his work to protect and restore coral reefs. Alfredo Quarto updated us on Mangrove restoration projects on several continents. Anamarija Frankic of UMass Boston and the Green Harbors Project has been reestablishing oyster and mussel reefs along the urban coastlines. George Buckley from Harvard gave the natural history and importance of horseshoe crabs. Dwayne Shaw, from Downeast Salmon Federation, spoke about bringing back river herring in New England streams. John Todd and Brian Von Herzen gave several examples of ecological design to bring back the ocean food webs. Katherine Deuel of the Pew Charitable Trust spoke about 'forage fish' like sardines and menhaden which are the key to re-establishing the big fish to places like New England. The Pew group is a leader in getting coastal communities to think about creating "Living Shorelines."

As the oceans warm and the seas rise, might we see the possibility of mangroves and corals moving into new areas farther north? Could these Living Shorelines with many diverse ecosystems become significant carbon sinks? Let’s find out. We have learned a great deal in the last decade about these possibilities.

Another example of strategic thinking regarding climate change is the Rice University Severe Storm Center (SSPEED). It is a collaboration between the Rice civil and environmental engineering departments and many environmental and community organizations in the Houston area. The SSPEED Center is working to protect as much coastal land as possible south of Houston along the Gulf Coast as a buffer to major hurricanes. Development and impermeable surfaces in the Houston area has made it very vulnerable to flooding: Hurricane Ike and Hurricane Harvey have been devastating. As sea level rises, there is now a lot of interest in rethinking land use on the coast. See the proposal for a Lone Star Coastal National Recreation Area: http://www.sspeed.rice.edu/lscnra. Jim Blackburn, the director at SSPEED, is a lawyer, environmental engineer, and nature enthusiast, and is featured in the video at this link: https://www.youtube.com/watch?v=P0YewbjwXq8

Can living shorelines be a significant carbon sink as the sea level rises? We are just beginning to study the possibilities, so the jury is still out. It is hopeful, though, considering how much interest has increased in a very few years.

Summary:

This period is the most challenging time in human history. The consequences for not facing this challenge are huge. Sea-level rise will be significant and will take decades to reverse under the best scenarios. As the Arctic Ocean becomes ice free and its waters become warmer, we face an increasing probability of a runaway methane spike. Now is the time to get started!!!

Nature’s Ecosystems have the capacity to reduce atmospheric CO_2 levels to 300 ppm within a few decades. Enhancing biodiversity and Holistic Management are essential for this to happen. Humans must adopt a very different approach to ecosystem management on half or more of the available lands.

A determined human effort with millions of people involved and eager to restore these symbiotic processes, just might lead to 300 ppm again by the return of Halley’s Comet in 2061. It can certainly be a rewarding project for those involved.

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