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

Volume 3, Number 1, July 2019

Table of Contents

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

About Biodiversity for a Livable Climate **3**
- Suggested Citation 4
- Acknowledgements 4
- Conversion table 5

Introduction **5**

Biodiversity in forest dynamics **7**
- Compilation of article summaries on forest dynamics 10
  - Restoring natural forests is the best way to remove atmospheric carbon, Lewis et al. 2019 10
  - The global tree restoration potential, Bastin et al. 2019 11
  - The significance of retention trees for survival of ectomycorrhizal fungi in clear-cut Scots pine forests, Sterkenburg et al. 2019 12
  - Plant-soil feedbacks and mycorrhizal type influence temperate forest population dynamics, Bennett et al. 2017 13
  - Nitrogen-fixing red alder trees tap rock-derived nutrients, Perakisa & Pett-Ridge 2019 14

Climatic controls of decomposition drive the global biogeography of forest-tree symbioses, Steidinger et al. 2019 15
Hydraulic diversity of forests regulates ecosystem resilience during drought, Anderegg et al. 2018 17
Tree diversity regulates forest pest invasion, Guo et al. 2019 17
Restoration of living environment based on vegetation ecology: theory and practice, Miyawaki 2004 18
The legacy of 4,500 years of polyculture agroforestry in the eastern Amazon, Maezumi et al. 2018 19

Ecological intensification 20
Compilation of article summaries on ecological intensification 23
Ecological intensification: local innovation to address global challenges, Tittonell et al. 2016 23
Ecological intensification: harnessing ecosystem services for food security, Bommarco et al. 2013 25
Evidence that organic farming promotes pest control, Muneret et al. 2018 27
The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe, Martin et al. 2019 28

Blessed unrest, transformative change 30
Compilation of article summaries envisioning societal change 32
A global agenda for soil carbon, Vermeulen 2019 32
A global deal for nature, Dinerstein 2019 33
Joint statement on post-2020 global biodiversity framework 2050 Convention on Biological Diversity vision: “Living in Harmony with Nature,” Birdlife International et al. 35
A Green New Deal for Agriculture, Patel & Goodman 2019 36
The future is rural, Bradford 2019 36
Stories of blessed unrest 38
Minibigforest in Nantes 38
Greta Thunberg and a million international student strikers 38
The Waorani people stand up for their rainforest homeland 39
Pondoland says no to mining 40
Methow Beaver Project:enlisting beavers to make wetlands in compensation for declining mountain snowpack 41

Kids fight for their future 41

Worthy miscellany **42**

Indigenous hunters have positive impacts on food webs in desert Australia, Penn State 2019 42

Blue carbon stocks of Great Barrier Reef deep-water seagrasses, York et al. 2018 42

Vegetation as a major conductor of geomorphic changes on the Earth surface: toward evolutionary geomorphology, Corenblit & Steiger 2009 43

Gaia and natural selection, Lenton 1998 44

References **46**

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

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About Biodiversity for a Livable Climate

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

- ***A think tank***, creating research and reports (such as this Compendium), and presenting conferences on the science and practice of eco-restoration with speakers from around the world.
- ***An educational organization***, offering presentations, courses and materials, including over 200 videos of speakers (with over 150,000 views on YouTube) from our 12 conferences since November 2014 (bio4climate.org/conferences), with many restoration and climate-positive examples from both scientists and practitioners.
- ***An advocate*** that reaches out to other organizations to encourage and facilitate the incorporation of eco-restoration as a climate solution into their own messaging and actions. We seek to connect to other groups and projects to help nourish and advance their own growth, and carry messages among groups to collaboratively learn and build on each other's efforts, and occasionally facilitate the emergence of new groups. Since

climate affects everyone, every organization has to deal with it in its own way, and we strive to help with the transition.

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

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

Suggested Citation

Compendium of Scientific and Practical Findings Supporting Eco-Restoration to Address Global Warming, Vol 3 No 1, July 2019, https://bio4climate.org/resources/compendium/. This is a collection of article summaries and commentary that will grow as new literature becomes available and as older literature is re-discovered.

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

Conversion table

hectares vs. acres	1 ha ≈ 2.5 ac
megagrams vs. tons	1 Mg = 1 metric ton
teragrams vs. tons	1 Tg = 1 million metric tons
petagrams vs. gigatons	1 Pg = 1 billion metric tons (1 Gt)
weight[1] carbon vs. weight CO_2	12/44
parts per million CO_2 vs. weight of carbon[2]	1 ppm CO_2 ≈ 2 Gt carbon

Introduction

As in every edition of this compendium, here we assemble and summarize research offering evidence of the power of ecosystems to address climate breakdown. The themes presented:

- forest dynamics
- ecological intensification and
- transformative change

were chosen based on recurrent themes of mostly recent reports and studies. Not surprisingly given its centrality to ecosystem function, the idea of biodiversity weaves through all three themes.

Forests, especially tropical forests, are considered the lungs of the world because of their vigorous breathing in of carbon dioxide and breathing out of oxygen. Protecting existing forests and regenerating previously cleared forests is widely understood as a key component of mitigating climate change. What's not as well appreciated is the role of biodiversity in the ecological functionality of forests. For reforestation to sequester requisite amounts of CO2, slow down water during storms and provide adequate habitat for species otherwise condemned to extinction, reforestation should aim to closely mimic natural, biodiverse forests. The studies presented here examine various symbioses in natural forests that drive forest dynamics. The ecosystem simplification that comes with monoculture plantations risks losing these important interspecies partnerships.

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[1] We refer to carbon in soils and biomass, etc. by weight of carbon; atmospheric carbon may be referred to by weight of carbon *or* by weight of CO_2, a frequent source of confusion

[2] Ppm is a *volume* measurement, 1 ppm is approximately equal to 2 gigatons carbon by *weight* - and yes, this can be confusing too. Moving 1 ppm CO_2 from the atmosphere results in 2 Gt carbon added to soils or other carbon sink.

Ecological intensification relies on biodiversity to address agriculture's double objective of increased productivity with minimal environmental harm. Upending deeply ingrained beliefs that high yield and ecosystem regeneration are mutually exclusive outcomes, ecological intensification focuses on replacing high-tech inputs with ecosystem services capable of delivering equivalent agronomic outcomes. To put ecological intensification's productivity potential in perspective, consider that natural ecosystems are far more productive and resistant to pest infestations than are croplands, despite no fertilizer or pesticide use. As for crop yield? A core difference between ecology-based versus high-tech/high-input farming systems is the variety of crops harvested, due to more complex rotations on ecologically managed farms. However, the total per-acre yield between the two systems is likely to be comparable. Moreover, because ecological farming practices protect and build the soil, they are likely to be more productive in the future as drought, heat waves and flooding become more frequent. In short, a global proliferation of highly productive, ecologically functional farms can contribute enormously to healing the planet.

Transformative change - how does that relate to the theme of biodiversity? First, a growing awareness of biodiversity's sharp global decline is prompting a spate of proposals for transformative change aiming to restore not only biodiversity, but also climate stability and democracy. Second, biodiversity in a figurative sense, meaning human diversity represented by hundreds of thousands of tiny NGOs in every corner of the globe, is rising from the embers of a civilization in decay to solve the problems threatening our collective wellbeing and survival. It is within the culturally, socially and geographically diverse local communities of the world that transformative change is most readily initiated and achieved. This local action has been dubbed 'blessed unrest' by author Paul Hawken [Hawken 2007]. It represents a spontaneous, decentralized, leaderless global movement approximating humanity's immune system response to the ills caused by a long-standing vacuum of integrity and goodwill among the governments of the world.

In the concluding portion of this document, we recount just a handful of the millions of untold stories of blessed unrest. Perhaps these will be the stories that future generations tell to explain what catalysed the transformative systemic change that rescued humanity from the brink of social and ecological collapse. Leading up to that, we report on relevant discoveries and analyses from scientists and others who are putting the pieces together to explain not only the extent of harm done to the planet, but also to illuminate some of the drivers of the biosphere's vitality, and how to navigate the way forward from here.

Biodiversity in forest dynamics

Understanding what makes forests thrive is important in light of mounting calls for reforestation and forest conservation as antidotes both to species loss and climate breakdown. Moreover, distinguishing between natural forest regeneration and timber plantations is critical to achieving intended goals.

> Intact forests, and especially tropical forests, sequester twice as much carbon as planted monocultures. These findings make forest conservation a critical approach to combat global warming. Because about two-thirds of all species on Earth are found in natural forests, maintaining intact forest is vital to prevent mass extinction [Dinerstein 2019: 1].

Dozens of country signatories to the Bonn Challenge have pledged to reforest nearly 300 Mha[3] out of a goal of 350 Mha by 2030. “However, plantations are the most popular restoration plan: 45% of all commitments involve planting vast monocultures of trees as profitable enterprises” [Lewis 2019: 26]. (Agroforestry accounts for 21% of pledged land, while natural forest regeneration accounts for 34% of commitments.)

Lewis et al. [2019] warn that the trend of tree plantations standing in for reforestation commitments is extremely problematic given the ecological superiority of natural, biodiverse forests. Dinerstein et al. [2019] explain why this is so.

> It is no coincidence that some of the most carbon-rich ecosystems on land—natural forests—also harbor high levels of biodiversity. Evolution has generated carbon-rich forests by packing in long-lived trees that also feed stable soil carbon storage pools. This packing effect is made possible by high levels of coexistence among diverse species and growth forms, and this coexistence has been made possible by the biotic interactions that generate competition and defense. It is the very pests, pathogens, pollinators, decomposers, and predators that comprise a tropical forest that generated the carbon- rich growth forms (in both wood and soil) that take the carbon out of the atmosphere [Dinerstein 2019: 3].

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[3] Mha = Megahectare (1 million hectares, approximately 2.5 million acres)

It is the very pests, pathogens, pollinators, decomposers, and predators that comprise a tropical forest that generated the carbon-rich growth forms (in both wood and soil) that take the carbon out of the atmosphere [Dinerstein 2019: 3].

Shedding light on what makes forests thrive, researchers are increasingly able to explain the mechanisms by which biodiversity drives forest dynamics. For example, red alder trees, which fix nitrogen in symbiosis with soil bacteria, increase availability not only of nitrogen, but also of potassium and calcium [Perakisa & Pett-Ridge 2019]. That's because excess fixed nitrogen acts as a weathering agent on bits of rock, leaching minerals into the soil. This increased nutrient availability removes limits to growth not only for the red alder, but also for surrounding trees.

Similarly, ectomycorrhizal (EM) fungi, in addition to providing nitrogen in exchange for photosynthate, form protective sheaths around their tree host roots, allowing saplings to develop under the canopy of parent trees [Bennett 2017]. Absent EM fungal protection, saplings are exposed to pests drawn to the immediate area due to the presence of other members of the same tree species, which draw host-specific pests. This symbiosis allows for trees forming EM symbioses to cluster, while tree species lacking this fungal partnership survive more readily as seedlings away from members of their own species. Thus, ultimately, a key driver of forest population dynamics is the unlikely, invisible, underground EM fungi.

This particular fungal type as well as countless other powerful, yet hidden, soil microorganisms are overlooked when forests are harvested for timber, and to disastrous effects. A recent Swedish study showed that: "In clear-cuts, ECM [EM] fungal relative abundance had decreased by 95%, while ECM fungal species richness had declined by 75%, compared to unlogged plots" [Sterkenburg 2019: 1]. This means that in addition to a nearly complete loss of overall soil fungal abundance, most fungal species disappeared. The researchers tested the effects of retaining 30% or 60% of trees during a logging event and found that ECM fungal diversity and relative abundance is preserved in proportion to the amount of retained trees.

One may conclude, therefore, that natural forest regeneration following timber harvest is likely to be more successful when more trees are retained, permitting the preservation of soil microorganism biodiversity. This finding of the severe effects of logging is especially important considering the key role EM fungi in particular play in mitigating and adapting to climate change.

> Associations with ectomycorrhizal fungi—but not arbuscular[4] mycorrhizal fungi—have previously been shown to enable trees to accelerate photosynthesis in response to increased concentrations of atmospheric CO2 when soil nitrogen is limiting, and to inhibit soil respiration by decomposer microorganisms. Because increased plant photosynthesis and decreased soil respiration both reduce atmospheric CO2 concentrations, the ectomycorrhizal symbiosis is associated with buffering the Earth's climate against anthropogenic change [Steidinger 2019: 404].

Not only microbial diversity, but also large animal diversity contributes to forest productivity and carbon sequestration/storage. Mammal diversity has been found to be positively correlated to carbon concentration in the soil due to an increase in feeding interactions, where "processing of fruits and direct biomass contributions by vertebrates and plants affect soil carbon concentration" [Sobral 2017]. Similarly (though the causality here is not explained), "forested areas that contain tigers have three times the carbon density compared to forests and degraded lands where tigers have been eradicated" [Dinerstein 2019: 11]. Even humans can contribute positively to forest and other ecosystems as the Australian Martu [Penn State 2019], ancient Amazonian [Maezumi 2018] and British Columbia coastal First Nations communities [Trant 2016] have shown.

Taking the importance of biodiversity to heart, the Miyawake Method of reforestation calls for urban and rural reforestation projects where 30-50 species to be densely planted in an area "according to the system of natural forests" [Miyawaki 2004]. In combination with compost and mulch application at planting time and diligent care in the first three years after planting, this approach can within 15-20 years generate a multi-story forest capable of shielding neighboring communities from storm damage.

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[4] Arbuscular mycorrhizal (AM) fungi, like EM fungi, forms a symbiosis with tree roots. Unlike EM fungi, however, AM fungi colonizes the interior of tree root cells and transfers principally phosphorus to plants in exchange for photosynthate.

Compilation of article summaries on forest dynamics

Restoring natural forests is the best way to remove atmospheric carbon, Lewis et al. 2019

In order to keep global warming under the 1.5C threshold, the IPCC warns that not only must we cut carbon emissions nearly in half by 2030, we must also draw massive amounts of CO2 out of the atmosphere.

> The Intergovernmental Panel on Climate Change (IPCC) suggests that around 730 billion tons of CO2 (730 petagrams of CO2, or 199 petagrams of carbon, Pg C) must be taken out of the atmosphere by the end of this century. That is equivalent to all the CO2 emitted by the United States, the United Kingdom, Germany and China since the Industrial Revolution [Lewis 2019: 25].

The IPCC further advises that forests and wooded savannas could store enough carbon to get us a quarter of the way there. “In the near term, this means adding up to 24 million hectares (Mha) of forest every year from now until 2030” [Lewis 2019: 26].

Through the Bonn Challenge, 43 countries have pledged to reforest nearly 300Mha out of a goal of 350Mha by 2030. “However, plantations are the most popular restoration plan: 45% of all commitments involve planting vast monocultures of trees as profitable enterprises” [Lewis 2019: 26], which stores much less carbon than do natural forests. Agroforestry accounts for 21% of pledged land, while natural forest regeneration accounts for 34% of commitments.

While timber plantations technically fit the definition of a forest (greater than 0.5 hectares in area, trees at least five meters high and more than 10% canopy cover, according to UN FAO),

> the key components of climate-change mitigation and biodiversity protection are missing. Plantations are important economically, but they should not be classified as forest restoration. That definition urgently needs an overhaul to exclude monoculture plantations [Lewis 2019: 27].

Illustrating vast differences in mitigation potential, Lewis et al. state that “if the entire 350 Mha [of the Bonn Challenge goal] is given over to natural forests, they would store an additional 42 Pg C by 2100. Giving the same area exclusively to plantations would sequester just 1 Pg C or, if used only for agroforestry, 7 Pg C” [Lewis 2019: 27].

The authors make four specific recommendations to ensure more effective climate change mitigation through conservation and restoration efforts:

(1) Countries should significantly increase the proportion of natural forest restoration in their commitments. (Natural forest restoration over an area the size of South Carolina could store 1 Pg of carbon by 2100.)

(2) Natural forest restoration should be prioritized in the tropics, where trees grow fastest and don't risk countering the albedo effect since there's never any reflective snow there anyway.

(3) "Target degraded forests and partly wooded areas for natural regeneration; focus plantations and agroforestry systems on treeless regions and, where possible, select agroforestry over plantations."

(4) Natural forest once restored must be protected.

The global tree restoration potential, Bastin et al. 2019

This study models the total amount of land globally that is suitable for reforestation, finding that there is sufficient space to meet the IPCC's recommendation of reforestation on 1 billion hectares to limit global warming to 1.5C by 2050. The potential forest land identified in this study excludes urban and agricultural land; rather, it "exists in areas that were previously degraded, dominated by sparse vegetation, grasslands, and degraded bare soils" [Bastin 2019]. Yet for reforestation efforts to meet this potential, time is of the essence. By 2050, climate change will have shrunk the additional amount of land capable of supporting forest ecosystems by about a quarter.

> The restoration of trees remains among the most effective strategies for climate change mitigation. We mapped the global potential tree coverage to show that 4.4 billion hectares of canopy cover could exist under the current climate. Excluding existing trees and agricultural and urban areas, we found that there is room for an extra 0.9 billion hectares of canopy cover, which could store 205 gigatonnes of carbon in areas that would naturally support woodlands and forests.This highlights global tree restoration as our most effective climate change solution to date. However, climate change will alter this potential tree coverage.We estimate that if we cannot deviate from the current trajectory, the global potential canopy cover may shrink by ~223 million hectares by

> 2050, with the vast majority of losses occurring in the tropics. Our results highlight the opportunity of climate change mitigation through global tree restoration but also the urgent need for action [Bastin 2019: 1].

The restoration of trees remains among the most effective strategies for climate change mitigation [Bastin 2019: 1].

> More than 50% of the tree restoration potential can be found in only six countries (in million hectares: Russia,+151; United States,+103; Canada, +78.4; Australia, +58; Brazil, +49.7; and China, +40.2), stressing the important responsibility of some of the world's leading economies.

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The significance of retention trees for survival of ectomycorrhizal fungi in clear-cut Scots pine forests, Sterkenburg et al. 2019

Industrialized forestry simplifies forest structure and harms biodiversity. To mitigate this harm, retention forestry has been adopted in places such as Sweden, where this study was conducted. "Retention forestry" avoids clearcutting and instead preserves some 5-30 percent of trees to benefit populations of birds, lichens, fungi and other types of organisms.

The authors focused on the effects of retention on ectomycorrhizal (ECM) fungi (also commonly abbreviated as "EM" fungi), an ecologically important group of species.

> ECM fungi represent a large part of the biodiversity in boreal forests. They depend on carbohydrates from their host trees and are vital for forest production, as uptake of nutrients and water by the trees is mediated by the soil ECM symbiosis. ECM fungal mycelium forms a basis for soil food webs. The largely cryptic life of ECM fungi has hampered understanding of their biology and their importance for ecosystem processes, impeding adaptation of forestry to sustain ECM fungal diversity [Sterkenburg 2019: 2].

Aiming to quantify the decline in ECM fungi species abundance and richness in relation to the proportion of trees logged, the authors established an experiment with two levels of trees retained (30% and 60%), which was then compared to unlogged forest (100% retained) and clear-cut forest (0% retained). They found that ECM fungal diversity and relative abundance is preserved in proportion to the amount of retained trees.

“In clear-cuts, ECM fungal relative abundance had decreased by 95%, while ECM fungal species richness had declined by 75%, compared to unlogged plots” [Sterkenburg 2019: 1]. The latter result meant that the less common species of ECM fungi were lost, while the more dominant ones survived. The authors noted that even at the Swedish Forestry Council’s sustainability threshold of 5% tree retention (i.e., 95% logged), some 75% of ECM species are lost. In other words, there’s no significant difference between clearcutting and retaining 5% of the trees in terms of the effects on the number of fungal species lost. To preserve fungal diversity, many more trees must be retained when logging.

This study illustrates the unseen damage to forest ecosystems of intensive logging, as well as the potential challenges of re-growing forests following clear-cutting, given a likely dearth of ECM symbionts to aid sapling development.

Plant-soil feedbacks and mycorrhizal type influence temperate forest population dynamics, Bennett et al. 2017

This study illustrates the important role of soil fungi in tree population dynamics of temperate forests. In general, when a particular plant species dominates an area of land, it attracts species that feed on it. In an experiment conducted in this study, the roots of surviving seedlings had 60% fewer lesions when they were planted beneath a tree species different than their own, compared to when they were planted beneath a member of their own species, “potentially because of increased root damage by antagonists” [Bennett 2017: 2].

However, seedlings inoculated by ectomycorrhizal (EM) fungi, which forms a protective sheath around its host’s roots and also efficiently transferring nitrogen to its host,

> had 840% higher survival and 75% lower lesion densities than those of uninoculated seedlings when planted beneath conspecifics [members of the same species], but inoculation had no effect beneath heterospecifics [members of another species]. In contrast, AM seedlings did not benefit from pre-inoculation, nor did pre-inoculation affect lesion densities, regardless of transplant location [Bennett 2017: 2].

Mycorrhizal fungi colonize plant roots, where they transfer nutrients to hosts in exchange for sugar produced through photosynthesis. Ectomycorrhizal fungi form a sheath around tree roots, while arbuscular mycorrhizal (AM) fungi colonize tree roots by penetrating root cell walls. In this study, as noted above, trees with EM fungi symbionts appear to be better protected from pathogens than are AM trees when growing amongst others of their own species. This dynamic affects the population dynamics of the forest by facilitating larger stands of EM trees, while inhibiting the clustering of AM trees.

In summary, “These results suggest that mycorrhizal type, through effects on plant-soil feedbacks, could be an important contributor to population regulation and community structure in temperate forests” [Bennett 2017: 1].

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Nitrogen-fixing red alder trees tap rock-derived nutrients, Perakisa & Pett-Ridge 2019

Red alder fix atmospheric nitrogen through a symbiosis with bacteria that colonize their roots. This study showed that when more nitrogen is produced than is needed by the plant, the resulting excess of nitric acid acts to dissolve bedrock minerals in the soil, making them available to plants.

> The substantial increase in mineral weathering by N-fixing [nitrogen-fixing] alder helps explain how this species takes up 65% more P [phosphorus] and 200% more Ca [calcium] than non-fixing Douglas-fir. Enhanced access to P is most likely important to N fixers, and is used to increase photosynthetic tissue mass and N-fixing nodule production to support growth. … Ecosystem supplies of both P and Ca can limit nonfixer tree growth where N is abundant, including in our forests. Alder-enhanced uptake of rock-derived Ca and its subsequent redistribution via litterfall may especially benefit bigleaf maple and western red cedar, two nonfixers with consistently high Ca demands that have limited direct access to rock-derived nutrients [Perakisa & Pett-Ridge 2019: 5012].

This study suggests possibilities for increasing forests’ capacity to absorb carbon and mitigate climate change through the ability of red alder (and potentially other nitrogen-fixing trees) to make otherwise limiting nutrients, including nitrogen, phosphorus and calcium, available within the forest ecosystem.

> Our finding that an N-fixing tree species can directly access rock-derived nutrients has implications for nutrient supplies that regulate tree growth and C uptake in forests. Inputs of fixed N can increase tree growth in N-limited forests, and could be further stimulated by access to rock-derived nutrients. Where N is already abundant and other nutrients are limiting, supplies of rock-derived nutrients can be even more important to forest growth and C uptake. It is presently unknown whether high rates of N fixation by trees are geographically widespread, and whether N fixers other than red alder can similarly access rock-derived nutrients [Perakisa & Pett-Ridge 2019: 5013].

Climatic controls of decomposition drive the global biogeography of forest-tree symbioses, Steidinger et al. 2019

This article describes three major types of microbial tree symbionts, why they matter, and maps their global distribution.

> Microbial symbionts strongly influence the functioning of forest ecosystems. Root-associated microorganisms exploit inorganic, organic and/or atmospheric forms of nutrients that enable plant growth, determine how trees respond to increased concentrations of CO2, regulate the respiratory activity of soil microorganisms and affect plant species diversity by altering the strength of conspecific[5] negative density dependence [Steidinger 2019: 404].

Arbuscular mycorrhizal and ectomycorrhizal fungi and nitrogen-fixing bacteria are the focus of the study.

> Plants that are involved in arbuscular mycorrhizal symbiosis comprise nearly 80% of all terrestrial plant species; these plants principally rely on arbuscular mycorrhizal fungi for enhancing mineral phosphorus uptake. In contrast to arbuscular mycorrhizal fungi, ectomycorrhizal fungi evolved from multiple lineages of saprotrophic[6] ancestors and, as a result, some ectomycorrhizal fungi are capable of directly mobilizing organic sources of soil nutrients (particularly nitrogen). Associations with ectomycorrhizal fungi—but not arbuscular mycorrhizal fungi—have previously been shown to enable trees to accelerate photosynthesis in response to increased concentrations of atmospheric CO2 when soil nitrogen is limiting, and to inhibit soil respiration by decomposer microorganisms. Because increased plant photosynthesis and decreased soil respiration both reduce

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[5] Members of one's own species.

[6] Saprotrophic species are those that feed on decaying organic matter.

> atmospheric CO2 concentrations, the ectomycorrhizal symbiosis is associated with buffering the Earth’s climate against anthropogenic change.
>
> In contrast to mycorrhizal fungi, which extract nutrients from the soil, symbiotic N-fixers (Rhizobia and Actinobacteria) convert atmospheric N2 to plant-usable forms. Symbiotic N-fixers are responsible for a large fraction of biological soil-nitrogen inputs, which can increase nitrogen availability in forests in which N-fixers are locally abundant [Steidinger 2019: 404].

Because increased plant photosynthesis and decreased soil respiration both reduce atmospheric CO2 concentrations, the ectomycorrhizal symbiosis is associated with buffering the Earth’s climate against anthropogenic change [Steidinger 2019: 404].

The study finds that climatic controls on litter breakdown determine fungi type in a given region, where colder climates favor ectomycorrhizal fungi, which are more efficient at extracting nutrients from organic material, and warmer climates favor arbuscular mycorrhizal fungi, which efficiently extract phosphorus from the soil. Warmer climates also favor nitrogen-fixing bacterial symbionts. Based on symbiosis distribution vis-a-vis existing spatial climate gradients, the authors predict changes in forest symbiosis distribution as the climate changes overtime.

> To illustrate the sensitivity of global patterns of tree symbiosis to climate change, we use the relationships that we observed for current climates to project potential changes in the symbiotic status of forests in the future. Relative to our global predictions that use the most-recent climate data, model predictions that use the projected climates for 2070 suggest that the abundance of ectomycorrhizal trees will decline by as much as 10%... Our models predict that the largest declines in ectomycorrhizal abundance will occur along the boreal–temperate ecotone, where small increases in climatic decomposition coefficients cause abrupt transitions to arbuscular mycorrhizal forests [Steidinger 2019: 407].

The authors explain that existing transitions between arbuscular and ectomycorrhizal forests are abrupt due to positive feedbacks maintaining these systems. For instance, the chemical composition of the leaves of trees forming ectomycorrhizal symbioses resists decomposition, meaning that their leaf litter reinforces the presence of ectomycorrhiza in cooler regions. Once a small temperature threshold is breached, however, climate controls on decomposition speed up litter breakdown and favor arbuscular mycorrhizal fungi, along with their tree hosts.

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Hydraulic diversity of forests regulates ecosystem resilience during drought, Anderegg et al. 2018

Higher forest biodiversity (specifically plant functional diversity related to water, or hydraulic, transport) engenders greater ecosystem resilience to drought. This is because different species respond differently to water stress - some species slow down their release of water (and heat) through transpiration sooner than others do. Plants' response to water availability in turn affects the local climate.

> Water, carbon and energy exchanges from the land surface strongly influence the atmosphere and climate; these exchanges are dominated by plants in most ecosystems. Plant physiological responses to water stress influence these fluxes, and the resulting land-surface feedback effects influence local weather as well as the regional atmospheric circulation. Furthermore, changes in vegetation physiology and cover can drive shifts in sensible and latent heat fluxes that intensify droughts [Anderegg 2018: 538].
>
> We have documented a fundamental effect of trait variation on ecosystem stability that directly influences the atmosphere and climate system. Temperate and boreal forest ecosystems with higher hydraulic diversity are more buffered to changing drought conditions [Anderegg 2018: 540].

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Tree diversity regulates forest pest invasion, Guo et al. 2019

Using data from 130,210 forest plots across the US, this study examines the effects of tree diversity on pest invasions. The authors found that tree diversity increases pest diversity by increasing the variety of host species available (i.e., facilitation), while also decreasing establishment of pests by increasing the number of non-hosts for any given pest species relative to the total number of trees (i.e., dilution). In other words:

> The relative proportion of component tree species (hosts vs. nonhosts) plays a key role in determining pest invasions, as indicated by our evidence that host diversity may

> promote pest diversity while neighboring nonhost species could enhance the associational resistance of host species to nonnative pest invasions [Guo 2019].

More specifically, the study observed a hump-shaped relationship between tree and pest diversity.

> Pest diversity increases with tree diversity at low tree diversity (because of facilitation or amplification) and is reduced at higher tree diversity (as a result of dilution). Thus, tree diversity likely regulates forest pest invasion through both facilitation and dilution that operate simultaneously, but their relative strengths vary with overall diversity [Guo 2019].

Other factors that influence pest invasions in forest ecosystems include: “climate, resource availability, spatial scale, and habitat fragmentation related to human disturbances.” Furthermore, “recent analyses indicate that pest species continue to be introduced and spread around the globe. Under climate and land use changes, many tree species could expand, contract, or undergo latitudinal/elevational shifts in their geographical ranges” [Guo 2019].

These findings underscore the importance of biodiversity in maintaining healthy and stable ecosystems, while also highlighting the complexity of ecosystems (given the non-linear relationship between tree and pest diversity) and the challenges that poses for restoration.

Restoration of living environment based on vegetation ecology: theory and practice, Miyawaki 2004

> Natural environments have been devastated and destroyed worldwide by recent rapid development, urbanization and industrialization. It is no exaggeration to say that the basis of human life is now threatened (Miyawaki 1982a,b).
>
> We ecologists have been giving warnings against the devastation of nature through study results, and have produced some good effects. Besides criticism, however, we should contribute to the wholesome development of human society by active concern for nature restoration and reconstruction (Miyawaki 1975, 1981) [Miyawaki 2004: 83].

As suggested in these introductory words, Akira Miyawaki is a Japanese ecologist who has dedicated decades of his life to the study and implementation of forest restoration. He emphasizes the importance of restoring barren or degraded land more quickly than the time it takes for natural forest succession to occur, which can be 150-300 years, depending on the regional climate. By contrast, the methods he recommends can yield results within 15-20 years in terms of establishing forests mature enough to protect communities against natural disasters, such as earthquakes and storms. The principles of what has become known as the “Miyawaki Method” are based on mimicking natural forest growth patterns and thus feature: high biodiversity, preference for native species, relatively high planting densities, and healthy soil.

Communities undertaking such restoration efforts must first survey the landscape to determine the “potential vegetation” for the area based on what remains of native tree communities. Next, seeds must be gathered for some 30-50 species of native trees, and then propagated in greenhouses. After a year or two, once the seedlings have strong, well-developed roots, they can be planted. Miyawaki refers to planting events as “festivals” because the community dynamic is important for increasing public understanding of the relevance of ecological restoration and igniting a collective willingness to protect the plantings well into the future.

Miyawaki concludes with these words:

> These forests of complex multilayer communities have disaster-mitigation and environmental protection functions in each region. In the Great Hanshin Earthquake, which hit the Kobe district, western Japan in January 1995, there was no damage to trees in Japanese traditional temple forests, the potential natural vegetation, however, huge structures made of non-living materials collapsed, including elevated railways, highways and tall buildings (Miyawaki 1998). On a global scale, natural forests help to avoid global warming by absorbing carbon dioxide. Restoration and regeneration of ecologically diverse forests is inevitable for citizens in every region to survive in the next century, and the next millennium [Miyawaki 2004: 89].

The legacy of 4,500 years of polyculture agroforestry in the eastern Amazon, Maezumi et al. 2018

This study combines archaeology, archaeobotany, palaeoecology and palaeoclimate investigation to shed light on the legacy of pre-Columbian land management practices on today’s Amazon rainforest. Evidence points to a millennial-scale cultivation practice that at once maintained ecosystem integrity while sustaining a large and growing human civilization.

> Here, we show that persistent anthropogenic landscapes for the past 4,500 years have had an enduring legacy on the hyperdominance of edible plants in modern forests in the eastern Amazon. We found an abrupt enrichment of edible plant species in fossil lake

> and terrestrial records associated with pre-Columbian occupation. Our results demonstrate that, through closed-canopy forest enrichment, limited clearing for crop cultivation and low-severity fire management, long-term food security was attained despite climate and social changes. Our results suggest that, in the eastern Amazon, the subsistence basis for the development of complex societies began ~4,500 years ago with the adoption of polyculture agroforestry, combining the cultivation of multiple annual crops with the progressive enrichment of edible forest species and the exploitation of aquatic resources. This subsistence strategy intensified with the later development of Amazonian dark earths, enabling the expansion of maize cultivation to the Belterra Plateau, providing a food production system that sustained growing human populations in the eastern Amazon. Furthermore, these millennial-scale polyculture agroforestry systems have an enduring legacy on the hyperdominance of edible plants in modern forests in the eastern Amazon. Together, our data provide a long-term example of past anthropogenic land use that can inform management and conservation efforts in modern Amazonian ecosystems [Maezumi 2018: 540].

This largely hidden history of the Amazon illuminates a path forward today as humanity grapples with the combined challenges of maintaining food production for a growing global population, while preserving and restoring forests and curbing biodiversity collapse. As suggested here, ecological restoration and agricultural productivity to sustain growing populations are not mutually exclusive enterprises, but in fact can be synergistic.

Ecological intensification

The concept of ecological intensification in agriculture offers a framework for handling the question of how to produce enough food for a growing global human population while simultaneously protecting biodiversity. It draws on the language of ecosystem services, which includes supporting services such as soil formation, regulating services (pollination and pest control), provisioning services (production of a consumable good) and cultural services (educational and recreational) tendered by nature upon which humans depend.

Despite being anthropocentric simplification the complex web of relationships that make up an ecosystem, the concept of ecosystem services is useful in drawing attention to humanity's reliance on nature. In the context of agriculture, recognizing the processes (especially soil creation, habitat structure, nutrient mobilization through microbe-plant symbioses, and pollination) that undergird crop health, growth and yield can enable farmers to design farming systems that meet agronomic objectives while restoring ecosystem function to cropland.

Farmers can activate certain elements of ecosystem function according to the specific problems and opportunities they see on their farmland. For example, Martin et al. [2019] explain that simply maximizing the amount of edge around cropland (for example, with smaller fields) boosts pollinator and pest predator activity in crop fields, thereby increasing yield. Similarly, increasing soil organic matter reduces the need for fertilizer, thereby reducing pressure from pests such as aphids that proliferate on nitrogen fertilized crops, and thus also reducing the need for pesticides [Garratt 2018]. Furthermore, weed colonization of cropland can potentially limit insect and pathogenic infestations [Muneret 2018].

Scenarios for meeting global food demand through ecological intensification of agriculture focus on closing yield gaps through a combination of methods in countries with low rates of agricultural productivity and higher rates of food insecurity, while maintaining yields in already high-yielding countries through a transition to ecological practices. This way, more food is produced in the places where it is most needed and in a way that minimizes (and potentially even halts) biodiversity loss. In the meantime, agricultural productivity is maintained through a transition to ecological practices in already high-yielding contexts.

> The greatest contribution to humanity from the most productive and industrialized areas of the world would be to maintain current productivity using less inputs of non-renewable resources and reducing their huge environmental impact; in other words, producing ‘the same with less’ [Tittonell 2016: 23].

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To clarify the premises of ecological intensification, one can examine a contrasting approach to increasing global crop yield while minimizing biodiversity loss (its name, “sustainable intensification,” is similar to “ecological intensification,” and may confuse matters somewhat). An underlying premise of sustainable intensification is that increasing both agricultural yield and wildlife habitat in a particular place and time are mutually exclusive objectives.

Eschewing the viability of agricultural extensification (expanding the amount of land dedicated to agriculture), given well-known environmental problems associated with conversion of wild or semi-wild land to cropland, Egli et al. [2019] argue for increasing yields on existing farmland. The authors presume an inherent conflict between biodiversity preservation and agricultural intensification, however, where the latter is deemed achievable only through the high input methods that dramatically boosted yields in the 20th Century while also eroding biodiversity.

> High input agriculture negatively affects multiple taxa and multiple dimensions of biodiversity, in particular farmland species. These negative effects have mostly been attributed to habitat simplification, inputs of fertilizer, pesticides, and irrigation.

Despite such externalities, the authors remain optimistic about future yield increases through industrial practices.

> Past trends and future projections suggest large production increases through intensification on existing croplands. Yield increases contributed three quarters of the agricultural production gains between 1985 and 2005, and were mainly achieved through enhanced fertilization, irrigation and pest control, shortening of crop rotations and fallow periods, mechanization, and planting of improved crop varieties [Egli 2019: 2].

The authors introduce the possibility, therefore, of global land-use optimization: countries whose biodiversity-loss potential from agricultural intensification is lower (such as in Eastern Europe, Russia and North America) should maximize agricultural production. This would increase the global food supply enough that agricultural production could be reduced in global hotspots of biodiversity, thereby protecting biodiversity where it is the richest.

There are several problems with this strategy. As the authors themselves note, it would result in reduced agricultural output in high-biodiversity countries with an already lower level of food security and higher economic dependencies on the agricultural sector. In addition, further concentration of food production would deepen reliance on a global food system subject to international market volatility and relying on emissions-heavy long-distance shipping. Moreover, this study assumes yield on existing cropland can still increase to reach 80% of its potential, despite that yield growth from industrial innovation has already stagnated and the mineral resources that drive these techniques are dwindling. Furthermore, flooding, heat waves and droughts occurring with ever greater frequency will particularly stress crops growing in conditions of monoculture and damaged soils.

Lastly, the authors neglect to account for the potential of urban agriculture and forest food farming to increase agricultural production without converting wildlands, and, more generally, the possibility that agroecological practices are capable of increasing or maintaining yield in the process of restoring ecosystem function.

When all you have is a hammer, everything looks like a nail. For more than 50 years, the Green Revolution approach to farming has been our hammer, making weeds and insects look uniformly like nails, to stretch a metaphor. We've been taught to treat every other living thing growing among the crops in our fields (or yards or gardens) as the enemy, while ecological intensification teaches us to understand the interdependent relationships between different species growing together. It calls on us to search out the ways our crops benefit from the presence of various species in their midst (including the microorganisms we cannot even see), and to optimize those synergies in the skilled expression of our craft as farmers (or gardeners).

Compilation of article summaries on ecological intensification

Ecological intensification: local innovation to address global challenges, Tittonell et al. 2016

World agriculture cumulatively produces enough to feed the whole human population and more, yet hundreds of millions of people on the planet are hungry due to problems of access to food. Noting that agricultural productivity is unevenly distributed around the globe, this book chapter proposes food security through ecological intensification in areas with low productivity and higher rates of hunger. This strategy runs counter to a dominant narrative that agricultural productivity even in high-input, high-yielding farming systems in industrialized countries should increase to fight world hunger. Rather, these authors posit, developed countries should adopt ecological intensification to maintain existing high levels of productivity by replacing synthetic and high-tech inputs with practices enlisting ecosystem services.

> In the most productive and industrialised areas of the world the concept of 'more with less' is certainly engaging but rather utopic, as these agricultural systems operate mostly beyond their physical and economic efficiencies already. It is hard to get 'more' from these systems and this should not be a priority from a global food security perspective, as such production does not contribute to alleviate hunger in the poorest regions of the world. The greatest contribution to humanity from the most productive and industrialised areas of the world would be to maintain current productivity using less inputs of

> non-renewable resources and reducing their huge environmental impact; in other words, producing “the same with less” [Tittonell 2016: 23].

To illustrate the point that best practices are context specific, the authors describe a variety of approaches to ecological intensification undertaken in various parts of the world. In Uruguay, ranchers help preserve ecologically important, biodiverse grasslands by changing their grazing practices to enhance pasture and livestock productivity with no external inputs. In addition to revitalizing the grasslands, ranchers increased their incomes, allowing them to stay in business and preserve the grassland rather than selling it for conversion to crop production.

In Ethiopia, wheat productivity improves when grown under the canopy of Faidherbia albida, a prevalent local tree, which provides shade at critical moments of wheat development, increases moisture availability, and decreases the incidence of disease. “These benefits were found to result in wheat producing 23% more grain and 24% more straw under the canopy of F. albida compared to sole wheat [Tittonell 2016: 12].”

> The analysis of agricultural production systems that reproduce the ecological structure of the native savannah in the Ethiopian highlands showed that biodiversity should not only be seen as a ‘service’ from farming landscapes but rather as the basis for their functioning [Tittonell 2016: 22].

The authors call for the anchoring of ecological intensification of agriculture into social, cultural and policy structures. This could be done through local innovation, policy supporting such innovation, and through multi-stakeholder platforms for dialogue bringing together researchers, local, niche innovators, and actors representing the dominant food system.

> Options for the ecological intensification of agriculture can be inspired by the type of interactions between structures and functions that can be observed in nature, by the practical experience of local indigenous knowledge, and by combining these with the latest scientific knowledge and technologies. Ecological intensification calls for a constant dialogue between the practical wisdom of farmers and our own scientific wisdom [Tittonell 2016: 25].

To accelerate change, grassroots movements should seek to influence policy toward acknowledging “diversity in development directions for the agricultural sector” [Tittonell 2016: 20].

> Thus, as the private sector will continue to invest in patentable technologies – understandably – to reinforce their position in the current socio-technical regime, the key

> role of the public sector should be to reinforce the diversity of approaches, prioritizing alternative rather than mainstream technologies, creating favorable ‘openings’ in established socio-technical regimes, and embracing the complexity and the associated transaction costs of system innovation programs or what could be called ‘co-innovation systems’. In other words, investing in the creation and support of new niches rather than supporting technological ‘solutions’ that are already embedded in current regimes [Tittonell 2016: 25].

Ecological intensification: harnessing ecosystem services for food security, Bommarco et al. 2013

This review examines the concept of ecological intensification as a way to increase global food production by enhancing the ecological functionality of farmland.

> We present ecological intensification as an alternative approach for mainstream agriculture to meet [future climatic, economic and social] challenges. Ecological intensification aims to match or augment yield levels while minimizing negative impacts on the environment and ensuing negative feedbacks on agricultural productivity, by integrating the management of ecosystem services delivered by biodiversity into crop production systems [Bommarco 2013: 230].

The idea of ecological intensification stems from the concept of ecosystem services, which refers to the benefits humans derive from ecosystems. These services are grouped into four types: supporting (such as soil formation by microorganisms), regulating (such as pest control, crop pollination, climate regulation and water purification), provisioning (such as food, fiber, fuel and water) and cultural (such as education, recreation and aesthetic).

> Ecological intensification is based on managing service-providing organisms that make a quantifiable direct or indirect contribution to agricultural production [Bommarco 2013: 230].

The authors specify that: “crop yield has been defined as a provisioning ecosystem service, but the yield that is harvested in a given location depends largely on several supporting and regulating services” [Bommarco 2013: 231], such as soil production and pollination. And they note that these supporting and regulating ecosystem services underpin all agricultural production, including high-input industrial systems. For example, no matter how healthy and productive a crop is, yield will suffer if it’s not well pollinated, an observation consistent with

Liebig's Law of the Minimum. "One or several of these services can limit production and, even if all other services are optimized, no or little additional output will be attained until this ecosystem service shortfall is addressed" [Bommarco 2013: 231].

Beyond fulfilling a simple mechanistic role as a medium for crops to root into, soils provide multiple ecosystem services that support crop growth.

> Soil services that promote plant growth include pest and disease regulation, nutrient flow, and soil formation and structure that allow for root penetration, gas exchange, water retention, and erosion control. These processes are mediated by an immense, diverse, and largely unexplored biological community of mainly bacteria and fungi, but also protozoa, nematodes, arthropods, and earthworms [Bommarco 2013: 232].

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The management practices required to activate and optimize these soil services involve increasing soil organic matter (SOM) and diversifying crop rotation.

Ecosystems also provide the regulating services of biological pest control and crop pollination. Natural pest control can enhance or maintain yield even in pesticide-based production systems. However, the overuse of pesticides can severely damage ecosystem-based pest regulation, leading to pest resurgence or crop production system collapse. Strategies to enhance pest-predator populations "include landscape-level diversification by creation or conservation of natural and resource-rich habitat, combined with directed or diversified crop rotation and decreased pesticide pressure" [Bommarco 2013: 234]. Similarly, "pollinators can be promoted at the field or farm scale by enhancing floral resources and nesting sites, thereby potentially reducing the part of the yield gap caused by pollination deficits" [Bommarco 2013: 234].

In conclusion, the authors recommend that ecological intensification strategies increasingly replace conventional, industrial practices in developed countries, where the average yield potential has largely already been met, while using ecological intensification in combination with conventional strategies to close the yield gap in parts of the world where yields are low.

Evidence that organic farming promotes pest control, Muneret et al. 2018

Citing the problems posed globally by pesticide use and farmland expansion, this study looks at the potential of organic farming, seen as a popular prototype of ecological intensification, to limit pest infestations. Ecological intensification "is based on optimizing the ecological functions that support ecosystem services to increase the productivity of agro-ecosystems" [Muneret 2018: 361], and thus serves as a framework for evaluating farming system changes that could handle both ecological stress/collapse and human population growth. "Organic farming is a certified production system based on the principle of using farming practices that are expected to enhance ecological processes while prohibiting the use of external synthetic inputs" [Muneret 2018: 361].

> Our findings in particular show that organic farming practices are able to match or outperform conventional pest control practices against pathogens and animal pests [such as insects] whereas weeds are much more abundant in organic than in conventional systems. Thus, ecological intensification based on organic farming can contribute to the control of animal pests and pathogens by enhancing biological control services and limiting their infestation levels [Muneret 2018: 365].

Whereas conventional pest control emphasizes top-down control with pesticide, ecological pest control is achieved through multiple processes:

> Once established, pest populations within agro-ecosystems are affected, to varying degrees, by three ecological processes: bottom-up effects mediated by soil or plant communities involving, for instance, plant quality or habitat structure, horizontal processes within a given trophic level such as competition for resources between individuals or populations, and top-down control by natural antagonists such as predation or parasitism [Muneret 2018: 363].

Given the benefits of biodiversity for enhancing these three ecological effects, the authors explain that weeds, which are not as well suppressed in organic systems, may actually be beneficial in terms of limiting infestation by animals/insects and pathogens.

> Our analysis shows that organic farming results in much higher weed infestation. This result is supported by previous studies that have shown higher abundance and diversity of plant communities within organic arable fields. We assume that this higher weed infestation, in turn, most likely influences animal pest and pathogen populations. These bottom-up effects of plant communities on higher trophic levels have been demonstrated and more abundant or diverse plant communities have been found to limit insect and disease infestation through direct and indirect mechanisms because of higher structural complexity or lower habitat quality under increased plant diversity. Although this needs further investigation, the observed performance of organic farming on animal pest and pathogen infestation may result from bottom-up effects generated by the higher weed infestation levels in organic cropping systems [Muneret 2018: 364].

Although the authors didn't examine the effects of pest infestations on yield, they note that previous studies have suggested that weeds do not necessarily result in crop yield reductions in organic systems.

Although this needs further investigation, the observed performance of organic farming on animal pest and pathogen infestation may result from bottom-up effects generated by the higher weed infestation levels in organic cropping systems [Muneret 2018: 364].

The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe, Martin et al. 2019

This paper analyzes 49 studies (1515 landscapes encompassing both organic and conventional agricultural production) in Europe to determine "effects of landscape composition (% habitats) and configuration (edge density) on arthropods[7] in fields and their margins, pest control, pollination and yield" [Martin 2019: 1].

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[7] Insects and other invertebrates with segmented bodies and articulated appendages.

Edge density is measured as the length of edge per area of land. Edges between adjacent crop fields and between crop fields and semi-natural areas such as grasslands or other land patches not used for crops allow for “exchange between landscape patches” [Martin 2019: 4] for pollinators, pest predators and other providers of ecosystem services. High edge density is associated with smaller field size, and lower edge density with larger field size.

> Complex landscapes where small and/or irregularly shaped fields and habitat patches prevail have a high density of edges. Due to increased opportunities for exchange, these landscapes are likely to support spillover of dispersal-limited populations between patches [Martin 2019: 3].

Researchers found that:

> In landscapes with high edge density, 70% of pollinator and 44% of natural enemy species reached highest abundances and pollination and pest control improved 1.7- and 1.4-fold, respectively. Arable-dominated landscapes with high edge densities achieved high yields. This suggests that enhancing edge density in European agroecosystems can promote functional biodiversity and yield-enhancing ecosystem services [Martin 2019: 1].

Just as high edge density is shown here to maintain yield, low edge density, especially when combined with a lower amount of surrounding semi-natural habitat, can reduce yield.

> Reduced pollination and pest control at low edge density may have been compensated by external inputs in productive landscapes. … Intermediate to low yields in landscapes with high % arable, low % semi-natural habitat and low edge density may underpin the risks of ongoing conventional intensification resulting in yield stagnation or reduction despite high agricultural inputs [Martin 2019: 9].

This article illustrates the important role of ecosystem services in maintaining crop yield, as well as the relatively simple management decisions farmers can make to enhance the habitat of arthropods providing those services.

Blessed unrest, transformative change

One million of an estimated 8 million species on Earth are at risk of extinction in the coming decades, according to a May 2019 report from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). Children today will live as adults in a world without the Milky Stork, without the Caquetá Tití Monkey, and without the Thongaree's Disc-nosed Bat, and more generally without 40% of today's amphibian species and with a third fewer shark and reef-forming coral species.

It's not merely a sentimental loss of charming creatures we face, but an unravelling of ecosystems, which are knit together by biodiversity, and the accompanying loss of the life-sustaining services nature provides to humans. This was the message of the report's 400-plus authors, who emphasized that biodiversity collapse is comparable to and intertwined with climate change in scale and severity.

> Nature, through its ecological and evolutionary processes, sustains the quality of the air, fresh water and soils on which humanity depends, distributes fresh water, regulates the climate, provides pollination and pest control and reduces the impact of natural hazards. For example, more than 75 percent of global food crop types, including fruits and vegetables and some of the most important cash crops such as coffee, cocoa and almonds, rely on animal pollination. Marine and terrestrial ecosystems are the sole sinks for anthropogenic carbon emissions, with a gross sequestration of 5.6 gigatons of carbon per year (the equivalent of some 60 percent of global anthropogenic emissions). Nature underpins all dimensions of human health and contributes to non-material aspects of quality of life – inspiration and learning, physical and psychological experiences, and supporting identities – that are central to quality of life and cultural integrity, even if their aggregated value is difficult to quantify [Diaz 2019: 2].

The report warns that ecosystem deterioration is global and that its direct drivers – pollution, climate change, land and sea-use change, direct exploitation, and invasive species invasions – are accelerating. "Most international societal and environmental goals, such as those embodied in the Aichi Biodiversity Targets and the 2030 Agenda for Sustainable Development, will not be achieved based on current trajectories" [Diaz 2019: 5]. Reversing course from the catastrophic outcomes realizable throughout the 21st Century is possible, according to the report, but only through "transformative change" – in other words "fundamental, system-wide reorganization across technological, economic and social factors, including paradigms, goals and values" [Diaz 2019: 21].

> Acting immediately and simultaneously on multiple indirect and direct drivers has the potential to slow, halt and even reverse some aspects of biodiversity and ecosystem loss [Diaz 2019: 7].

Change is transformative when aimed at the underlying drivers of a system. As IPBES explains, indirect drivers of ecosystem deterioration are the institutions that govern social relations including, for example, systems of property rights, governance systems, treaties, and informal social norms and rules. Institutions are designed to produce certain beneficial outcomes, yet in the process also produce predictable negative outcomes.

> Since current structures often inhibit sustainable development and actually represent the indirect drivers of biodiversity loss, such fundamental, structural change is called for. By its very nature, transformative change can expect opposition from those with interests vested in the status quo, but such opposition can be overcome for the broader public good. If obstacles are overcome, commitment to mutually supportive international goals and targets, supporting actions by indigenous peoples and local communities at the local level, new frameworks for private sector investment and innovation, inclusive and adaptive governance approaches and arrangements, multi-sectoral planning and strategic policy mixes can help to transform the public and private sectors to achieve sustainability at the local, national and global levels [Diaz 2019: 7].

The transformative change envisioned here is a world where local and national governments are inclusive and internationally accountable. In other words, our societies are governed by institutions disposed to an equitable sharing of the responsibilities and benefits of global citizenship, and they act in service not only to the powerful, but are also responsive and supportive toward those without money or power. Capacity building is focused on local communities, where policy changes become manifest.

How to realize such change? IPBES suggests several leverage points, where efforts made to create a sustainable society can have a disproportionate effect. Cultural or value-system leverage points include “enabling visions of a good quality of life that do not entail ever-increasing material consumption” [Diaz 2019: 8] expanding a widely held value of responsibility to include the impacts of consumption; addressing social inequalities; ensuring inclusive decision-making; and promoting education and the maintenance of diverse knowledge systems, including scientific, local and indigenous knowledge.

Specific actions recommended include: promoting sustainable/agroecological farming and ecosystem-based fishing practices, and the development of urban green infrastructure to bolster climate change mitigation and adaptation. It also recommends fostering an evolution in economic/financial systems to reduce inequality and overconsumption and to steer away from the paradigm of economic growth.

Emerging in tandem with the IPBES assessment are a diversity of complementary proposals/analyses, summarized below, which articulate pathways forward deemed transformative enough to limit the severity of and/or adapt to climate breakdown.

Overall, these papers point to the importance of changing the cultural narratives that guide human behavior. Education that draws on scientific and indigenous knowledge, local capacity building and alliance building across political divisions are offered as levers with the potential to change societies' dominant narratives. An emergent cultural narrative might recognize biologically active, carbon-rich soil as a firmer basis than i-phones, plastic water bottles and the like for the provision of human safety, pleasure and happiness in life. And with widespread adoption of such a narrative, the public might be galvanized to win policy changes robust enough to reverse course from catastrophic outcomes.

An emergent cultural narrative might recognize biologically active, carbon-rich soil as a firmer basis than i-phones, plastic water bottles and the like for the provision of human safety, pleasure and happiness in life.

Compilation of article summaries envisioning societal change

A global agenda for soil carbon, Vermeulen 2019

This paper calls for efforts to make farmers, land managers, policy makers, and the public at large keenly aware of the link between soil carbon and its more widely appreciated social outcomes, such as agricultural productivity and food security, improved water quality, flood and drought mitigation, lower rates of migration, biodiversity preservation, and climate change mitigation.

The authors identify three priorities for global action to build soil carbon stocks: (1) build an overarching case and vision for action, led by political champions; (2) build a stronger business case and track-record of success among public and private investors; and (3) establish a more compelling value proposition for farmers and land managers.

Specifically, Vermeulen et al. propose that champions in countries already prioritizing soil carbon in national policy lead efforts to generate greater awareness, such as through

> persuasive narratives and campaigns [that] might link soil health and carbon storage to broader societal outcomes with wider political traction. These include double-digit increases in yield potential, particularly on degraded lands, higher household and national food security, reduced risks from disasters, improved water quality and lower rates of displacement and migration [Vermeulen 2019: 3].

They also propose that soil carbon take center stage in discourses on sustainable agriculture, from which it has largely been absent.

To build a business case among potential investors in soil health, the authors suggest, for example, creating "small-scale funds to flow to commercial demonstrations of soil organic carbon that can then be ready for widespread proliferation" [Vermeulen 2019: 3].

The authors stress the importance of demonstrating to farmers the multi-faceted long-term value achieved by incorporating soil-building practices into day-to-day farming operations, including: (1) enhanced productivity, (2) improved risk management (for example, resilience to drought), (3) superior market access (for example, certified value chains), (4) financial returns to carbon assets, and (5) government support (for example, environmental subsidies).

Another priority is "to move beyond stand-alone protocols by building soil organic carbon into existing frameworks from which it is absent, such as UNCCD, UNFCCC, Ramsar and the Global Reporting Initiative" [Vermeulen 2019: 4]. In other words, given the foundational role of soils in ecosystem function (and thus the delivery of vital ecosystem services), improving soil health must be treated as the powerful leverage point that it is for resolving multiple overlapping crises.

A global deal for nature, Dinerstein 2019

This paper recommends protecting 30% of Earth's surface for conservation by 2030 and 50% by 2050. It also proposes building capacity for indigenous and other local peoples to enhance ecosystem integrity and sequester carbon in non-protected lands, halting energy infrastructure projects, and reducing plastics and toxic pollution.

The authors frame a “Global Deal for Nature” (GDN) as complementary to the 2015 Paris Agreement for achieving the internationally recognized goal of limiting global warming to 1.5°C. While the Paris Agreement focuses on critical emissions reductions, the GDN expands the scope of measures needed to include ecosystem and biodiversity conservation. The authors explain that the Paris agreement serves as a strong starting point, but is only a half-deal. It will not alone save the diversity of life on Earth or conserve ecosystem services upon which humanity depends.

> Since the crucial role of intact, diverse systems has also been demonstrated to be essential for carbon storage, the GDN will need to emphasize mechanisms for protecting intactness both inside and outside of protected areas … well before 2050 [Dinerstein 2019: 12].

Contextualizing development of the idea of a GDN as part of a greater reassessment of the role of nature in the midst of a planetary emergency, the authors explain that:

> The concept of a GDN as a policy mechanism emerged from an earlier study restricted to protecting biodiversity in the terrestrial realm. We expand that perspective to the freshwater and marine realms while simultaneously lending support to an alternative pathway to remaining below 1.5°C that relies heavily on aggressive conservation of remaining habitats. This approach not only safeguards biodiversity but also is the cheapest and fastest alternative for addressing climate change and is not beholden to developing carbon removal technologies unlikely to be effective or to scale in the time-bound nature of the current twin crises [Dinerstein 2019: 1].

The authors recommend that a GDN prioritize: (1) protecting biodiversity, (2) mitigating climate change, and (3) reducing threats to ecosystem intactness and persistence of species. The strategy for the first priority – protecting biodiversity – is to expand the percentage of Earth’s surface that is conservation protected to 30% by 2030, aiming for 50% protection by 2050. Currently, less than 15% of land is protected, and only half of currently protected land is connected by ecological corridors to facilitate animal migrations, while only 2-4% of the world’s ocean area is protected. To avoid the risks of (a) prioritizing low-biodiversity sites at the expense of biodiversity hotspots, or (b) an uneven representation of ecoregion types achieving protected status, the authors organized conservation targets according to 846 terrestrial ecoregions.

For the second priority – mitigating climate change – the authors propose that land outside conservation protected areas be managed in a way that maintains ecosystem intactness, prevents emissions and sequesters carbon. This would include, for example, indigenous lands, where people often lack tenure rights. Ensuring secure land tenure to indigenous people would allow them to continue managing land in a way that supports the vitality of the ecosystems on which they depend.

The third priority – reducing major threats – would involve scrutinizing or halting new infrastructure projects (especially agricultural land expansion, road construction and energy development) on natural lands. In addition, it would involve reducing hunting and poaching, as well as the production and use of plastics and toxins.

Joint statement on post-2020 global biodiversity framework 2050 Convention on Biological Diversity vision: "Living in Harmony with Nature," Birdlife International et al.

In the lead up to the 2020 UN Convention on Biological Diversity, a consortium of conservation groups has also called for 30% both of oceans and 30% of land surface to be conservation protected. Specifically, The United Nations Foundation, Birdlife International, National Geographic and 10 other organizations call for a New Deal for Nature and People to prevent extinctions, reverse the decline of species populations, stabilize natural ecosystems and their services, and restore degraded lands. The call acknowledges the leadership of Indigenous Peoples, who should play a key role in the management of protected areas.

This 2-page vision statement opens with the following:

> The Convention on Biological Diversity aims to ensure the conservation, sustainable use and equitable sharing of the benefits of biological diversity. Securing Earth's biological diversity is a moral obligation. It is also critical in averting catastrophic climate change and ecosystem collapse. Achieving the aims of the Convention on Biological Diversity is integrally linked with tackling climate change and is critical for realizing the Sustainable Development Goals, as a diverse and healthy planet and is the foundation of human health, security, well-being and development.

A Green New Deal for Agriculture, Patel & Goodman 2019

In the U.S., some visions for food system change are anchored in the policy framework of the Ocasio-Cortez/Markley Green New Deal, itself viewed by many as a proposal for transformative change. Noting that the way we eat accounts for a quarter of greenhouse gas emissions and that “the food system is breaking the planet,” Patel and Goodman argue that the Green New Deal could redirect public funds from grain commodities, used largely for processed foods, bioenergy and meats raised in confinement, toward production of healthy foods. More evenly distributed support for greater numbers of farmers could significantly reduce rural poverty while easing pressure on and even regenerating ecosystems.

Yet farmer organizations on the right (Farm Bureau) and left (Farmers Union) have disparaged the Green New Deal, which the authors explain is because the proposal challenges a politically driven cultural view that industrial farming systems are more efficient and thus superior. Thus, transformative change, according to these authors who draw on the original New Deal for guidance, lies in building alliances among farmers, farm workers and consumers, which are capable of confronting this cultural narrative.

They suggest that confronting food system monopolies (especially in the meat industry) could bind farmers of all political stripes together, and that the question of food prices could bring farmers and consumers together. “For a rural Green New Deal to work in the 21st Century, everyone’s income needs to increase… Instead of driving down the costs of farming to make food cheap enough for urban workers to buy on stagnating wages, all workers must make enough to afford food that’s sustainably produced.”

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The future is rural, Bradford 2019

Taking an altogether different angle, Jason Bradford of the Post Carbon Institute assumes radical societal change is inevitable and imminent, and focuses not on how to precipitate change but instead on how to adapt to it. “The future is rural” [Bradford 2019] is essentially a primer on how to navigate the profound changes society will undergo during the 21st Century due to climate breakdown and resource scarcity. It begins with an assertion that today’s “mass urbanization has been made possible by the prodigious exploitation of fossil fuels.” In other words,

> Due to the concentrated energy in oil, with its ability to power heavy equipment and transport goods over long distances, cities have been able to achieve the scale they do today by drawing support from a land base often several hundred times their own area.

Yet these resources are dwindling. Furthermore,

> Not only are concentrated raw resources becoming rarer, but previous investments in infrastructure (for example, ports) are in the process of decay and facing accelerating threats from climate change and social disruptions [Bradford 2019: 1].

Thus, “contrary to the forecasts of most demographers, urbanization will reverse course as globalization unwinds during the 21st century” [Bradford 2019: 1].

The report explains that for multiple reasons, renewable energy will not seamlessly or completely be able replace fossil fuel use, in spite of a deep cultural belief in technological progress. And as cities falter and urban food shortages occur, people will be compelled to disperse into the countryside and to develop skills to ensure their food security.

> Food, its scarcity, the desire and opportunity to grow it, and the need to do it in ways that are appropriate to place and circumstance, will drive demographic shifts this century. People with life experiences and training aimed at urbanism are going to need a rapid education on what it takes to live off the land, and so-called conventional farmers and ranchers will have a steep learning curve to adopt more frugal and sustainable methods [Bradford 2019: 19].
>
> .

Having established a vision of the unfolding of the 21st Century, dubbed the “Great Simplification” and “characterized by fewer monetary transactions and an increase in subsistence and informal economies,” the author presents alternative agricultural systems, including agroecology, permaculture and holistic management, with potential to overcome the problems created by current farming systems. Included at the margins of the text is key technical information about soil composition, soil types and horizons, and livestock anatomy, as if to get laymen up to speed on agricultural basics for their future rural livelihoods.

In short, the Post Carbon Institute anticipates that resource scarcity will precipitate the collapse and subsequent reorganization of societies, along with their guiding narratives. By necessity, people will learn to consume less and better appreciate our inexorable dependence on the land. Other authors reviewed above suggest the potential to avoid ecological and social collapse by changing the cultural narratives that perpetuate overconsumption and overexploitation of people and nature.

Stories of blessed unrest

The following sketches are but a tiny sampling of the countless ways people throughout the world push back against the socio-economic and political forces of destruction both of ecosystems and of the social fabric of society. Adopting Paul Hawken's terminology and characterization of "blessed unrest" as a spontaneous, decentralized global social movement, we here present a diverse though far from representative series of vignettes of everyday heroes. May such stories light the fire for new heroes to perpetually emerge in defense of all life on Earth.

Minibigforest in Nantes

Hearing of plans underway for a four-lane highway near their home in Nantes, France, local residents Jim and Stephanie responded by planting a small forest. The idea was not only to block out the added sound and air pollution, but also to try to compensate for the assault on the planet of any road expansion. The couple was inspired by Shubhendhu Sharma, who spoke at the 2018 Nantes festival Aux Arbes[8]. Sharma showed the audience how 300 trees of 30-some species could be planted in the space of six parking places. He described the Miyawaki Method, which mimics natural forests in terms of biodiversity and density, outperforms the growth rate of monoculture plantations tenfold, and works well in urban areas because it takes so little space. Within the following year, Jim and Stephanie, along with dozens of volunteers and school kids, planted more than 2000 trees on two sites. To encourage Miyawaki-style afforestation projects everywhere, the couple launched the initiative Minibigforest; this is only the beginning for them.

https://mrmondialisation.org/nantes-ils-font-pousser-des-micro-forets-100-fois-plus-riches-en-biodiversite/

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Greta Thunberg and a million international student strikers

At the age of 15, Greta Thunberg began sitting on the steps of the Swedish parliament with a handmade sign reading: "skolstrejk för klimatet" or "school strike for the climate." The decision to act came about seven years after she first learned of climate change. The fact that adults didn't seem bothered to do anything about the global crisis shocked her, and then sent her into a

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[8] Aux Arbes is French for "to the trees." The name of this festival is perhaps a reference to a 2007 hit song in France: "Aux Arbes Citoyens," which has an ecological message; see: https://en.wikipedia.org/wiki/Aux_arbres_citoyens.

depression. Activism pulled her out of depression and thrust her onto the international stage. It didn’t take long for her solo picketing efforts to spark a global movement spanning 125 countries of more than a million kids striking from school for climate. Greta intends to continue striking outside the Swedish Parliament until it passes legislation that upholds commitments made in the Paris Climate Accord.

https://www.theguardian.com/world/2019/mar/11/greta-thunberg-schoolgirl-climate-change-warrior-some-people-can-let-things-go-i-cant

Excerpted from a Guardian guest editorial by climate strikers Greta Thunberg (Sweden), Anna Taylor (UK), Luisa Neubauer (Germany), Kyra Gantois, Anuna De Wever and Adélaïde Charlier (Belgium), Holly Gillibrand (Scotland), and Alexandria Villasenor (USA):

> This movement had to happen, we didn’t have a choice. The vast majority of climate strikers taking action today aren’t allowed to vote. Imagine for a second what that feels like. Despite watching the climate crisis unfold, despite knowing the facts, we aren’t allowed to have a say in who makes the decisions about climate change. And then ask yourself this: wouldn’t you go on strike too, if you thought doing so could help protect your own future?
>
> So today we walk out of school, we quit our college lessons, and we take to the streets to say enough is enough. Some adults say we shouldn’t be walking out of classes – that we should be “getting an education”. We think organising against an existential threat – and figuring out how to make our voices heard – is teaching us some important lessons.

https://www.theguardian.com/commentisfree/2019/mar/15/school-climate-strike-greta-thunberg

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The Waorani people stand up for their rainforest homeland

When the Waorani people of the Ecuadorian Amazon heard their government was planning to sell drilling rights to their land to international oil companies, they mobilized. They mapped the land to illustrate to the Western world its otherwise unseen cultural, historical and ecological richness. These maps include “historic battle sites, ancient cave-carvings, jaguar trails, medicinal plants, animal reproductive zones, important fishing holes, creek-crossings and sacred waterfalls,” according to an online petition they launched in partnership with the NGO Amazon Frontlines. Then the Waorani sued the government for not properly consulting them when the decision was made in 2012 to dice up the rainforest into auctionable blocks of land. In

April 2019, the Ecuadorian court ruled in favor of the Waorani, immediately suspending any sale of the land and setting a precedent for other communities resisting oil extraction in their lands.

> The government's interests in oil is not more valuable than our rights, our forests, our lives.
>
> - Nemonte Nenquimo, one of the Waorani plaintiffs and representative of the Coordinating Council of the Waorani Nationality Ecuador Pastaza (CONCONAWEP).

The Waorani win follows a win against mining operations last year by the indigenous Kofan community also in the Ecuadorian Amazon.

https://www.aljazeera.com/news/2018/05/ecuador-indigenous-waorani-launch-petition-save-amazon-180523102935421.html

https://www.aljazeera.com/news/2019/04/indigenous-waorani-sue-ecuadorian-government-land-rights-190411210110279.html

https://www.aljazeera.com/news/2019/04/indigenous-waorani-win-landmark-legal-case-ecuador-gov-190426221504952.html

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Pondoland says no to mining

On the other side of the Amazon and across the South Atlantic Ocean, the small South African community of Xolobeni won a similar court case. Like the Waorani, the people of Xolobeni demanded that they be consulted rather than being forced to cede their land to mining interests - in this case to an Australian titanium mining company. Also like the Waorani, they were defending not only their lives, livelihoods, their health and wellbeing, but also an ecologically rich corner of the planet. Xolobeni is in Pondoland, a dune-covered stretch of the coast that is home to endemic species and frequented offshore by whales.

> The law says we have a right to be consulted, but what we say doesn't seem to matter. We have told the company many times that we don't want their mine. How many times do we have to say no?
>
> - Nonhle Mbuthuma, local resident

The court agreed that local communities must give their consent before mining is allowed on their land.

https://www.theguardian.com/environment/2018/nov/22/south-african-community-wins-court-battle-over-mining-rights

https://www.theguardian.com/environment/2018/jul/21/i-thank-god-i-am-alive-standing-firm-against-mineral-extraction-in-south-africa
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Methow Beaver Project:enlisting beavers to make wetlands in compensation for declining mountain snowpack

The deep winter snow falls on the mountains around the Methow Valley in the state of Washington are declining. To manage problems with drought, the Methow Beaver Project has been capturing, tagging, matching male and female beavers and releasing them in key valley areas. The project workers know beavers are master engineers that know how to preserve their homes and food supply, to the benefit of water quality and many other animals and plants in the area. Beaver reintroduction projects are also underway in Nevada, Utah and Wyoming. In 2018, Scott Helker, a Libertarian candidate running to become governor of Colorado, was asked, “Would you support asking Coloradans to raise billions of tax dollars for projects that would increase water supplies and help prevent a projected water shortage mid-century?” He answered, “No. I can create the same results without raising billions of dollars. Ask me how.” Answer: with beaver reintroduction projects.

https://www.npr.org/2018/06/24/620402681/the-bountiful-benefits-of-bringing-back-the-beavers

http://methowsalmon.org/mbp_about.html

https://www.coloradoindependent.com/2018-governor-race/governors-race-questionnaire/scott-helker-questionnaire/

Kids fight for their future

iMatter is a tight-knit national group of passionate pre-college individuals who are making real impacts in their communities. They are showing up in city halls and state offices, demanding their elected officials at every level possible commit to bold and visionary climate action.

Students from Brookline High School in Massachusetts submitted resolutions to their town legislators, saying they're worried about their future and the future of the environment; their cities agreed and are supporting the Green New Deal. Alec Loorz started the organization Kids vs. Global Warming in California with his mom, Victoria Loorz in 2007, when he was 13 years old. The organization eventually changed its name to iMatter. Alec went on to spearhead the Our Children's Trust lawsuit against federal and state governments of the United States to secure climate recovery plans that will restore the balance of Earth's climate systems.

www.imatteryouth.org/about-us

https://patch.com/massachusetts/brookline/brookline-students-ask-town-get-behind-green-new-deal

https://thinkprogress.org/our-childrens-trust-young-people-climate-change-lawsuit-d3c45c6bd21f/

Worthy miscellany

Indigenous hunters have positive impacts on food webs in desert Australia, Penn State 2019

When Australian authorities removed indigenous Martu people from their traditional lands in the desertic center of the continent in the mid-1900s, endemic species there declined or went extinct. Researchers observed that the Martu's hunting regime of small burning patches of land reduced the size of wildfires while also boosting populations of native species such as dingo, monitor lizard and kangaroo. The absence of the Martu after the 1950s resulted in domination by invasive species, which killed much of the native wildlife.

Blue carbon stocks of Great Barrier Reef deep-water seagrasses, York et al. 2018

The Great Barrier Reef (GBR) protects northeast Australia from wave exposure, while also creating habitat for a vast expanse of shallow- and deep-water seagrasses between the reef and the shoreline. Deep-water seagrasses here occupy an area roughly the size of Switzerland.

While the carbon storage capacity of shallow-water seagrasses, dubbed ‘blue carbon,’ are known to be extremely high, the amounts of carbon stored in deep-water seagrasses (greater than 15 meters depth) is less well known, and expected to be lower due to these plants’ smaller stature and relative sparseness.

The authors found, however, that “deep-water seagrass contained similar levels of organic carbon (OC) to shallow-water species, despite being much sparser and smaller in stature” [York 2018: 1]. Furthermore, deep-water seagrass sediments contained about nine times more OC than surrounding bare areas.

> If the OC stocks reported in this study are similar to deep-water [seagrass] meadows elsewhere within the GBR lagoon, then OC bound within this system is roughly estimated at 27.4 million tons [York 2018: 1].

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Vegetation as a major conductor of geomorphic changes on the Earth surface: toward evolutionary geomorphology, Corenblit & Steiger 2009

Geomorphology is the study of landforms and processes and how they developed. This conceptual commentary proposes that the emergence and evolution of life, especially vegetation, has played a major role in physically shaping the Earth. For example, plant roots trap and hold sediment (preventing erosion), resulting in the formation of hillsides, sand dunes, fluvial islands, river banks, floodplains, and river channels, for example. Without vegetation to hold sediment in place, it would be blown or washed away, creating different land patterns. Roots also contribute to rock weathering, resulting in soil formation and even the formation of marine black shale, while aboveground, plants create a rough surface which affects flows of matter and energy. Indirectly, in being the primary source of energy for animals and microorganisms, plants “also control geomorphic processes through their engineering activities in soils and at the surface of the Earth.”

Trees play a central geomorphological role:

> In particular the development of the lignin-containing plants (shrubs and trees) in the middle Devonian (380 Ma[9]) have produced the most significant geomorphic changes. Their complex and resistant root and stem systems combined with their slower decomposition has contributed to increase global sediment stability and storage in time and in space on the Earth’s surface [Corenblit & Steiger 2009: 894].

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[9] “Ma” means millions of years ago.

The authors contextualize the role of life in geomorphology in terms of energy sources available to do geomorphic work. Vegetation dynamics, driven by photosynthesis, which converts solar energy into stored chemical energy, is one of four such energy sources. The other three are: gravity, solar energy, and geothermal activity. This article helps us to visualize Earth's systems (in particular lithosphere and biosphere) as interwoven, where biology drives not only life processes, but land formation process as well.

Gaia and natural selection, Lenton 1998

The Gaia hypothesis invites us to imagine Earth as an integral living system in order to explore the mechanisms by which life helps create and maintain the conditions for life, such as an oxygenated atmosphere.

“The Gaia theory proposes that organisms contribute to self-regulating feedback mechanisms that have kept the Earth's surface environment stable and habitable to life” [Lenton 2000: 439]. This theory was developed by James Lovelock, a chemist who observed that Earth's atmosphere is in a constant state of disequilibrium,

> in which highly reactive gases, such as methane and oxygen, exist together at levels that are different by many orders of magnitude from photochemical steady states. Large, biogenic fluxes of gases are involved in maintaining such disequilibrium. This perturbed state is remarkable in that the atmospheric composition is fairly stable over periods of time that are much longer than the residence times of the constituent gases, indicating that life may regulate the composition of the Earth's atmosphere. This concept became the foundation of Gaia theory [Lenton 2000: 439].

The theory is based on the evolutionary biology concept of natural selection, focusing on traits that alter the environment and the resulting feedback from that environmental change on the organisms with the traits that produced it. Lenton offers a few examples to illustrate such feedbacks, starting with the “Daisyworld” model, where black pigment in daisies confers advantage in an environment with below-optimal temperatures. By absorbing heat, the black daisies grow better than their white counterparts and their population dominates. The global effect of a growing population of individually warm daisies raises the overall temperature of the world. At this point, the population of white daisies begins to rebound and the global temperatures cool again.

> Gaia theory aims to be consistent with evolutionary biology and views the evolution of organisms and their material environment as so closely coupled that they form a single, indivisible, process. Organisms possess environment-altering traits because the benefit that these traits confer (to the fitness of the organisms) outweighs the cost in energy to the individual [Lenton 2000: 440].
>
> Some activities that alter the environment are so advantageous (to the organisms carrying out the activities) that they become widespread, fundamental properties of organisms. (An example is photosynthesis, the implications of which have been studied by modelling the Archaean–Proterozoic transition.) Other activities are favorable only under particular environmental conditions and hence are subject to selection. In such cases, it is often changes in one environmental variable that determine whether a trait remains selectively favorable. If the spread of the trait alters this environmental variable, it also alters the forces of selection determining its own value [Lenton 2000: 442].

Furthermore, ecosystems-level environmental feedbacks can be understood in terms of natural selection. For example:

> The trees of the Amazon rainforest, through generating a high level of water cycling, maintain the moist environmental conditions in which they can persist (a positive feedback on growth and selection). Nutrients are also effectively retained and recycled. If too much forest is removed, the water-regulation system can collapse, the topsoil is washed away and the region reverts to arid semi-desert, a change that may be difficult to reverse [Lenton 2000: 445].

Lenton explains that while there are geochemical mechanisms involved in regulating the climate, “it is clear that organisms are involved in many environmental feedbacks on Earth, and their effects need to be considered” [Lenton 2000: 441]. For example, acid rain weathers calcium-silicate rocks resulting in the formation of calcium carbonate by removing carbon dioxide from the atmosphere, thus cooling the Earth. Warmer average global temperatures would lead to more rain, thus more weathering and the cooling effects of that negative, self-correcting feedback. “However, geochemical feedbacks [such as this one] operate slowly and are not very responsive to perturbation” [Lenton 2000: 441]. Rock weathering organisms can amplify the weathering effects of the rain, hastening the negative feedback. Thus, there’s an intertwining of processes that regulate the climate.

The significance of this article is that if life has been at least partly responsible for creating and maintaining the habitability of Earth’s climate for the past 3.5 billion years, then it has a key role to play today as we grapple with how to keep global temperatures from rising above 1.5C.

Ecosystems are clearly victimized by climate chaos, while also being directly damaged by avoidable human activity, such as land-clearing for development and agriculture and the ubiquitous use of chemical toxins and plastics. Yet if ecosystems are also a driver of climatic conditions, then it is critical to protect them from further harm and to nurture their growth and stability. Humans can become Gaia's nursing team – we can improve the conditions for her recovery to the point when her own systems kick in and bring her back to health.

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