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

Volume 1, Number 2, March 2018

Table of Contents

Note: Click on Table of Contents item for hyperlink to that section.

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

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About Biodiversity for a Livable Climate

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

- ***A think tank***, creating research and reports (such as this Compendium), and presenting conferences on the science and practice of eco-restoration with speakers from around the world.
- ***An educational organization***, offering presentations, courses and materials, including over 190 videos of speakers 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 1 No 2, March 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, Christopher Haines, Fred Jennings and Philip Bogdonoff. 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 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

Introduction

In this second 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 biodiversity and regenerative agriculture in stabilizing ecosystems and the climate. We review a selection of a large and growing trove of

[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 added to soils or other carbon sink.

research demonstrating the relevance of biodiversity and regenerative agriculture for an effective response to the climate crisis.

We also include important and valuable information that is validated through land-management and other practice that has not yet appeared in peer-reviewed literature, which tends to be conservative and biased towards mainstream assumptions.[3] We consider these practices “positive variants” which hold great promise in addressing current rapidly growing environmental crises, including global warming.

Biodiversity and regenerative agriculture represent fertile ground for finding solutions, and should therefore be in the forefront of public discourse. Yet despite mounting and compelling evidence of a link, the relationship between biodiversity and the climate is not necessarily intuitive, nor is the connection often made in mainstream news or in political negotiations. Even in the face of biodiversity collapse, we broadly fail to prioritize biodiversity, let alone consider it as a key factor in the search for solutions to the climate crisis.

With respect to agriculture, an interest in agriculture-based climate solutions is evident among scientists, and this interest appears to be reaching the political sphere as well. Yet there is an apparent reluctance to look outside the context of the current, export-oriented, input-intensive system of agriculture. Instead, there is an assumption that we can improve the conservation potential of agriculture while remaining within the current agricultural paradigm, under the pretext that high external inputs are needed to "feed the world."

Indeed, agriculture is a linchpin issue for humanity. Our survival as a civilization depends on viable agriculture systems. However, input-intensive agriculture has given us false hopes about technology-aided yield potential, while at the same time diminishing the soil's inherent ability to provide for plant health and nutrition in an era of increasingly harsh climatic conditions for crop and livestock production. Yet agricultural land, which covers some 40% of Earth’s land surface [Foley 2005], could be a source of planetary regeneration. Indeed, it appears to be ONLY through regenerative agriculture that we will be able to feed ourselves in the future, since high-input agriculture is ultimately a far more fragile system. Industrial agriculture is more vulnerable to weather extremes, pest invasions, and highly reliant on increasingly scarce and expensive external inputs.

The purpose of this Compendium, and of Bio4Climate’s approach overall, is to assemble and showcase solutions to global warming that are largely already known, all of them rooted in ecosystem restoration. Since studies demonstrating the power of biological processes, biodiversity, and intact ecosystems to restore balance to the climate system are dispersed across multiple disciplines that may often be unaware of one another’s work, we attempt to shed light on such relationships and consider the climate crisis in a complex systems framework.

Understanding the planet as a complex system, encompassing myriad living and non-living subsystems, opens up our awareness to the interdependence among seemingly unrelated processes, and to the possibility of indirect and cascading effects and abrupt changes. It helps us to accept and appreciate the vast complexity of billions of simultaneous processes that

[3] For further discussion of peer review, see this Compendium, Vol 1 No 1, Appendix A, Perils of Peer Review, https://bio4climate.org/wp-content/uploads/Compendium-Vol-1-No-1-July-2017-Biodiversity-for-a-Livable-Climate-1.pdf.

cannot be fully controlled, and yet also to recognize the patterns that restore balance to the systems sustaining human life (such as how protected and revived soil accumulates carbon and water that would otherwise be in the atmosphere or ocean. See Appendix B for further discussion of a systems approach to climate change.)

At the same time, these ecosystem approaches will be successful only if they are actually undertaken and replicated systematically, the world over. Therefore, it behooves us to contemplate the urgency of the crisis before us. The positive feedbacks[4] in climate, as witnessed by the dramatic accelerations of weather crises and many environmental degradations such as extinctions (including the unprecedented disappearance of insects), plankton loss, and disrupted timing of lifecycles and species migrations, raise such alarm that even while focusing on promising solutions, we must fully acknowledge our current dire situation. (See Appendix A for further discussion of current urgencies.)

The articles featured in this Compendium reveal the power of ecosystem properties and processes, when protected from human hyper-exploitation, to restore life and health to human society and to many other organisms upon whose wellbeing we are entirely dependent. Specifically, the effect of biodiversity at various taxonomic levels on ecosystem productivity rivals that of abiotic factors [Weigelt 2009, Duffy 2017, Lehmann 2017, Sobral 2017]. Furthermore, often-overlooked groups of species play major roles in ecosystems. Notably, fungi are associated with high soil carbon content and productivity, and with phosphorus cycling [Bailey 2002, Johnson 2017, Berthold 2016, Mills 2017].

In fact, there is poor understanding of the phosphorus[5] cycle unless you include the work of the fungi. Mark McMenamin, who spoke at Bio4Climate's Oceans Conference in 2016,[6] wonders why land has perhaps 100 times the biomass and triple the productivity compared to the oceans [McMenamin 2016]. His theory, "Hypersea" [McMenamin 1996] proposes that high productivity on land is a result of the ways biodiversity creates "upwellings," which bring up essential minerals and water, often from deep in rocky soils, to facilitate photosynthesis. Fungi retrieve micronutrients for plants in exchange for the energy provided by the glucose produced by green plants.

In the ocean, phosphorus is available if there are upwellings from the bottom by winds, seamounts or currents. Phosphorus, nitrogen and other minerals are rapidly consumed by algae and if they are not replenished regularly then algae growth stops. The ocean is largely an "aqueous desert" because movement of nutrients to the surface from the deeper ocean is relatively rare.

Thus, Hypersea is about upwelling of nutrients. High productivity on land is because of fungi - plant symbioses. But human chemical agriculture has interrupted this system. By adding enormous amounts of nitrogen, phosphorus, and potassium at great expense, we have

[4] A positive feedback loop is a process that, once initiated, sustains or amplifies itself. For example, Arctic summer ice melting due to warmer global temperatures exposes dark water to sunlight, which warms the water further thereby melting more ice, until eventually all the summer ice is gone. The result is a profound disruption of global weather patterns.

[5] Phosphorus is essential to make DNA, RNA, and the energy carrier molecule ATP, which is essential to many enzymatic reactions in all cells.

[6] Oceans conference information may be found at http://bio4climate.org/oceans-2016/.

temporarily increased crop yields. However, these inputs cause bacteria populations to multiply and consume the mycorrhizal fungi networks. Because of this, nutrient flow from deep in the soil slows or stops.

Yet, to the extent that humans are capable of disrupting phosphorus, nitrogen, carbon, water and other cycles that are at once driven by and sustaining of Earth's biosphere, we are also capable of acting to repair these cycles as Trant [2016] and Treuer [2017] illustrate - ancient and modern peoples alike have improved ecosystem productivity by composting food wastes, for example.

The books *Drawdown* and *Geotherapy* similarly offer a wealth of specific, proven and practical steps for restabilizing the climate. "Humanity has the means at hand. Nothing new needs to be invented. The solutions are in place and in action. Our work is to accelerate the knowledge and growth of what is possible" [Hawken 2017]. Indeed, illuminating that picture of what is possible is the purpose of this Compendium.

Geotherapy

Geotherapy: Innovative Methods of Soil Fertility Restoration, Carbon Sequestration, and Reversing CO_2 Increase. Edited by Thomas J. Goreau, Ronal W. Larsen and Joanna Campe [Goreau 2015]

The term "geotherapy" was coined by Richard Grantham, an evolutionary biologist and geneticist who, in his later years, turned his attention to the deteriorating state of Earth in the current era, the Anthropocene. He regarded the planet as ill, as a patient, in need of treatment.

The first geotherapy conference was held in 1991 in France, preceding the first international climate conference in Rio in 1992. It was underfunded and the papers presented could not be published. In the meanwhile the international community focused virtually all of its attention on climate as a greenhouse gas problem, and the powerful biological drivers of not only climate but most processes on Earth receded into the background.

This book is an invaluable contribution to redressing serious oversights on the part of mainstream climate science. For example, anthropogenic climate change began long before the industrial revolution, as leading soil scientist Rattan Lal states in his Preface to *Geotherapy*:

> One of the consequences of the drastic anthropogenic perturbation of the biosphere is the depletion of the ecosystem and soil carbon pools. Rather than commencing with the onset of the industrial revolution around 1750, anthropocene began with the beginning of settled agriculture 10 to 12 millennia ago. Over this period, more carbon may have been emitted into the atmosphere from deforestation and land use conversion than from fossil fuel combustion until the end of the twentieth century. Thus, recarbonization of the biosphere in general and that of the soil carbon pool in particular is important to the

> maintenance and enhancements of ecosystem functions and services. [Goreau 2015: xv-xvi]

Geotherapy is an anthology of thirty-four scientific articles that sketch a roadmap to planetary health. Topics covered range from biochar to rock powders to waste nutrient recycling to remediation with plants to carbon farming (farming with soil health a primary concern), and more. The articles are well-illustrated, well-referenced, and accessible to a layperson generally familiar with scientific writing. It's a guidebook with many shovel-ready approaches as well as theoretical explanations. The sense of both urgency and hope in bringing back living systems to the anthropocene landscape is palpable:

> If soils are not restored, crops will fail even if rains do not; hunger will perpetuate even with emphasis on biotechnology and genetically modified crops; civil strife and political instability will plague the developing world even with sermons on human rights and democratic ideals; and humanity will suffer even with great scientific strides. Political stability and global peace are threatened because of soil degradation, food insecurity, and desperateness. The time to act is now. [Rattan Lal in Goreau 2015: xvi]

Biodiversity and why it matters

Biodiversity refers to the outcome of 3.8 billion years of evolution since single-cellular life appeared on Earth. It is a concept embodied by an endless variety of life forms and strategies undertaken within the kingdoms of life. Biodiversity allows for a dynamic web of interactions, whereby countless organisms reliably supply one another with sufficient nutrients and shelter for survival. In technical terms, biodiversity is a measure of the total number of species in an area (species richness) weighted by the distribution of individuals across species (species evenness) [Barbour 1987: 162], and is commonly used simply to describe a particular ecological community.

Yet, because biodiversity is increasingly threatened, its relevance to the normal functioning of Earth's systems is coming into sharper focus. Biodiversity is a primary source of the stability and productivity in ecosystems [Hautier 2015, Duffy 2017], and enhances soil carbon sequestration [Sobral 2017, Lehmann 2017, Udawatta 2011]. In the words of researcher Johan Rockström of the Stockholm Resilience Centre, "the composition of trees, plants, microbes in soils, phytoplankton in oceans, top predators in ecosystems…together constitute a fundamental core contributor to regulating the state of the planet." Rockström continues: "Without biodiversity, no ecosystems. No ecosystems, no biomes. No biomes, no living regulator of all the cycles of carbon, nitrogen, oxygen, carbon dioxide and water" [Hance 2018].

An important component of biodiversity is "functional diversity," which refers to "the range and value of those species and organismal traits that influence ecosystem functioning" [Tilman 2001: 109]. In other words, specific traits of various species, like the ability to photosynthesize, to decompose dead organic matter, or to control herbivore populations, affect the way an ecosystem operates.

The reintroduction of wolves in Yellowstone Park illustrates this: when wolves were reintroduced they reduced overgrazing by elks in the valleys, which allowed aspen, willow and cottonwood trees to grow back into forest, in turn stabilizing the banks of the river. The return of trees brought back birds and beavers. The beaver dams are believed to have brought back otters, muskrats, fish, ducks, reptiles and amphibians. The wolves also controlled coyote populations, allowing mice and rabbit populations to rebound and attract other predators, including ravens and bald eagles. This magnificent ecosystem-wide ripple effect from reintroducing the top predator is called a "trophic cascade" [Ripple 2011], and it was poignantly illustrated in a short video narrated by George Monbiot [Monbiot 2014].

In short, particular species and groups of species, including ones we may not like, know or care about, play vital roles. In the collection of articles below, we highlight the ecological importance of biodiversity in general, as well as varieties of particular species with remarkable roles to play in the perpetuation of a biologically productive and habitable world. Notably, fungi play a starring role.

Compilation of biodiversity articles

Biodiversity

Mammal diversity influences the carbon cycle through trophic interactions in the Amazon, Sobral 2017

In a mixed forest-savanna landscape of tropical Guyana researchers found that mammal diversity is positively related to carbon concentration in the soil. The authors explain that this is due to increased feeding interaction associated with greater mammal diversity, and specify that animal abundance per se did not increase carbon content in the soil. "The lack of effect of both tree biomass and animal abundance on the response variables highlights the relevance of species richness" [Sobral 2017: 2].

> "…mammal and tree richness increase the number of feeding interactions observed. The amount of organic remains (fruit and seed parts, non-fruit plant parts, faeces and animal parts) on the ground is predicted by the number of feeding interactions, and is positively related to carbon concentration in the soil. The organic remains that most affect soil carbon concentration were animal and fruit remains, which were themselves driven by carnivory and frugivory[7] interactions suggesting that both processing of fruits and direct biomass contributions by vertebrates and plants affect soil carbon concentration" [Sobral 2017: 3]
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Biodiversity effects in the wild are common and as strong as key drivers of productivity, Duffy 2017

"Biodiversity has a major role in sustaining the productivity of Earth's ecosystems" [Duffy 2017: 263]. This is the conclusion drawn from an analysis of 133 estimates reported in 67 field studies

[7] "Frugivory" is consumption of fruits.

on the effects of species richness (number of species) on biomass production, isolating biodiversity as a variable from other factors that affect productivity (nutrient availability and climate). The results validate theoretical predictions and corroborate lab experiments showing that greater biodiversity leads to greater ecosystem production, while also refuting prevailing doubts about the significance, after accounting for other factors, of biodiversity's effect on productivity.

> Because of the long history of skepticism that species diversity affects productivity of natural ecosystems, the strength and consistency of results presented here were unanticipated. In every case we found the opposite of long-standing views expressed in the ecological literature. Ecosystems with high species richness commonly had higher biomass and productivity in observational field data from a wide range of taxa and ecosystems, including grassland plants, trees, lake phytoplankton and zooplankton, and marine fishes. Observed positive associations of biodiversity with production in nature were stronger when covariates were accounted for, stronger than biodiversity effects documented in controlled experiments, and comparable to or stronger than associations with climate and nutrient availability, which are arguably two of the strongest abiotic drivers of ecosystem structure and functioning, as well as major global change drivers. Our results also corroborate findings of a recent synthesis of experimental data reporting that biodiversity effects are comparable in magnitude to major drivers of global change, and extend related conclusions based on observational data from forests and dryland plants to a broad range of ecosystems [Duffy 2017: 263].

> Integration of this perspective [on the vital role of biodiversity] into global change policy is increasingly urgent as Earth faces widespread and potentially irreversible losses and invasions of species, which are already changing ecosystems [Duffy 2017: 263].

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Soil biota contributions to soil aggregation, Lehmann 2017

This meta-analysis finds that biodiversity across groups, especially between bacteria and fungi, contributes more to soil aggregation than species from just one group acting alone. For example, fungi specialize in binding macroaggregates, while bacteria can also bind microaggregates, and earthworms can "grind and remould ingested particles into new aggregates" [Lehmann 2017: 1]. There were no such effects from within-group biodiversity, however.

> Soil biota potentially contribute to soil aggregation in a number of ways. For example, bacteria can exude biopolymers that act as binding agents for aggregates on the micrometre scale, fungal hyphae can entangle particles to hold them together (on the micrometre to millimetre scale) and geophagous animals, such as earthworms, grind and remould ingested particles into new aggregates and create biopores (on the millimetre to centimetre scale). Due to these various contributions of soil biota to soil aggregation, there is also a clear potential for complementarity among soil aggregation mechanisms, as has been shown in isolated studies [Lehmann 2017: 1].

> These findings support the hypothesis that there is functional complementarity contributing to soil aggregation, and the results highlight that this functional complementarity mainly resides at the level of the HTC [Higher Taxonomic Category] . The presence of pronounced organismal interaction effects highlights the opportunity to use soil biota mixtures tailored for enhancing soil aggregation (for example, inoculation for use in restoration). This result also emphasizes the need to manage for overall high levels of soil biodiversity, especially across HTCs, in agroecosystems, which would facilitate the development of such interactions [Lehmann 2017: 4].

Anthropogenic environmental changes affect ecosystem stability via biodiversity, Hautier 2015

This study illustrates the importance of biodiversity for maintaining ecosystem stability. It tests the hypothesis that "other drivers of global environmental change may have biodiversity-mediated effects on ecosystem functioning - that changes in biodiversity resulting from anthropogenic drivers may be an intermediate cause of subsequent changes in ecosystem functioning" [Hautier 2015: 337]. Researchers found that "changes in plant diversity in response to anthropogenic drivers, including N, CO_2, fire, herbivory[8], and water, were positively associated with changes in temporal stability of productivity," and that "this positive association was independent of the nature of the driver" [Hautier 2015: 338]. In other words, the experimental interventions (N, CO_2, fire, etc.) affected biodiversity, which in turn affected ecosystem stability; the interventions didn't affect ecosystem stability directly, but only through changes in biodiversity as an intermediary.

> For example, whether a 30% change in plant diversity ... resulted from elevated N, CO_2, or water or from herbivore exclusion, fire suppression, or direct manipulation of plant diversity, stability tended to decrease in parallel by 8%... This conclusion is supported by analyses showing that there was no remaining effect of anthropogenic drivers on changes in stability after biodiversity-mediated effects were taken into account [Hautier 2016: 338].

[8] Herbivory is the consumption of plants.

Biodiversity for multifunctional grasslands: equal productivity in high-diversity low-input and low-diversity high-input systems, Weigelt 2009

This English grasslands study, comparing alternative strategies for increasing productivity, showed that "increasing plant species richness levels were more effective than the imposed levels of increasing management intensity" [Weigelt 2009: 1701]. The management intensification strategy included synthetic fertilization and mowing, while the biodiversity strategy increased species richness from 1 to 16 species. The authors conclude that:

> For permanent grasslands, which cover one third of the utilised agricultural area in Europe (Smit et al., 2008), highly diverse communities composed of complementary species and N2-fixing legumes could provide an excellent agro-economic and ecological option for sustainable and highly productive grassland use [Weigelt 2009: 1704].

Low-cost agricultural waste accelerates tropical forest regeneration, Treuer 2017

This study illustrates how ecosystem restoration enhances biodiversity and productivity. A one-time application in 1998 of 1,000 truckloads of agricultural waste (orange peels) to 3 ha of degraded pasture accelerated tropical forest regeneration in this Costa Rica study. The treatment led to a tripling in species richness (24 tree species from 20 families, compared to 8 tree species from 7 families in the control plot), and 176% increase in aboveground biomass after 16 years, and without any human input after the original orange waste treatment of that site. The thick layer of orange peels suppressed existing non-native pasture grasses and added macro- and micronutrients to the soil, ultimately allowing for the natural (unmanaged) repopulating of the treated area from adjacent forest seedstock.

> Our results provide nuance and detail to what was overwhelmingly obvious during informal surveys in 1999 and 2003: depositing orange waste on this degraded and abandoned pastureland greatly accelerated the return of tropical forest, as measured by lasting increases in soil nutrient availability, tree biomass, tree species richness, and canopy closure. The clear implication is that deposition of agricultural waste could serve as a tool for effective, low-cost tropical forest restoration, with a particularly important potential role at low-fertility sites [Treuer 2017: 6].

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Remarkable roles of unremarked creatures

The articles below offer a sampling of the myriad ecosystem roles played by species we may not think much about. For example, fungi, an exemplar ecosystem cooperator, buries carbon in the soil, sources otherwise unavailable nutrients like phosphorus for plant growth, and facilitates bacterial evolution. Great whales transport nutrients through the ocean for other species to consume. Dung beetles reduce methane emissions from manure, while also fertilizing grasses. Termites and ants promote vegetation growth in arid climates by creating tunnels that catch and hold rainwater, and by making nutrients available to plants.

Nutrient acquisition by symbiotic fungi governs Palaeozoic climate transition, Mills 2017

Fossil evidence shows that early land plants hosted fungal symbionts, which are likely to have facilitated phosphorus acquisition by plants and thus increased net primary production, perpetuating the transition to a cooler, oxygen-rich environment suitable for animal life. Mills' study tests this hypothesis by integrating plant-fungal phosphorus acquisition into a biogeochemical model of the Paleozoic climate transition. The study finds "significant Earth system sensitivity to phosphorus uptake from mycorrhizal fungi" [Mills 2017: 7], and that "efficient phosphorus uptake at superambient CO_2 results in enhanced carbon sequestration, which contributes to a reduction in CO_2 and drives a rise in O_2" [Mills 2017: 6].

Understanding drivers of an historic climate cooling is obviously relevant today given current atmospheric CO_2 accumulation. This study points to the importance of plant-fungal symbioses and phosphorus cycling, and thus to the importance of building and protecting soil health to allow such symbioses to flourish.

Mycelia as a focal point for horizontal gene transfer among soil bacteria, Berthold 2016

Fungus is a key component of healthy soil. It is known to "translocate compounds from nutrient-rich to nutrient-poor regions… facilitate the access of bacteria to suitable microhabitats for growth, enable efficient contaminant biodegradation, and increase the functional stability in systems exposed to osmotic stress" [Berthold 2016: 5]. This study shows that, in addition, mycelia facilitate bacterial evolution, thereby bolstering bacterial diversity and adaptability.

> Abstract: Horizontal gene transfer (HGT) is a main mechanism of bacterial evolution endowing bacteria with new genetic traits. The transfer of mobile genetic elements such as plasmids (conjugation) requires the close proximity of cells. HGT between genetically distinct bacteria largely depends on cell movement in water films, which are typically discontinuous in natural systems like soil. Using laboratory microcosms, a bacterial reporter system and flow cytometry, we here investigated if and to which degree mycelial networks facilitate contact of and HGT between spatially separated bacteria. Our study shows that the network structures of mycelia promote bacterial HGT by providing continuous liquid films in which bacterial migration and contacts are favoured. This

finding was confirmed by individual-based simulations, revealing that the tendency of migrating bacteria to concentrate in the liquid film around hyphae is a key factor for improved HGT along mycelial networks. Given their ubiquity, we propose that hyphae can act as a focal point for HGT and genetic adaptation in soil.

The rhizosphere - roots, soil and everything in between, McNear 2013

A variety of intimate, symbiotic relationships exist between the roots of plants and the microorganisms in the soil. For instance, mycorrhizal fungi colonize the surface of plant roots, effectively extending them further through the soil to collect nutrients otherwise out of reach. These mycorrhizal branching structures, known as hyphae, emanating from plant roots also improve soil aggregation and hence improve water infiltration and aeration. In return, Mycorrhiza can demand up to 20-40% of photosynthetically derived carbon from their plant hosts. In the world of rhizospheric bacteria, Rhizobia[9] are well known for their key role in fixing atmospheric nitrogen for plant uptake. Yet there are, additionally, more than two dozen known genera of rhizobacteria that help plants grow, either directly by releasing growth stimulants (phytohormones) and enhancing mineral uptake, or indirectly by fighting off plant pathogens.

Fungal to bacterial ratios in soils investigated for enhanced C-sequestration, Bailey 2002

Testing paired sites in four ecosystem types, this study finds that higher fungal activity in soil is associated with higher soil carbon content, and that disturbing the soil reduces fungal activity. The paper's introduction explains why fungi have been found to store more carbon than do bacteria – for example, fungi can store up to 26 times more carbon from leaf litter than bacteria. This is because the chemical composition of fungal biomass is more complex and more resistant to degradation; also, fungi have higher carbon assimilation efficiencies than do bacteria, and thus store more of the carbon they metabolize.

Whales as marine ecosystem engineers, Roman 2014

Baleen and sperm whales, known collectively as the great whales, include the largest animals in the history of life on Earth. With high metabolic demands and large populations, whales probably had a strong influence on marine ecosystems before the advent of industrial whaling: as consumers of fish and invertebrates; as prey to other large-bodied predators; as reservoirs and vertical and horizontal vectors for nutrients; and as detrital sources of energy and habitat in the deep sea. The decline in great whale numbers, estimated to be at least 66% and perhaps as high as 90%, has likely altered the structure and function of the oceans, but recovery is possible and in many cases is already underway. Future changes in the structure and function of the world's oceans can be expected with the restoration of great whale populations.

[9] Rhizobia are nitrogen-fixing bacteria living in nodules formed in the roots of leguminous plants.

The role of dung beetles in reducing greenhouse gas emissions from cattle farming, Slade 2015

"Dung beetles (Scarabaeidae: Scarabaeinae, Aphodiinae, Geotrupidae) are some of the most important invertebrate contributors to dung decomposition in both temperate and tropical agricultural grasslands. As such, they may help mitigate GHG [Greenhouse Gas] emissions and aid carbon sequestration through removing dung deposited on the pastures, increasing grass growth and fertilization" [Slade 2015: 1]. This Finland study analyzed the percent of GHGs removed by dung beetles at three levels: dung pat, pasture, and dairy/beef production life-cycle, finding reduced GHG emissions of 7%, 12%, and 0.05 to 0.13%, respectively. Dung beetles reduce methane emissions by aerating the dung pats, thereby preventing methane-producing anaerobic decomposition of the dung.

The reason dung beetles have a minimal effect in the full life-cycle analysis for Finland cattle is that the animals spend only a short portion of the year grazing in pasture, and thus emissions from dung on pasture is "dwarfed in comparison to other emissions of milk and meat production, such as methane emissions from enteric fermentation, nitrous oxide emissions from soils, and carbon dioxide emissions from energy use" [Slade 2015: 5]. However, "in regions where outdoor livestock grazing is more commonly used, the emissions from manure left on pasture will have a larger contribution to total agricultural emissions, with estimated fractions ranging from 11% in Asia up to 35% in Africa. Such patterns are combined with likely differences in dung beetle efficiency: In tropical regions, dung beetles can remove the majority of a fresh dung pat within the first few days after deposition – whereas in temperate conditions, a substantial fraction will remain throughout the grazing season" [Slade 2015: 5].

The authors recommend further research in tropical regions, predicting: "that effects at all levels from dung pats through pastures to the whole lifecycle of milk or beef production may be strongly accentuated at low latitudes" [Slade 2015: 5].

Termite mounds can increase the robustness of dryland ecosystems to climatic change, Bonachela 2015

> Termites are particularly important in savannas of Africa, Australasia, and South America, and their nest structures ("mounds") shape many environmental properties; analogous structures built by ants and burrowing mammals are similarly influential worldwide. Mound soils differ from surrounding "matrix" soils in physical and chemical composition, which enhances vegetation growth, creating "islands of fertility." Moreover, mounds are frequently spatially over-dispersed owing to competition among neighboring colonies, which creates spotted vegetation patterns [Bonachela 2015: 652].

This study seeks to characterize landscape patterns created by termites in order to distinguish between that and other causes of spotted vegetation patterns that have been assumed to indicate imminent ecological collapse. "Rather, mound-field landscapes are more robust to aridity, suggesting that termites may help stabilize ecosystems under global change" [Bonachela 2015: 651].

Ants and termites increase crop yield in a dry climate, Evans 2011

Testing the effects of ants and termites on crop yield in an arid part of Australia, this study showed "that ants and termites increase wheat yield by 36% from increased soil water infiltration due to their tunnels and improved soil nitrogen" [Evans 2011: 1]. The authors conclude: "Our results suggest that ants and termites have similar functional roles to earthworms, and that they may provide valuable ecosystem services in dryland agriculture, which may become increasingly important for agricultural sustainability in arid climates" [Evans 2011: 1].

> ***Ants and termites have similar functional roles to earthworms, and . . . they may provide valuable ecosystem services in dryland agriculture, which may become increasingly important for agricultural sustainability in arid climates*** **[Evans 2011: 1].**

Agriculture as planetary regeneration

Agricultural production must produce enough food for almost 10 billion people by 2050 [FAO 2017],[10] and yet a third of all land is degraded [FAO 2015] and nearly all agricultural land has lost significant amounts of SOC (Soil Organic Carbon). So we have a puzzle to solve: how to produce more from less, and in the face of a more chaotic climate system. Between 1960 and 1990, the increased use of synthetic fertilizers, pesticides, irrigation, and modern seed varieties nearly doubled world cereal yield [FAO 1996]. Because of this apparent success, it's not unreasonable to think the answer to the puzzle involves the same combination.

However, we now face a convergence of extremely dangerous crises – global warming, cascading species extinctions, antibiotic resistance, and ubiquitous chemical and nutrient pollution – all of which are aggravated by the current fossil-fuel-intensive industrial model of agriculture. Indeed, the current food system accounts for nearly 30% of total greenhouse gas emissions [Vermeulen 2012]. Furthermore, nearly half of harvested crops are lost because it is thrown away before being eaten or due to overconsumption (food consumption in excess of

[10] This population growth is anticipated but not inevitable. Widespread catastrophe and poor (or wise) human decisions may significantly alter these outcomes.

nutritional requirements) [Alexander 2017]. In spite of this, 11% of the world's people are still hungry [FAO 2017].

Yet, for each agricultural problem, there is a known solution. For instance, agriculture has the potential to be a carbon sink. Many scientists have found that implementing various conservation practices can sequester up to 1 ton of carbon per hectare per year (1t C/ha/yr), or an estimated ~20% global emissions offset if such practices were broadly implemented [Smith 2008, Lal 2016]). Yet others have measured sequestration rates upwards of 8t C/ha/yr. While climate and soil type play a role in the variation among sequestration rates, farming practices are a major factor.

Studies with lower sequestration rates tend to isolate just one or two soil-building practices. For example, Minasny et al. [2017] compiled sequestration rates from around the world to assess the viability of the France-led "4 per 1000" initiative (seeking to offset the annual increase in atmospheric CO_2 by increasing soil carbon by 0.4% per year). The authors estimate that an annual rate of 0.2-0.5t C/ha/yr "is possible after adoption of best management practices on arable land such as reduced tillage in combination with leguminous cover crops" [Minasny 2017: 61]. However, most of some 40 studies of best management practices assessed only one or two practices, often minimally improved, such as "reduced use of summer fallow," "rice-rice with NPK," "inorganic fertilizer," and "pasture" (without mention of how the pasture was managed) [Minasny 2017: 64]. In other words, the "improved" practices here include even the use of synthetic fertilizer, which can generate more crop biomass and thus more residue, but has also been shown to diminish soil organic carbon [Khan 2007].

By contrast, researchers in New Mexico [Johnson 2017] recorded an annual carbon sequestration rate of 10.7t C/ha/yr from fungal-dominant compost in a 4.5-year trial, and they estimate a potential rate of 19.2t C/ha/yr. Chief investigator David Johnson found that increased plant growth is closely correlated with the fungal to bacterial ratio of the soil. Similarly, Machmuller et al. [2015] measured carbon sequestration rates in the southeastern United States of 8t C/ha/yr following conversion of row crop agriculture to management-intensive grazing, leading to an approximately 75% increase in soil carbon within six years.

The studies showing higher sequestration rates reveal what many farmers already know: that it takes not just one, but multiple regenerative practices, to really build soil organic matter (SOM). California Farmers Paul and Elizabeth Kaiser, for instance, use 5-10 times more compost than average, never till, rotate fields with an extremely diverse mix of vegetable varieties, surround their crops with native trees, shrubs and flowers and have thus built up a thick topsoil containing 10% SOM [Oppenheimer 2015; Kaiser 2017]. North Dakota Farmer Gabe Brown began practicing no-till in 1994. Since then, he has added cover crops (a diverse mix of 70 species), complex crop rotations, orchards, livestock grazing (including cattle, sheep, pork and chicken), vegetable production, and bees. By limiting soil disturbance and favoring biodiversity, Brown reports SOM increased from 1.7% in 1993 to as high as 11% in 2013. Over the same period, rainfall infiltration has increased from ½ inch per hour to more than 15 inches per hour [Brown 2016].

Looking at the big picture, researchers at the Rodale Institute [2014] estimate that if all cropland were converted to a regenerative model, it would sequester 40% of annual CO_2 emissions. Adding regeneratively managed pastures to the picture would add another 71%, effectively exceeding the world's yearly carbon dioxide emissions. Teague et al [2016] came up with similar results, estimating that regenerative conservation cropping and adaptive multi-paddock grazing can turn North American agricultural soils from a carbon source in conventional agriculture into a carbon sink at rate of ~3t C/ha/yr. Key factors include the use of no-till, diversified crop rotation, cover crops, organic soil amendments and reducing use of nitrogen (N) fertilizer.

The billion-dollar question, though, remains: can regenerative agriculture feed the world's ever-expanding population? There is considerable evidence that it can, and in fact the opposite question (can the current model of industrial agriculture feed the world?) deserves at least as much scrutiny, given that so far the answer has been no.

In 2009, a multi-stakeholder team of hundreds of people from every region of the world released the International Assessment of Agricultural Knowledge Science and Technology for Development [IAASTD 2009], which provides a framework for a new global approach to agriculture. It poses the question: how can agricultural knowledge, science and technology (AKST) "be used to reduce hunger and poverty, improve rural livelihoods, and facilitate equitable … sustainable development" [IAASTD 2009: 3] in a global context of mounting social inequity, poverty, human migration, biodiversity loss, and climate change, among other concerns.

Their answer hinges on the concept of multifunctionality of agriculture, or "the challenge … to simultaneously meet development and sustainability goals while increasing agricultural production" [IAASTD 2009: 4]. It calls for a "fundamental shift" in AKST that recognizes "farming communities, farm households, and farmers as producers *and* managers of ecosystems" [IAASTD 2009: 4], and values both scientific research and traditional and local knowledge. With a focus on multifunctionality,

> AKST can contribute to radically improving food security and enhancing the social and economic performance of agricultural systems as a basis for sustainable rural and community livelihoods and wider economic development. It can help to rehabilitate degraded land, reduce environmental and health risks associated with food production and consumption and sustainably increase production [IAASTD 2009: 5].

Thinking of agriculture as multifunctional means valuing agricultural land not only in terms of its capacity for maximum output, but also for its vital role in providing wildlife habitat, sequestering carbon, absorbing and storing rainfall, recycling nutrients, providing for nutritionally balanced diets, and providing the means for an adequate livelihood in farming. And there is abundant evidence that not only do regenerative methods provide these multiple services, they can also be as productive as fossil-fuel-intensive methods, and even more so in times of drought. A 22-year Pennsylvania study [Pimentel 2005] comparing the productivity of conventional versus organic systems showed that while corn yields were comparable overall, during five dry years of the study the organic systems were 28% to 34% more productive than their conventional counterparts.

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Similarly, a nine-year Iowa study [Liebman 2013] comparing corn and soybean yields in 2-year, 3-year, and 4-year rotations resulted in higher yields from the more diverse 3-yr and 4-yr rotation systems than for the conventional 2-yr system, despite substantial reductions in the use of synthetic N fertilizer, herbicides, and fossil-fuel energy in the longer rotations. The longer rotations also incorporated cover crops and manure fertilizer at planting time, as opposed to the 2-year rotation, which incorporated only synthetic fertilizer, and involved no cover cropping.

These results run counter to other studies that have reinforced the belief that industrial agriculture is necessarily more productive. The authors of the Rodale report offer an explanation for this apparent contradiction:

> Meta-analyses of refereed publications show that, on average, organic yields are often lower than conventional. But the yield gap is prevalent when practices used in organic mimic conventional, that is, when the letter of organic standards is followed using an input mentality akin to conventional chemical-intensive agriculture [Rodale 2014: 15].

In other words, a more fundamental commitment to regenerative methods is necessary to bring productivity up to par with that of conventional/industrial methods. Removing the inputs that undergird the success of industrial agriculture will cause the system to falter unless the nutrients and pest resistance provided by those inputs are replaced by that which is proffered through healthy, living soil ecosystems. Indeed, the transition period from industrial system to regenerative system is typically characterized by a drop in yield until the previously damaged soil has come back to life.

Healthy, carbon-rich soil is a powerful engine for plant growth, thanks in large part to the presence of billions of microorganisms working in concert with plants. This includes bacteria living in the roots of leguminous plants that fix plant-available nitrogen, other bacteria defending plants against disease, hyphae-forming fungi attaching to the end of roots and effectively extending those roots deeper into the soil to retrieve micro-nutrients. There are fungi that mine otherwise unavailable soil phosphorus and deliver it to plants, and fungi that help to build the structure of the soil by binding clumps of soil together in aggregates. This aggregation, in turn, facilitates soil aeration and water-holding capacity, while also holding soil organic carbon in place.

It is ironic that in the process of delivering synthetic inputs to feed plants and prevent disease, industrial methods destroy the microorganisms and soil structure that would otherwise serve these purposes. However, for soil to perform these functions in the context of agricultural production requires thoughtful management aiming to protect soil and recycle nutrients. Harvesting a crop removes nutrients from a system, which then need to be replaced. In a wild ecosystem, nutrients consumed are generally replaced by plant litter and animal waste. Nutrients are also made available to plants in healthy, undisturbed soils, by microbial action on mineral particles and rocks. Regenerative agricultural systems mimic this nutrient cycling through compost and manure application, cover cropping, and no-till (which protects the soil, allowing microorganisms to flourish). Moreover, regenerative agriculture mimics wild systems by striving for biodiversity, which improves the stability and productivity of ecosystems.

Also challenging is the fact that a majority of researchers demonstrating climate mitigation through better agricultural conservation practices (Minasny 2017, Zomer 2017, Grimson 2017, Lal 2016, Smith 2008, West & Post 2002, for example) stop short of considering carbon sequestration from a full suite of conservation practices representing a more fundamental commitment to regenerative agriculture. Making only minimal conservation improvements while maintaining the same industrial system tends to result not only in minimal sequestration outcomes, but also lower yields. As noted above, this in-between approach to agriculture risks sacrificing the strengths tendered by a full suite of practices, whether from the industrial or the ecological model.

Murmurings from every corner of the globe reveal that many already acknowledge the imperative, especially for wealthy countries, to radically change our way of living, including the design of our agricultural systems. The vision for societal change varies from cutting fossil fuel emissions to zero within a decade; to building a commons-oriented de-growth economy that values life and sharing over the hoarding of material wealth; to transitioning to a community-based, equitable, agro-ecological food-system.

Specifically responding to the question of how to feed more people with less, like a riddle from the Sphinx, requires thinking outside the box and acknowledging our imperative to radically change ourselves. It's not enough simply to improve the current industrial agricultural model if, at best, that merely slows progress toward climate tipping points (when the positive feedback loops accelerate global warming beyond our control). Tweaking the current system with small improvements toward inadequate goals is what Margaret Klein Salamon calls "climate gradualism." For all its political practicality, this approach is like putting a band-aid on a severed limb, and is irrational from the perspective of preserving human civilization in the face of climate breakdown.

In our technophilic society, it may come as a surprise that building biologically active, carbon-rich soil is the answer both to the climate crisis and to the question of how to feed more with less. While protecting and rehabilitating wild ecosystems are also essential, rebuilding the soil in agricultural lands through a regenerative, multifunctional approach is arguably the key to protecting human civilization.

In our technophilic society, it may come as a surprise that building biologically active, carbon-rich soil is the answer both to the climate crisis and to the question of how to feed more with less.

The articles that follow are a small sampling of many recent studies examining various aspects of agricultural ecosystems and food production in the face of climate breakdown. Each provides a glimpse into the range and depth of nature-based tools at our fingertips to transform agriculture into a wellspring of planetary resilience.

Compilation of agriculture articles

Natural climate solutions, Griscom 2017

This is one of the most comprehensive mainstream studies to date of a broad spectrum of natural climate solutions by thirty-two co-authors and supported by The Nature Conservancy. The report examines "20 conservation, restoration, and/or improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands." The authors "find that the maximum potential of NCS [Natural Climate Solutions] —when constrained by food security, fiber security, and biodiversity conservation—is 23.8 petagrams[11] of CO2 equivalent . . . This is ≥30% higher than prior estimates, which did not include the full range of options and safeguards considered here." [Griscom 2017: 11645]. The study seeks to assess both the potential emissions from land use as well as the carbon-sequestration potential.

The study posits a target of <2° C as the conventionally agreed-upon safe limit:

> Warming will likely be held to below 2 °C if natural pathways are implemented at cost-effective levels . . . and if we avoid increases in fossil fuel emissions for 10 y and then drive them down to 7% of current levels by 2050 and then to zero by 2095 [p. 11647]

The authors state that their estimates are intentionally conservative because (1) they do not include potential benefits of payments for high-money-value ecosystem services in stimulating NCS efforts; (2) they exclude various management practices where data were not "sufficiently robust for global extrapolation," e.g., no-till, adaptive multi-paddock grazing, etc.; and (3) significant additional investment would be required to keep warming at 1.5° C. [Griscom 2017: 11648]

[11] I.e., 23 Gigatons. 1 petagram = 1 billion tons (gigaton, Gt). 23.8 Gt of CO_2 is the equivalent of 6.5 Gt C, or ~3.25 parts per million (ppm) of atmospheric carbon.

Detail is provided on contributions of specific mitigation pathways, such as forests, wetlands, grasslands, etc., and on challenges as well. For example, “Despite the large potential of NCS, land-based sequestration efforts receive only about 2.5% of climate mitigation dollars.” [Griscom 2017: 11648] This observation is consistent with our observations of limited available resources for the most basic NCS education. Other challenges include deforestation for farming and animal husbandry, losing high carbon sequestration benefits of wetlands due to reclamation, and impacts of climate feedbacks such as fire, drought, temperature increases, etc.

We applaud Griscom et al. for an excellent and comprehensive analysis and review of many of the factors in natural climate solutions. We do, however, believe that (1) the potential of nature’s solutions is far greater than Griscom et al. estimate, and (2) that the temperature limits (1.5^{o} - 2^{o} C) are too high and too dangerous - considering that natural processes are already changing, drastically and for the worse, with an average global temperature increase of barely 1^{o} C (see Appendix A: Urgency of the Biodiversity and Climate Crisis).

The differences between the perspectives of Griscom et al. and those adopted in this Compendium are paradigmatic. Griscom et al. acknowledges that their estimates are conservative, looks at a set of studies that tends toward the mainstream and is primarily based on established and widespread practice. This is perfectly reasonable in the process of what Thomas Kuhn calls “normal science” (see Compendium Vol. 1 No. 1 for an extensive discussion of Kuhn’s landmark work). Unfortunately the process of normal science for accepting new thinking and discoveries usually takes decades, and we are currently in the throes of an extinction, and an emergency with respect to biodiversity, and climate change. Therefore we have to accelerate our response. Accordingly, Bio4Climate searches for studies that tend to examine *positive variants*, i.e., examples of what is possible beyond current conceptual boundaries. We emphasize goals to strive for, even if the data are not yet “sufficiently robust for global extrapolation.” The robustness of such data will increase with more intentional focus.

An interesting side effect of the paradigm difference is that numerous sources that we cite, many from the scientific literature, don’t appear in NCS references (for example, Richard Teague [Teague et al. 2016], Gabe Brown [Brown 2016], Tom Goreau [Goreau 2015], Rebecca Ryals and Whendee Silver [Ryals and Silver 2013], David Johnson [Johnson 2017], Paul and Elizabeth Kaiser [Kaiser 2017], Terry McCosker [McCosker 2000], Carol Evans and Jon Griggs [Evans et al., 2015], to name just a few). Nor are there discussions of permaculture or agroforestry, two of the more promising areas of research and practice in land management that lead to climate-positive results.

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Drawdown, Hawken, ed. 2017

Edited by innovator and entrepreneur Paul Hawken, *Drawdown* is a remarkable and comprehensive work presenting eighty well-vetted solutions and twenty promising "coming attractions" to remove carbon from the atmosphere and restore planetary health. Hawken engaged numerous scientists, modellers, advisers, artists and writers, resulting in a beautifully illustrated and comprehensive exploration of possibilities for reversing global warming.

The impact of the book as a whole is as important as each solution: *Drawdown* presents a universe of actions that go far beyond what we can imagine if we consider only emissions reductions and alternative energy. It leads to an entirely different climate conversation from the one we're used to, and offers many threads of hope.

Drawdown has something for everyone, covering sectors of Energy, Food, Buildings and Cities, Land Use, Transport, and Materials. Near the top of the list is Women and Girls, whose education has dramatic effects on population and is one of the most important climate positive steps we can take. Of course technology offerings abound, but they are amply balanced by discussions of biology and social change, often sorely missing in debates on global warming. Of particular interest in this Compendium are biological strategies; we'll mention just three of them here.

Agroforestry in Burkina Faso

> After terrible droughts in the 1980s resulted in a 20% reduction in rainfall and millions of deaths by starvation, farmer Yacouba Sawadogo enhanced a traditional practice of digging rain-capturing pits by adding manure. There were seeds in the manure and as a result trees began to grow, holding soils together with roots, protecting plantings from wind gusts that before had required frequent re-sowing, and opening channels that

moved water into the soils and raised water tables. This foray into agro-forestry spread across the rural countryside to widespread beneficial effect.

Of great significance is that the expertise, invention and community organizing were native and local, required no foreign aid or expensive soil inputs, and in terms of money cost nothing. This is what sustainability can look like. [Hawken 2017: 118-120]

Pasture Cropping

In 1979, after a devastating fire destroyed his two-thousand acre farm in Australia, Colin Seis began to question why crops and animals couldn't be profitably raised on the same land, effectively doubling output. Persisting through a difficult transition, Seis saw water retention improvements, decreased input costs, a virtual end to insect infestation, and measures of soil fertility and carbon content go up along with profits. Today, pasture cropping is practiced on over two thousand Australian farms and is spreading throughout the world. [Hawken 2017: 175]

Intensive Silvopasture

Silvopasture, the most common form of agroforestry, is the practice of combining trees and woody shrubs with pasture grasses. The result is healthier plant and animal growth, including sequestering a respectable one to four tons of carbon per acre. It is currently practiced on over one billion acres worldwide.

For remarkable next steps enter the *intensive* part of silvopasture, starting with a quickly growing, edible leguminous shrub, *Leucaena leucocephala* in Australia and Latin America (different species of shrubs are suitable in different ecosystems). Water retention improves, biomass increases, species biodiversity doubles, animal stocking rates almost triple, ambient temperatures decrease by 14 to 23 degrees F in the tropics, meat production increases by a factor of 4 to 10, and perhaps most strikingly, soil carbon sequestration rates have exceeded 10 tons per acre (conventional agriculture can claim 1 ton of carbon per acre or less, or even net carbon loss to the atmosphere). [Hawken 2017: 181]

Intertidal resource use over millennia enhances forest productivity, Trant 2016

Abstract: Human occupation is usually associated with degraded landscapes but 13,000 years of repeated occupation by British Columbia's coastal First Nations has had the opposite effect, enhancing temperate rainforest productivity. This is particularly the case over the last 6,000 years when intensified intertidal shellfish usage resulted in the accumulation of substantial shell middens. We show that soils at habitation sites are higher in calcium and phosphorous. Both of these are limiting factors in coastal temperate rainforests. Western red cedar (Thuja plicata) trees growing on the middens were found to be taller, have higher wood calcium, greater radial growth and exhibit less top die-back. Coastal British Columbia is the first known example of long-term intertidal

> resource use enhancing forest productivity and we expect this pattern to occur at archaeological sites along coastlines globally [Trant 2016: 1].

Although focused on forests and not farmland, this study shows that, as in the Amazon, where indigenous people created SOM-rich terra preta soil (akin to biochar-enhanced soil), human populations can increase soil quality and ecosystem productivity beyond what the potential would have been absent human activity.

This is an interesting point with respect to global potential for soil carbon sequestration. Scientists often refer to an equilibrium point, up to which soils can regain carbon previously lost through exploitive human activity. Equilibrium is generally seen as being the point at which new SOC levels are equivalent to or somewhat less than what they were prior to human exploitation of the soil, and never greater than the original amount. While Trant et al. [2016] have found evidence of calcium and phosphorus (not carbon) enrichment due to human activity, their findings raise questions about the extent to which intentionally building soils through all the methods we know to maximize carbon storage could increase various soils' presumed equilibrium points.

> ***Human occupation is usually associated with degraded landscapes but 13,000 years of repeated occupation by British Columbia's coastal First Nations has had the opposite effect, enhancing temperate rainforest productivity*** **[Trant 2016: 1].**

The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls, Jackson 2017

This review examines "the state of knowledge for the stocks of, inputs to, and outputs from SOM around the world" [Jackson 2017: 422], with a view toward developing better understanding of processes that stabilize SOM. It explains the biological processes involved in carbon cycling and storage, finding that "root inputs are approximately five times more likely than an equivalent mass of aboveground litter to be stabilized as SOM" [Jackson 2017: 420]. Litter input can either increase or decrease SOM, despite the assumption in most carbon models that there is a linear relationship between litter input and transformation of carbon into more stable forms. This finding suggests that perennials and other deep-rooting plants have an important role to play with respect to carbon sequestration. As the author puts it:

> Managing carbon inputs and relative allocation, for instance, through selection for deep roots or for greater belowground allocation in crops (Kell 2011), has been suggested as a way to increase SOM formation and stabilization in such systems (Bolinder et al. 2007, Eclesia et al. 2016). However, plant breeding has traditionally selected for aboveground

yields alone; therefore, potential trade-offs between yield and root production must be carefully evaluated (DeHaan et al. 2005). New tools for monitoring root systems and in situ SOM in the field are needed (Molon et al. 2017) [Jackson 2017: 422]. . . .

The importance of root inputs for SOM formation is likely attributable to both their chemical composition and, almost certainly, their presence in the soil; upon death, they immediately interact with soil minerals, microbes, and aggregates. Roots tend to be characterized more by aliphatic compounds that are readily sorbed to mineral surfaces, and their composition (and that of root exudates) can increase microbial carbon use efficiency (CUE), defined as the ratio of microbial growth to carbon uptake, more than litter can. High CUE promotes microbial growth and carbon stabilization in mineral-associated soil pools, and low CUE favors biomass respiration (Manzonietal.2012a) [Jackson 2017: 423]. . . .

Soils hold the largest biogeochemically active terrestrial carbon pool on Earth and are critical for stabilizing atmospheric CO2 concentrations. Nonetheless, global pressures on soils continue from changes in land management, including the need for increasing bioenergy and food production [Jackson 2017: 420].

> . . . ***plant breeding has traditionally selected for aboveground yields alone; therefore, potential trade-offs between yield and root production must be carefully evaluated*** **[Jackson 2017].**

National comparison of the total and sequestered organic matter contents of conventional and organic farm soils, Ghabbour 2017

An analysis of hundreds of soil samples collected from organic and conventional farms around the US shows higher average percentages both of total SOM and of humic substances - a measure of carbon sequestration - for organic farm soils compared to conventional farm soils. The mean percent humification (humic substances divided by total SOM) for organic soils is 57.3%, compared to 45.6% for conventional soils.

Agroforestry strategies to sequester carbon in temperate North America, Udawatta & Jose 2012

This meta-analysis estimates total carbon sequestration potential in the US from various agroforestry practices to be 530 TgC/year (530 million metric tons), equivalent to about 1/3 of annual US carbon emissions from fossil fuel combustion. Based on their literature review, the authors estimate per-hectare sequestration rates (based on aboveground and belowground carbon accumulation) for each practice as follows: 6.1t C/ha/yr (silvopastoral), 3.4t C/ha/yr (alleycropping), 6.4t C/ha/yr (windbreaks), 2.6t C/ha/yr (riparian buffer).

Compost, manure and synthetic fertilizer influences crop yields, soil properties, nitrate leaching and crop nutrient content, Hepperly 2009

A sequestration rate of 2.363t C/ha/yr was demonstrated where compost made of dairy manure and leaves was applied to fields in a three year rotation of corn-vegetable-small grain, with leguminous cover crops. The same rotation treated with chemical fertilizer instead of compost resulted in a net loss of -0.317t C/ha/yr.

Legume-based cropping systems have reduced carbon and nitrogen losses, Drinkwater 1998

This study compared three corn-soybean cropping systems: (1) conventional 2-yr rotation with chemical inputs, and residues returned to soil; (2) a longer (than 2 years), organic rotation with grass/legume hayed and returned to soil in manure; and (3) a longer (than 2 years) organic rotation with grass/legume turned back into the soil directly. Even though the conventional system returned more total residue to the soil, carbon sequestration was significantly lower for the conventional system than for the two organic, legume-based systems. Authors suggest that this is due to greater temporal plant diversity from the longer rotations, and higher quality residue (greater N:C) in the two legume-based organic systems. Furthermore, CO_2 emissions were lower in the legume-based organic systems due to 50% lower energy use.

Even though the conventional system returned more total residue to the soil, carbon sequestration was significantly lower for the conventional system than for the two organic, legume-based systems. Authors suggest that this is due to greater temporal plant diversity from the longer rotations, and higher quality residue (greater N:C) in the two legume-based organic systems. [Drinkwater]

Appendix A: The urgency of the climate crisis

Global Warming has been a message of warning since climate research and discussions began roughly two hundred years ago in western science. Today, the predominance of the future tense in the climate dialogue has set the tone and expectations that however many times the "window of opportunity" for meaningful climate action were to close, it would surely open again. Casting targets in the seemingly distant future such as 2050 (more seemingly distant in 1992 than today), provided a psychological cushion that eased us into a dreamlike state where even repeatedly failed international negotiations still left time for reprieve and salvation.

Biodiversity for a Livable Climate has, to a certain extent, been complicit in this silence-in-urgency. There has been so much fear, confusion and denial of climate reality that we as an organization wanted to calm the conversation over the past three years to provide a safer place, a place of openness to new perspectives, to consider alternatives that most people hadn't yet addressed nor imagined.

On the one hand, we feel that this strategy has shown some success. By emphasizing the positive, particularly amidst the frenzy induced by the 2016 election cycle, we have continued to introduce biodiversity and eco-restoration strategies to thousands of people, provided many examples of positive action, and helped build support for regenerative land management on many millions of acres. There is a palpable difference in the conversation and research today than there was only two years ago, and we should all celebrate that (and that's part of the purpose of this compendium).

On the other hand, the positive feedback loops in climate,[12] as witnessed by the dramatic accelerations of weather crises, and many other environmental degradations such as extinctions (including unprecedented disappearance of insects), species migrations, plankton loss, and disrupted lifecycle timing, raise the urgency to such a level of alarm that even wanting to focus on the positive developments must make room for acknowledging our current dire situation.

Over the past thirty years, if we communicators of catastrophe have learned anything, it's that it's both extremely difficult *and* delicate to scare people into positive action. At the outset of the climate endeavor the assumption was that if we just give people the facts, we would all pretty much line up in a march of rational behavior.

As it turns out, in some senses the least of our problems with eco-collapse is the eco-collapse itself. The primary problem has been human psychology and culture, particularly the culture of civilizations, which relies on overshoot and inevitable collapse. We have met the enemy, and more truly than perhaps even Walt Kelly and the organizers of Earth Day 1970 realized, the enemy is deeply us [Kelly 1970].

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[12] A positive feedback loop is a process that, once initiated, sustains and amplifies itself. For example, Arctic summer ice melting due to warmer global temperatures exposes dark water to sunlight, which warms the water further thereby melting more ice, until eventually all the summer ice is gone. The result is a profound disruption of global weather patterns.

While there are likely already some very unpleasant surprises in the pipeline, and outcomes are by no means certain, there is good news as well: the urgency is addressable. The tectonic level of destruction that we've set up in but a blink of geological time is reversible. The solutions are largely already known. What we're struggling with is the psyche of that most puzzling of species, *homo sapiens*.

At this point, therefore, it behooves us to briefly outline the current urgency to paint what we hope is a clearer picture, based on a realistic foundation that rejects wishful thinking in favor of action moving forward.

Again, there is some good news: the *zeitgeist*, the spirit of the times which emerges from the sum total of human culture and the planetary context in which it must function, is finally setting a determined course towards a global systems approach. The *zeitgeist* has, in the nick of time, begun to address root causes of ecosystem collapse and not just obvious symptoms, as painful as they are. Symptoms are as varied as Nature itself, but root causes - anthropogenic degradation and desertification of the biosphere - are surprisingly straightforward.

We can solve this, and indeed, as we put our dominance of Nature behind us we already are. Nature will be happy to collaborate if only we were to pledge our allegiance to a few immutable laws of biology established over billions of years: repeal just isn't in the cards. That's the heart of what this Compendium is about. The time is short, the burdens daunting, but for the sake of preserving and protecting life on Earth we have little choice.

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In 1958 Charles Keeling began recording the now-classic curve of carbon dioxide concentrations at the Scripps Mauna Loa Observatory in Hawaii (the sawtooth annual variations of 6-8 ppm are a result of increased uptake of CO_2 during the summer growing season in the Northern Hemisphere followed by the release of CO_2 during the winter).

In that same year, Oscar-winning director Frank Capra released a film on the weather for the Bell Laboratory Science Series. Towards the end of the film there is a brief dramatic clip of global warming, collapsing ice and belching industry, indicating that we had a surprisingly good idea of what climate effects were about in 1958. It is well worth a look, both for the climate observations and the sense of the scientific over-confidence of the post-atomic age (start at around 47:50 of the full version). [Bell Labs 1958]

The sense of climate urgency in 1958, however, subsumed in the enthusiasm over the aspirations of science and overshadowed by the anxiety of the cold war, was understandably remote.

Fast forward to 1988 and James Hansen's testimony before Congress. As reported in the New York Times,

> If the current pace of the buildup of these gases continues, the effect is likely to be a warming of 3 to 9 degrees Fahrenheit from the year 2025 to 2050, according to these projections. This rise in temperature is not expected to be uniform around the globe but

to be greater in the higher latitudes, reaching as much as 20 degrees, and lower at the Equator.

The rise in global temperature is predicted to cause a thermal expansion of the oceans and to melt glaciers and polar ice, thus causing sea levels to rise by one to four feet by the middle of the next century. Scientists have already detected a slight rise in sea levels. At the same time, heat would cause inland waters to evaporate more rapidly, thus lowering the level of bodies of water such as the Great Lakes. [http://www.nytimes.com/1988/06/24/us/global-warming-has-begun-expert-tells-senate.html?pagewanted=all]

These predictions, using basic data and newly evolving models, were stark, even from today's perspective. Hansen and others initiated the beginnings of a global emergency mindset. But despite leading to a series of international conferences and treaties, they were caught in a mire of political and economic resistance that has thus far proved an almost immovable force. While progress has been made on many fronts in the efforts to address greenhouse gases, none has yet yielded differences which will change the course of climate events. That will require a systems approach to the natural world that is only now in the process of coming to fruition, and which is the topic of this Compendium.

Hansen has gone on to become one of the most powerful and courageous voices in the mainstream climate science arena, stepping beyond his role as scientist and into the public and political arenas. He has given measured but insistent voice to the current urgency:

Global temperature is a fundamental climate metric highly correlated with sea level, which implies that keeping shorelines near their present location requires keeping global temperature within or close to its preindustrial Holocene range. However, global temperature excluding short-term variability now exceeds 1° C relative to the 1880–1920 mean and annual 2016 global temperature was almost 1.3° C. We show that global temperature has risen well out of the Holocene range and Earth is now as warm as it was during the prior (Eemian) interglacial period, when sea level reached 6–9m higher than today. Further, Earth is out of energy balance with present atmospheric composition, implying that more warming is in the pipeline, and we show that the growth rate of greenhouse gas climate forcing has accelerated markedly in the past decade. The rapidity of ice sheet and sea level response to global temperature is difficult to predict, but is dependent on the magnitude of warming. Targets for limiting global warming thus, at minimum, should aim to avoid leaving global temperature at Eemian or higher levels for centuries. Such targets now require "negative emissions", i.e., extraction of CO_2 from the air. If phasedown of fossil fuel emissions begins soon, improved agricultural and forestry practices, including reforestation and steps to improve soil fertility and increase its carbon content, may provide much of the necessary CO_2 extraction. In that case, the magnitude and duration of global temperature excursion above the natural range of the current interglacial (Holocene) could be limited and irreversible climate impacts could be minimized. In contrast, continued high fossil fuel emissions today place a burden on young people to undertake massive technological CO_2 extraction if they are to limit climate change and its consequences. Proposed methods of extraction such as bioenergy with carbon capture and storage (BECCS) or

> air capture of CO_2 have minimal requirement of negative CO_2 emissions estimated costs of USD 89–535 trillion this century and also have large risks and uncertain feasibility. Continued high fossil fuel emissions unarguably sentences young people to either a massive, implausible cleanup or growing deleterious climate impacts or both. [Hansen et al., 2017]

A dire picture indeed.

Notwithstanding Hansen's steady voice, there are reasons for more urgent statements still. Positive feedbacks, i.e., climate accelerations, are asserting prominence, particularly in the striking accumulations of high temperature records and unprecedented weather calamities occurring during 2017.

On July 19, 2012, popular climate author Bill McKibben wrote "Global Warming's Terrifying New Math: Three simple numbers that add up to global catastrophe - and that make clear who the real enemy is." [McKibben 2012] The real enemy according to McKibben is the purveyors of fossil fuels.

McKibben puts forth what he calls three terrifying numbers:

> 2 degrees C, a dubious safe limit
>
> 565 Gt, the maximum additional carbon by mid-century to keep within that safe limit
>
> 2,795 Gt, the carbon in already-proven coal, gas and oil reserves

Given the rate at which we were burning fossil fuels, the math doesn't offer a good prognosis, and McKibben concludes that, "So far, as I said at the start, environmental efforts to tackle global warming have failed." [McKibben 2012]

Over five years later on December 1, 2017, McKibben wrote "Winning Slowly Is the Same as Losing: The technology exists to combat climate change – what will it take to get our leaders to act?" [McKibben 2017] His sense of alarm is clear:

> If we don't win very quickly on climate change, then we will never win. That's the core truth about global warming. It's what makes it different from every other problem our political systems have faced. . . . It won't stand still.

McKibben is also sensible with respect to his perspective on Donald Trump's administration, i.e., that we were failing on climate long before the new president arrived, with the possible implication that we may even be avoiding our own failures by obsessing with his:

> [W]e weren't moving fast enough to catch up with physics before Trump. In fact, it's even possible that Trump – by jumping the climate shark so spectacularly – may run some small risk of disrupting the fossil-fuel industry's careful strategy.

While McKibben hails the ongoing progress in opposing the fossil fuels industry, the urgency of the timing and limited effectiveness of the actions weighs heavily upon him:

> At 350.org, we're rolling out a vast Fossil Free campaign across the globe this winter, joining organizations like the Sierra Club to pressure governments to sign up for 100 percent renewable energy, blocking new pipelines and frack wells as fast as the industry can propose them, and calling out the banks and hedge funds that underwrite the past. It's working – just in the last few weeks Norway's sovereign wealth fund, the largest in the world, announced plans to divest from fossil fuels, and the Nebraska Public Service Commission threw yet more roadblocks in front of the Keystone pipeline.
>
> But the question is, is it working fast enough? Paraphrasing the great abolitionist leader Theodore Parker, Martin Luther King Jr. used to regularly end his speeches with the phrase "the arc of the moral universe is long but it bends toward justice." The line was a favorite of Obama's too, and for all three men it meant the same thing: "This may take a while, but we're going to win." For most political fights, it is the simultaneously frustrating and inspiring truth. But not for climate change. The arc of the physical universe appears to be short, and it bends toward heat. Win soon or suffer the consequences.

From Bio4Climate's perspective, McKibben's frank assessment and even despair are laudable. Admitting failure is an opening to new solutions. What is discouraging is his reluctance to at least consider the full potential of eco-restoration to overcome both geophysical and political obstacles to positive action on multiple pressing environmental issues, including climate.[13]

On June 20, 2017 an Australian organization, Breakthrough [Breakthrough 2017],[14] produced a no-nonsense report entitled *Disaster Alley: Climate Change, Conflict & Risk*.[15] Among its blunt points:

- From tropical coral reefs to the polar ice sheets, global warming is already dangerous. The world is perilously close to, or passed, tipping points which will create major changes in global climate systems.
- The world now faces existential climate-change risks which may result in "outright chaos" and an end to human civilisation as we know it.
- These risks are either not understood or wilfully ignored across the public and private sectors, with very few exceptions.
- Global warming will drive increasingly severe humanitarian crises, forced migration, political instability and conflict. The Asia–Pacific region, including Australia, is considered to be "Disaster Alley" where some of the worst impacts will be experienced.

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[13] There have been times when McKibben has spoken about the potential of eco-restoration (see Only Way to Have a Cow [https://orionmagazine.org/article/the-only-way-to-have-a-cow/] and his signing onto a *Rutland Herald* article in 2017 [http://www.rutlandherald.com/articles/using-soil-to-fight-climate-change/]), but strangely these are exceptions that have had no apparent effect on the course of his activism, or that of 350.org.
[14] The National Centre for Climate Restoration (Breakthrough) is an independent think tank that develops critical thought leadership to influence the national climate debate and policy making, https://www.breakthroughonline.org.au/about.
[15] https://www.breakthroughonline.org.au/disasteralley

- Building more resilient communities in the most vulnerable nations by high-level financial commitments and development assistance can help protect peoples in climate hotspots and zones of potential instability and conflict.

- Australia's political, bureaucratic and corporate leaders are abrogating their fiduciary responsibilities to safeguard the people and their future well-being. They are ill-prepared for the real risks of climate change at home and in the region.

- The Australian government must ensure Australian Defence Force and emergency services preparedness, mission and operational resilience, and capacity for humanitarian aid and disaster relief, across the full range of projected climate change scenarios.

- It is essential to now strongly advocate a global climate emergency response, and to build a national leadership group outside conventional politics to design and implement emergency decarbonisation of the Australian economy. This would adopt all available safe solutions using sound, existential risk-management practices.

While *Disaster Alley* is primarily concerned with the Asia-Pacific region, the issues are clearly global. Following closely on *Disaster Alley*, on September 6, 2017, Breakthrough published *What Lies Beneath: The Scientific Understatement of Climate Risks* [Breakthrough 2017b], which further emphasized the chronic underestimation of climate risk in mainstream science, *and the risks posed by poor risk analysis itself,* which is a chronic condition in much of mainstream climate science.

> It is now clear that climate change is an existential risk to human civilisation: that is, an adverse outcome that would either annihilate intelligent life or permanently and drastically curtail its potential. Temperature rises that are now in prospect, even after the Paris Agreement, are in the range of 3–5°C. The Paris Agreement voluntary emission reduction commitments, if implemented, would result in the planet warming by 3°C, without taking into account "long-term" carbon-cycle feedbacks. With a higher climate sensitivity figure of 4.5°C, for example, which would account for such feedbacks, the Paris path would lead to around 5°C of warming, according to a MIT study. A study by Schroder Investment Management published in June 2017 found — after taking into account indicators across a wide range of the political, financial, energy and regulatory sectors — the average temperature increase implied across all sectors was 4.1°C.
>
> Warming of 4°C or more could reduce the global human population by 80% or 90%, and the World Bank reports "there is no certainty that adaptation to a 4°C world is possible." A study by two US national security think tanks concluded that 3°C of warming and a 0.5 metre sea-level rise would likely lead to "outright chaos". A recent study by the European Commission's Joint Research Centre found that if global temperatures rise 4°C, then extreme heatwaves with "apparent temperatures" peaking at over 55°C (131° F) will begin to regularly affect many densely populated parts of the world. At 55°C or so, much activity in the modern industrial world would have to stop. ("Apparent temperatures" refers to the Heat Index, which quantifies the combined effect of heat and humidity to provide people with a means of avoiding dangerous conditions.) [p. 9]

Finally, on July 9, 2017, a climate reality bludgeon reached the American (and global) public with the publication of "Uninhabitable Earth" in *New York Magazine*.[16] More widely read by far than any of the other references here, author David Wallace-Wells interviewed numerous climate scientists about bad- and worst-case scenarios.

> It is, I promise, worse than you think. If your anxiety about global warming is dominated by fears of sea-level rise, you are barely scratching the surface of what terrors are possible, even within the lifetime of a teenager today. And yet the swelling seas — and the cities they will drown — have so dominated the picture of global warming, and so overwhelmed our capacity for climate panic, that they have occluded our perception of other threats, many much closer at hand. Rising oceans are bad, in fact very bad; but fleeing the coastline will not be enough.
>
> Indeed, absent a significant adjustment to how billions of humans conduct their lives, parts of the Earth will likely become close to uninhabitable, and other parts horrifically inhospitable, as soon as the end of this century.

Wallace-Wells digs wider and deeper, and while many climate scientists objected to at least some of his inferences and logic, overall he's on solid ground. It is, after all, the ground that these scientists helped prepare - and all in all, they did their jobs well.

To this sad litany we would only add that the most terrible, excruciating lethal strokes that we face from climate catastrophe are more likely the whimper than the bang. While sea-level rise, hurricanes and fires are dramatic, the primary cause of death for billions of people will be no food and no water.[17]

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[16] http://nymag.com/daily/intelligencer/2017/07/climate-change-earth-too-hot-for-humans-annotated.html

[17] See, for example, "'We fight with each other over water': rivers run dry in Mozambique – in pictures," *The Guardian*, Jan 24, 2018, https://www.theguardian.com/global-development/2018/jan/24/no-privacy-school-respite-mozambique-water-crisis

Appendix B: A systems approach to climate change

"The world is divided politically, but ecologically it is tightly interwoven." - Carl Sagan, 1980, *Cosmos*

The magnitude of troubles ailing humanity is dizzying, if not terrifying - any 10 minutes of exposure to the daily news can attest to this. It's hard to untangle the problems from each other, or to connect causes to effects, let alone to identify solutions that will work. That may well be because we tend to focus on symptoms rather than root causes. Wealth inequality, climate change and perpetual war are not inevitable conditions, but they are natural outcomes of the systems that produce them. With this in mind, here we explore solutions to the climate crisis from a systems perspective, meaning we seek to understand what complex systems are, how they work, and then to place what we observe of the world into this context.

Complex systems exist and behave the way they do based on the relationships among their component parts, as well as their interactions with other overlapping systems and subsystems. The Earth system is made up of a few major sub-systems: atmosphere, biosphere, hydrosphere, lithosphere, and human socio-economic systems [Donner 2009], within which countless other systems operate and interact. Elements, like carbon, cycle through systems as inputs and outputs, connecting systems to each other, and also collecting in various stocks, depending on rates of input and output.

> Ecosystems, and indeed the global biosphere, are prototypical examples of *complex adaptive systems*, in which macroscopic system properties such as trophic structure, diversity–productivity relationships, and patterns of nutrient flux emerge from interactions among components, and may feed back to influence the subsequent development of those interactions [Levin 1998:431].

In other words, every system is greater than the sum of its parts. This is due to the relationships among parts giving rise to distinct patterns of behavior expressed by the system itself, often referred to as emergent properties, which in turn affect component parts. The human body is an example of a complex system, where all the organs working together give life to a person, and the behavior or the person affects the health of her organs. At the same time, individuals influence larger complex systems of which we are a part, such as our labor and spending in an economy; we are in turn influenced by economic volatility.

To understand global warming in the context of the Earth system, then, is to focus on how many components of the system interact to produce this outcome. It is to understand not only that greenhouse gas emissions trap heat in the atmosphere, but also that vegetation cools the Earth through evapotranspiration thereby generating rainfall that would otherwise be absent, while also drawing carbon out of the atmosphere. It is to further understand that vegetation is better protected and more productive in the presence of a greater degree of biodiversity. It is to accept and appreciate the vast complexity of billions of simultaneous processes that cannot be fully controlled, and yet also to recognize the larger patterns that restore balance to the systems sustaining all life. And it is to more fully account for how human systems interact with the other Earth systems.

As many studies in this Compendium show, Earth abounds with connections and causes that may surprise us. For instance, groundwater depletion is a source of CO_2 emissions [Wood 2017], mushrooms cause rain [Hassett 2015], termite mounds mitigate drought effects [Bonachela 2017], and the Earth's vast biosphere evolved into being thanks to a fungi-plant partnership [Mills 2017]. Understanding the planet as a complex system, encompassing myriad living and non-living subsystems, opens up our awareness to the interdependence among seemingly unrelated things and processes, and to the possibility of indirect effects and unintended consequences.

A systems framework also helps us understand the urgency of the crisis, given dynamics of complex systems that can lead to abrupt, transformational changes in the system. For instance, there are often time and space lags between cause and effect, as well as indirect effects, obscuring our awareness of the causes and consequences of our actions. Each time we drive a car, for example, we contribute to air pollution, acid rain, and climate change, however slightly. Yet, in the moment of driving, we are spared any immediately perceptible evidence of these effects. "With respect to climate change, greenhouse gases have accumulated in piecemeal fashion, with each car, cow, power plant, etc., having a minor effect. However, combining these small-scale impacts, through space and time, has manifested in large-scale effects that affect the entire planet" [Ingwersen 2013:4]

In addition, complex systems are influenced by positive or negative feedback loops, which either amplify a change or control it, respectively. Due at least in part to positive feedback mechanisms, complex systems exhibit nonlinear responses, meaning "that a very small change in some parameters can cause great qualitative differences in the resulting behavior", as opposed to "the response of a linear system to small changes in its parameters or to changes in external forcing," which "is usually smooth and proportionate to the stimulation" [Rial 2004:12].

Nonlinear behavior is triggered when the trajectory of a gradual change crosses a "tipping point," or threshold, beyond which the system no longer maintains its equilibrium, and it changes abruptly into a new state. It's akin to the age-old expression, "the straw that broke the camel's back" - in other words, though increasingly strained the camel bore the weight of more and more straw, but only up to a point. An example of nonlinear change is the Arctic Sea, which hasn't been ice free for more than 100,000 years but is now declining by 13.2% per decade [NASA] and could lose its summer ice entirely within a matter of years.

Understanding the climate crisis as a symptom of the global destruction of multiple interacting earth systems, rather than simply as the result of a buildup of greenhouse gases, leads us to different solutions. As Rockstrom et al [2009] suggest, in the interest of preserving the stable Holocene climate system we have known since before the dawn of agriculture, humanity's response to climate change must account for multiple Earth system thresholds that are not to be crossed. "Since the industrial revolution (the advent of the Anthropocene), humans are effectively pushing the planet outside the Holocene range of variability for many key Earth System processes [Steffen et al. 2004].

Without such pressures, the Holocene state may be maintained for thousands of years into the future" [Rockstrom 2009:2]. The authors identify several other Earth system processes, including: ocean acidification, ozone depletion, aerosol loading, biodiversity loss, land-use change, nutrient and chemical pollution, and freshwater use, where "transgressing one or more planetary boundaries may be deleterious or even catastrophic due to the risk of crossing thresholds that will trigger non-linear, abrupt environmental change within continental- to planetary-scale systems" [Rockstrom 2009:1].

In other words, it's not enough to solve the climate crisis *only* by switching to 100% renewable energy if the many other processes leading to ecological collapse are left unchecked. The explanation Rockstrom et al. offer sensitizes us to the strong interdependence among earth systems and processes, showing, for instance, that global warming can interact with (exacerbate or be exacerbated by) biodiversity loss, and with the human systems. How we respond to climate change can exert a positive (amplifying) feedback, for example, by ramping up our energy-intensive industrial defenses (artificial seawalls, air conditioners, geoengineering), or a negative (controlling) feedback - restoring coastal wetlands to mitigate hurricane damage, and increasing urban tree canopy to cool cities.

Donella Meadows, a systems thinker and sustainability advocate, offers an approach to intervening in these complex and overlapping systems to influence outcomes. She notes that we often look for leverage points in the wrong places, such as in the parameters. Parameters are what control the rate of flux into or out of a system, such as CO_2 into or out of the atmosphere, and are often controlled through policy changes, such as changes in tax rates, minimum wage, and air quality standards, for instance [Meadows 1999]. Yet "if the system is chronically stagnant, parameter changes rarely kick-start it" [Meadows 1999: 8] because they are usually too small to trigger change in the overall goals or design of the system.

Meadows explains that a more powerful leverage point is the system's guiding paradigm, such as that of our socio-economic systems that infinite growth will necessarily improve the human condition. Perhaps what's needed is to reveal the current paradigm's blind spot: that the planet's resources, which fuel economic growth and absorb its waste products, are finite. Or a guiding paradigm of our political systems that downplays the role of biodiversity and ecosystem restoration/conservation by relying on emissions reductions to solve the climate crisis.

Paradigm change for an individual can happen in an instant, Meadows explains; for a whole society, it's more complicated, though still possible. "In a nutshell, you keep pointing at the anomalies and failures in the old paradigm, you keep coming yourself, and loudly and with assurance from the new one, you insert people with the new paradigm in places of public visibility and power. You don't waste time with reactionaries; rather you work with active change agents and with the vast middle ground of people who are open-minded" [Meadows 1999:18].

In our daily lives, we are well sensitized to the processes of our socio-economic systems - working for a paycheck, taking care of our families, and tending to our social networks. This is normal - it's called living one's life. We are much less sensitized to how our human systems interact with Earth systems, because any one person doesn't necessarily need to consider this link to ensure his/her near-term survival or wellbeing. An exception may be farmers, whose wellbeing does depend on the land, and who are thus more likely to be in tune with Earth systems in a local context.

In general, though, we (at least in the West) rely directly on cars, buses, pavement, electricity, refrigerators, grocery stores, and plastic packaging, and only indirectly on the ecosystem processes that make these technologies possible. This is a glaring blind spot in one of our guiding paradigms - that our technology can save us. It’s a failure to visualize the world as a complex system with all its components and subsystems open and interacting, and to clearly perceive how the ingrained patterns of our daily lives, manifesting from the design of our socio-economic systems, are driving the cycles of Earth’s systems beyond the limits of equilibrium.

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In short, the climate crisis we face isn’t just about greenhouse gases, biodiversity loss, poor soil health, or depleted aquifers, nor is it only about the food system, industrial society, poor individual choices, the military industrial complex, or unaccountable corporations, or any of a long list of ills. It’s about all of them in constant interactions, and our solutions need to account for that.

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