REGENERATIVE AGRICULTURE *and the* SOIL CARBON SOLUTION

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REGENERATIVE AGRICULTURE IS A WIN-WIN-WIN CLIMATE SOLUTION

that is ready for widescale implementation now.

WHAT ARE WE WAITING FOR?

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EXECUTIVE SUMMARY

The way we manage agricultural land matters. It matters to people, it matters to our society, and it matters to the climate.

In 2014, Rodale Institute released its landmark white paper entitled “Regenerative Organic Agriculture and Climate Change: A Down-to-Earth Solution to Global Warming.” That white paper was unquestionably influential: it stimulated corporate and governmental adoption of regenerative agriculture, it inspired many farming organizations and farmers to adopt regenerative practices, and it accelerated the recognition that agriculture done properly must be part of an effective global response to our climate crisis. However, while the 2014 paper was a necessary wake-up call, it was not sufficiently effective because change hasn’t happened fast enough. The ecological meltdown is accelerating. And its accelerating to a place where we now face the very real challenge of being able to grow enough nourishing food to support the ever-increasing human population. On World Soil Day in 2015, the Food and Agricultural Organization of the United Nations provocatively summed it up by stating "we have about 60 years of harvests left—and then?"

This deteriorating planetary condition, along with a deepening scientific understanding of and support for regenerative agriculture, is the ecological context for this new white paper. Farmers, ranchers, agronomists, and academic researchers have been on task for these past six years, and their great strides alone support the issuance of a fresh assessment of the state of science and practice.

Any success the 2014 white paper had must be viewed in a grim planetary context: in 2014, there were 397 parts per million (ppm) of atmospheric CO_2, while today the Earth is burdened with 416 ppm. Every ppm of atmospheric CO_2 correlates to the release of 2 billion tons of terrestrial carbon, so those nineteen parts per million since 2014 represent the transfer of 38 billion additional tons of carbon from below ground to the atmosphere.

Continuing the climate math, carbon dioxide is 3.67 times the weight of carbon, so this transfer of 38 billion tons of below-ground carbon resulted in the deposition of approximately 140 billion new tons of CO_2 contamination to the blanket of greenhouse gases already overheating our planet. There is no quarreling with this simple but deadly math: the data are unassailable. The World Climate Research Programme, in July 2020, projected that current CO_2 trends would “likely reach the doubling of pre-industrial ppm of CO_2 by 2060,”—up to 560 ppm. As a consequence, that body of distinguished scientists predicted our planet will likely see increased warming in the range of 2.6 °C to 3.9 °C. That magnitude of temperature increase is incompatible with the continuation of life as we know it. We will, if trends are not reversed, cease to inhabit a livable planet.

> ***This paper is not merely a revisiting of the problem or yet another dire report on the state of our planetary health. It is not another “wake up call” asking the reader to pay attention to the science or the climate change we can all see and feel around us. It is an invitation.***

While the planet continues to overheat, conventional agricultural production systems and arable land misuse have, over time, degraded approximately 75% of the Earth’s land areas. On top of that existing degradation, we are now losing an estimated 36 billion tons of soil every year, based on the 2017 consensus estimate of the European Commission Joint Research Centre. Once again, using simple but deadly math, this suggests that since 2014 (when the previous white paper was published) the planet has lost more than 200 billion tons of soil, or approximately 26 tons of topsoil for every human. As a global society, we continue to trade our soil and our future for short-term profits and status quo production models.

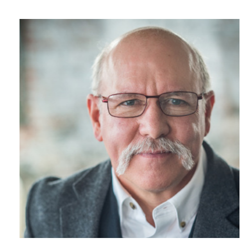
The environmental impacts of agricultural practices and translocation of carbon from terrestrial pools to atmospheric pools can be seen and felt across a broad spectrum of planetary species. Recent studies declared that we’re experiencing a biodiversity apocalypse, with 1,000,000 species at serious risk of extinction due to climate crisis and habitat loss. Couple that biodiversity collapse with the extreme water stress afflicting as many as seventeen nations (with a combined population of approximately 1.7 billion people), and it becomes clear that much of our planet is degraded.

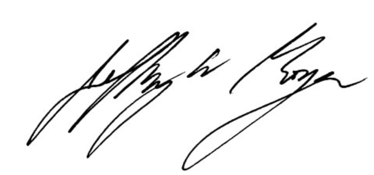
This paper is not merely a revisiting of the problem or yet another dire report on the state of our planetary health. It is not another “wake up call” asking the reader to pay attention to the science or the climate crisis we can all see and feel around us. It is an invitation. An invitation to journey in a new direction. It is intended to be both a road map to change and a call to action to follow a new path. One led by science and blazed by farmers and ranchers across the globe. Blessed with committed soil scientists and the talents of agricultural expert Dr. Jennifer Hayden, Rodale Institute has taken another look at the developing science—and calls upon the reader to take positive steps towards impactful change.

Based on peer-reviewed research and the seasoned observations of agronomists working around the world, this white paper confidently declares that **global adoption of regenerative practices across both grasslands and arable acreage could sequester more than 100% of current anthropogenic emissions of CO_2** and that stable soil carbon can be built quickly enough to result in a rapid drawdown of atmospheric carbon dioxide. We now know enough to have real hope, and with this hope comes the responsibility to journey down a new path.

This introduction is co-authored by representatives of two formative organizations in the regenerative movement. This white paper reflects the Rodale Institute’s unique perspective on regenerative agriculture. The DNA of the Rodale Institute is both regenerative and organic, and The Carbon Underground is honored to support Rodale Institute’s great legacy. Our organizations do not align on every nuance of what it means to be regenerative, as reflected in the two standards, Regenerative Organic Certification, and the Soil Carbon Index, associated with Rodale Institute and The Carbon Underground, respectively. While those standards differ in some important respects, we believe that what unites them is far more important than what separates them, and from a carbon perspective, these standards are best understood as complementary, not competitive. The regenerative movement is an ecosystem of involved farmers, ranchers, scientists, governments, and NGOs, and like all ecosystems it is enhanced by robust collaborative diversity.

Together we both sound the alarm and proclaim the regenerative farming solution: It’s time to start our journey with a brighter future for our planet and ourselves as the destination.





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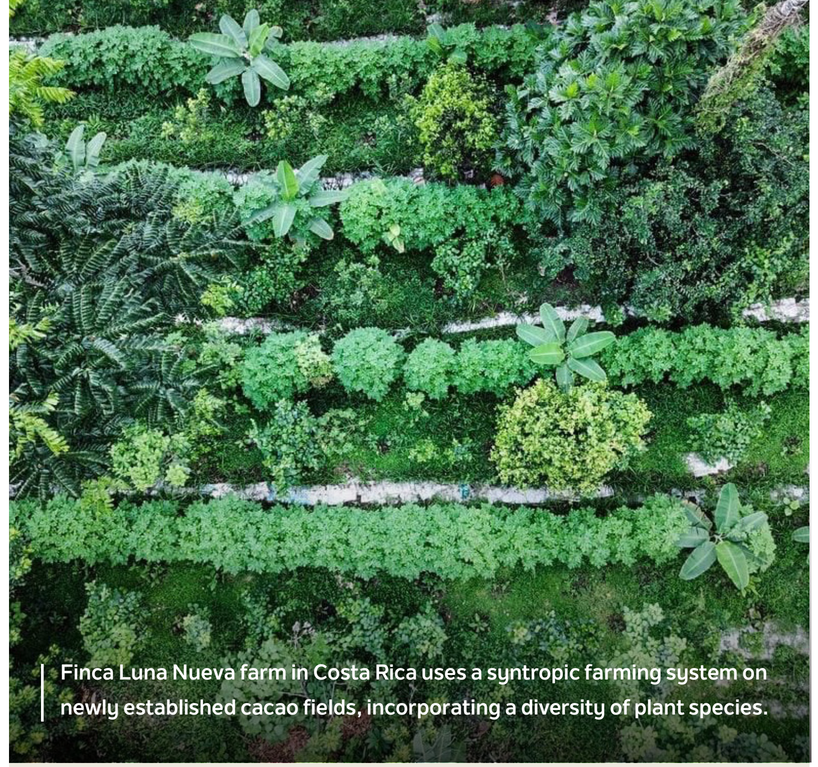
INTRODUCTION

Human activities radically alter the planet—a power that comes with a responsibility. Dominant societal narratives still favor economic rewards even as the climate crisis and multiple other interconnected environmental disasters shock our planet. Earth has a big say in what happens, but the planet needs us to cooperate in its healing for the sake of humans and all life. Rachel Carson predicted this moment in 1962, and yet her words remind us that it's not too late to change course:

> *"We stand now where two roads diverge. But unlike the roads in Robert Frost's familiar poem, they are not equally fair. The road we have long been traveling is deceptively easy, a smooth superhighway on which we progress with great speed, but at its end lies disaster. The other fork of the road — the one less traveled by—offers our last, our only chance to reach a destination that ensures the preservation of the earth."*
>
> —Rachel Carson in the Introduction to Silent Spring [3]

The globally connected food and farming system succeeds in producing an enormous oversupply of foodstuffs unimaginable to our great-grandparents because we've focused on calorie yields. It's no surprise to anyone paying attention that this carbohydrate abundance comes at a high price: widespread degradation of land, water and air; biodiversity and ecosystem losses; continued hunger and nutritional deficiencies paired with a rapid rise in obesity and related diseases; and destruction of rural communities and farmer livelihoods around the world [2]. The dominant farming system relies on synthetic and proprietary inputs that increase in cost every year, while commodity crop prices stagnate and soils deteriorate. These problems arise from chemical-based forms of agriculture, crop monocultures, and mismanagement of livestock, which now cover what were once the world's most fertile agricultural lands:

> *"The uniformity at the heart of these systems, and their reliance on chemical fertilizers, pesticides and preventive use of antibiotics, leads systematically to negative outcomes and vulnerabilities." [4]*



Finca Luna Nueva farm in Costa Rica uses a syntropic farming system on newly established cacao fields, incorporating a diversity of plant species.

What is Regenerative Agriculture?

Regenerative agriculture is a system of farming principles that rehabilitates the entire ecosystem and enhances natural resources, rather than depleting them.

Robert Rodale, son of American organic pioneer J.I. Rodale, used the term 'regenerative' to distinguish a kind of farming that goes beyond simply 'sustainable.' Regenerative agriculture:

> *"...takes advantage of the natural tendencies of ecosystems to regenerate when disturbed. In that primary sense it is distinguished from other types of agriculture that either oppose or ignore the value of those natural tendencies." [9]*

Regenerative agriculture is marked by working to achieve closed nutrient loops, reduction or elimination of biocidal chemicals, greater crop and biological diversity, fewer annuals and more perennials, and practices that mimic natural ecological processes. Some leaders of the movement also believe regenerative agriculture should extend beyond our treatment of natural resources and include commitments to animal welfare and social fairness. These pillars are included in the Regenerative Organic Certification [see page 23].

At the same time, the climate crisis bears down. A decade ago, the United Nations Environment Program (UNEP) said we needed to limit greenhouse gas emissions to 44 gigatons of carbon dioxide equivalent (44 $GtCO_2e$) by 2020 [5]. If we did nothing new to mitigate climate crisis, projections suggested that by 2020 annual emissions might be 56 $GtCO_2e$, leaving a gap of 12 $GtCO_2e$ between the carbon already in the atmosphere and our desire to continue living normally on Earth [5].

> ***The solution is farming. Not just business-as-usual industrial farming, but farming like the Earth matters.***

In 2018, total global emissions were 55.3 $GtCO_2e$—approaching the worst case scenario [6]. (A seven percent reduction every year for the next decade is needed to limit warming to 1.5°C) [6]. What's more, "**accelerated soil erosion may be the second largest source of anthropogenic emissions of greenhouse gases, and its credible estimates are not known**" [7]. We spent the last decade walking a path to a precipice. The emissions cuts needed now "may seem impossible," says Inger Andersen, the Executive Director of the UNEP, "but we have to try" [6].

And yet, there is hope right beneath our feet. There is a biotechnology for massive planetary rehabilitation that is tested and available for widespread dissemination right now. The cost is minimal and it is adaptable to local contexts the world over. It can be rolled out tomorrow providing multiple benefits beyond climate stabilization. The solution is farming. Not just business-as-usual industrial farming, but farming like the Earth matters. Farming in a way that restores the quality of soil, water, air, ecosystems, animals, and ultimately humanity. Farming that improves our soil's natural ability to function so the planet and all of its life can also function. This kind of farming is called regenerative agriculture.

Regenerative agriculture revitalizes land. It's a systems approach where farmers work with nature, not against it. It's a biological model based on principles of ecology. With the farmer's help, farm and rangeland can lock carbon underground, thereby restoring degraded soils, addressing food insecurity, and mitigating the impacts of the climate crisis on food production. Regenerative agriculture is also our best hope for a quick drawdown of atmospheric carbon dioxide. Let us learn from regenerative farmers who have been cooperating with nature, who have "solved for pattern" [8]. Their results are the inspiration that will fuel a wholesale shift away from the failed era of sustainability to a golden age of regeneration.

Agricultural Emissions

Agriculture as practiced across most of the world is not yet part of the solution—it's part of the problem. Rather than mitigating the climate crisis, it is a net producer of greenhouse gas emissions both directly through conventional industrial farming practices, and indirectly through land-use change and the greater food system [10]. Agriculture production accounts for around ten percent of annual emissions (6.2 Gt CO_2e) [11]. **The food system at large, including fertilizer and pesticide manufacture, processing, transportation, refrigeration and waste disposal, accounts for 30% or more of total annual emissions [11].**

With the widespread industrialization of farming in the mid-20th century, contemporary agricultural practices, such as synthetic fertilizers, pesticides, intensive tillage, monocropping, and yield-based management systems, accelerated the depletion of soil carbon stocks [10,12]. Most agricultural soils have lost from 30% to 75% of their original soil organic carbon to the atmosphere due to conventional farming practices [13]. Two-thirds of the world's corn and wheat cropland now have less than two percent soil organic carbon [14]. Nitrous oxide emissions have been rising due to nitrogen fertilizer over-use [11], and the intensification of livestock and rice production has exacerbated release of methane (CH4) [11].

Yet, there is hope. These degraded soils hold the promise for regeneration. Degraded farm soils are some of the best soils on the planet to achieve carbon drawdown: they are already highly managed, they're accessible, and they have the capacity to hold a lot of carbon—all it takes are management changes to make this happen. While soils are inherently different, agricultural soils were chosen because they are productive and they have the natural capacity to store carbon over long timescales.

Regenerative agriculture, with its focus on achieving positive ecosystem outcomes, can be practiced under many names: agroecology, organic, biodynamic, holistic, conservation, permaculture, management intensive grazing, agroforestry and more. There won't be a one-size-fits-all approach for regeneration of degraded farm and rangeland, but the vanguard of regenerative farmers and researchers know enough now to provide guidance for each farm given its specific physical, environmental, social and economic contexts. Farming in ways that sequester carbon is not just possible in many places, it's already happening across the world.

Soil Carbon Sequestration

Globally, soil organic matter contains three to four times as much carbon as either the atmosphere or terrestrial vegetation [5,14]. Even small changes in soil carbon can lead to large changes in the atmospheric concentration of carbon dioxide, either for better or for worse [5]. The UNEP is unequivocal:

> ***"To close the emissions gap, land use must transition rapidly from being a net source of emissions to a net sink." [4]***

Improved management of farm and ranchland with known, low-cost practices can both reduce greenhouse gas emissions and remove carbon dioxide from the atmosphere [8,15]. **Soil carbon sequestration works with biodiversity above and below ground—in plant and soil life—to capture carbon dioxide with photosynthesis, drawing it down underground as soil carbon, and locking it in soil organic matter through microorganism and mineral associations.**

If carbon sequestration rates attained by exemplary cases were achieved on crop and pastureland across the globe, regenerative agriculture would sequester more than our current annual carbon dioxide (CO_2) emissions (Figure 1, page 10), providing a mechanism to meet global carbon emissions goals, drawdown legacy carbon dioxide, and give us the time needed to bring emissions from other sectors in to balance.

Greenhouse Gases

The three most abundant greenhouse gases are carbon dioxide (CO_2), methane (CH4) and nitrous oxide (N_2O). Total greenhouse gas emissions are often expressed in a unit called carbon dioxide equivalent, or CO_2e. This unit puts all greenhouse gas emissions on a level field by expressing them in terms of the amount of carbon dioxide that would have the same global warming effect. In 2018, 55.3 Gt CO_2e were emitted. More than 2/3 of total emissions come from carbon dioxide alone: 37.5 GtCO_2.

Nearly 1 trillion metric tons of carbon emissions have accumulated in the atmosphere, leading to CO_2 concentrations of 407 ppm in 2018—47% above pre-industrial levels [13]. Soil carbon sequestration focuses on removing carbon dioxide from the atmosphere, but regenerative farming systems also reduce emissions of carbon dioxide, nitrous oxide and methane.

> ***Degraded farm soils are some of the best soils on the planet to achieve carbon drawdown.***

A POTENT CORRECTIVE

In 2018, global emissions of greenhouse gases were 55.3 metric gigatons (Gt CO_2e). The vast majority of these emissions—37.5 Gt—come from carbon dioxide, which could be reduced significantly by regenerative agriculture [4]. **Data from farming and grazing studies show the power of exemplary regenerative systems that, if achieved globally, would drawdown more than 100% of current annual CO_2 emissions.** Global extrapolations of carbon sequestration rates recorded by agricultural scientists in Table 1 are provided as a thought experiment showing the power of regenerative agriculture to drawdown atmospheric carbon dioxide.

TABLE 1: Carbon Sequestration Potentials

PLACE/STUDY	MANAGEMENT PRACTICES	MAIN CROP	CARBON SEQUESTRATION (Mg ha⁻¹ yr⁻¹)		GLOBAL EXTRAPOLATION[b] (Gt CO_2 yr⁻¹)	
			C+	CO_2	CO_2	% CO_2 Offset
Cropland – accounts for approximately 30% of arable farmed land						
Global [16]	Cover crops *(global metanalysis)*	Various	0.32	1.17	1.63	4.35
US, Mid-Atlantic [17]	Regenerative organic system - diverse rotation	Grain crop rotation	0.85	3.12	4.34	11.6
US, Mid-Atlantic [18]	Regenerative organic system - compost utilization	Corn & Wheat	2.36	8.66	12.04	32.11
Costa Rica [19]	Multistrata agroforestry	Cacao & Poro	4.16	15.27	21.23	56.61
Mediterranean [20]	Organic amendments	Olives	5.3	19.45	27.05	72.13
Global Tropical* [21]	Cover crops and green manure	Corn	5.8	21.28	29.60	78.93
US, Southwest* [22]	Fungal compost *(BEAM system)*	Carbon *(no traditional crop)*	10.27	37.69	52.41	139.76
Grazing or rangeland – accounts for approximately 70% of arable farmed land						
US, Midwest [23]	Regenerative grazing system (AMP)	Beef	3.59	13.17	43.04	114.77
US, Southeast [24]	Rotational grazing	Dairy	8.0	29.36	133.37	355.65

+ C is change in soil carbon in (Mg ha-1 yr-1) and CO2 is the equivalent of C as carbon dioxide.
b Total potential carbon sequestration in Gigatons (Gt) if all global cropland or grazing land converted to the respective regenerative system and percentage of carbon dioxide offset from 37.5 Gt CO2e global annual greenhouse gas emissions [4].
*Not peer-reviewed.

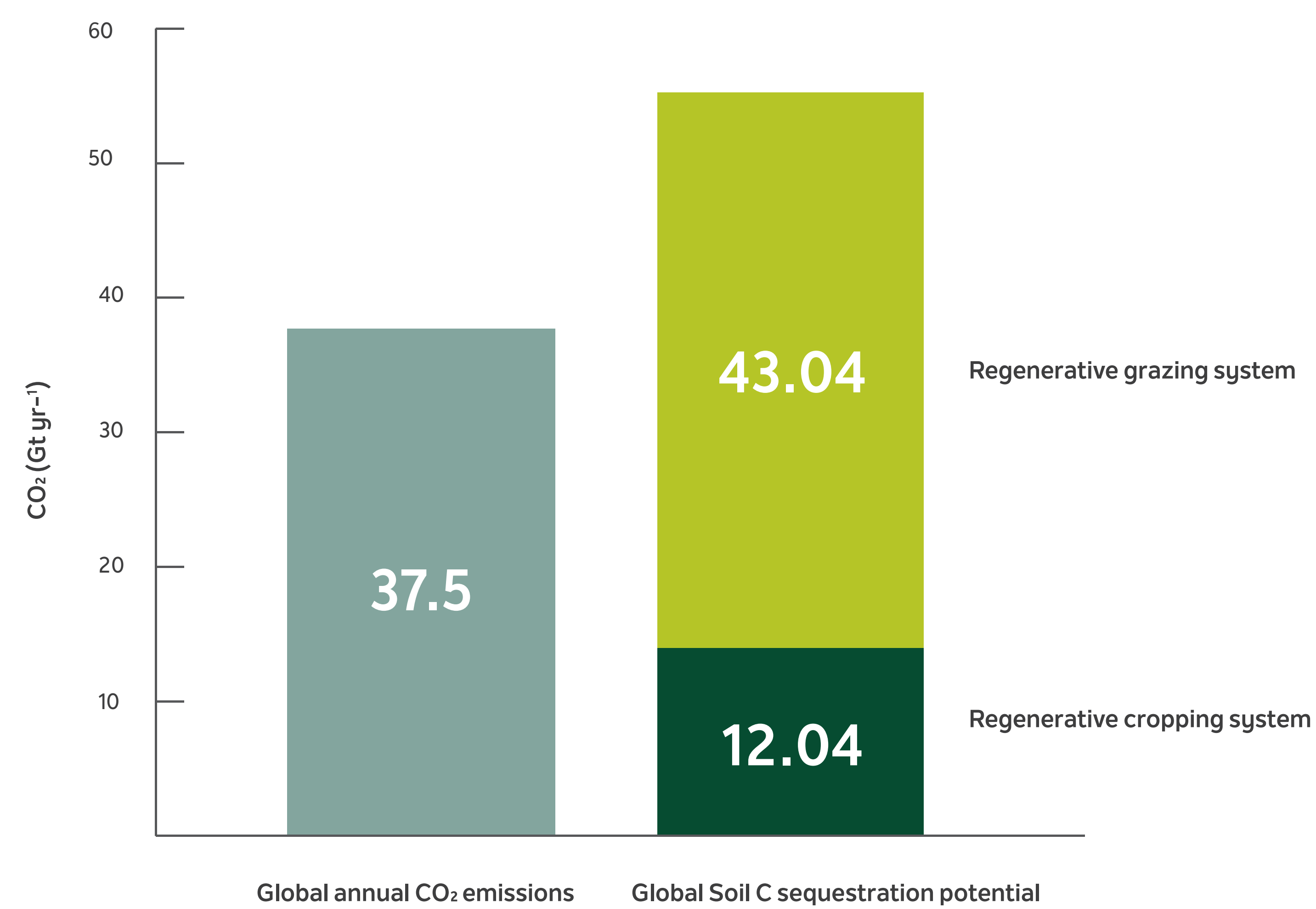
If only cover crops were adopted in otherwise conventional systems across all cropland [16] ~4% of annual CO_2 emissions might be sequestered. However, by bundling practices, if management of all current cropland shifted to a regenerative system like the Mid-Atlantic site [18] we could potentially sequester 8 times more than cover crops alone, or 32% of annual CO_2 emissions (~12 Gt CO_2). And, if all global pasture was managed to a regenerative model like the Midwestern US study [23], an additional 114% of all annual CO_2 emissions (~43 Gt CO_2) might be sequestered.

By those calculations, shifting both crop and pasture management globally to regenerative systems is a powerful combination that could drawdown more than 100% of annual CO_2 emissions (Figure 1), pulling carbon from the atmosphere and storing it in the soil.

While the thought experiment shows us the potential for soil carbon sequestration, soils are varied and it is unlikely that we can achieve such a sweeping shift in agricultural production quickly. But even small changes will have an impact—the Intergovernmental Panel on Climate Change (IPCC) reports "high confidence" in the evidence for soil carbon sequestration as an atmospheric carbon dioxide removal strategy [9].

There is a clear opportunity to restore degraded soils by capturing atmospheric carbon through regenerative agriculture. Investing in human capacity, knowledge infrastructure and safe, proven agricultural techniques can produce the change we need to stabilize the climate while providing significant co-benefits to farmers and consumers everywhere.

FIGURE 1: Carbon sequestration potential of global adoption of regenerative agriculture



REGENERATIVE PRINCIPLES *for* SOIL HEALTH *and* CARBON SEQUESTRATION

Regenerative agriculture is a systems approach to farming that builds soil health by supporting biodiversity above and below ground to return carbon and nutrients back to the soil.

Biodiversity is the primary driver of soil carbon sequestration and many more farm and ecosystem benefits [25]. Soil organic carbon, and the soil organic matter in which it resides, are vital to plant growth by mediating soil aggregation, temperature, water infiltration and retention, and nutrient cycling. Soil organic matter also aids ecosystem services: reducing erosion, filtering pollutants, and providing habitat and food for diverse species.

Without sufficient organic matter, soil cannot support microbial life or plant life without vast amounts of imported inputs. Two-thirds of conventional corn and wheat cropland soils have been depleted to less than two percent organic matter [12], limiting yields and requiring injections of chemical inputs. This is food production on life support, ignoring the vast potential for creating healthy food by healing the land. But there is another way. As J.I. Rodale, a founder of the organic movement in America, wrote on a blackboard in 1942:

Healthy Soil = Healthy Food = Healthy People

Crop and rangeland can be regenerated, soil organic matter can be recovered and soil life can thrive again—through regenerative agriculture.

While regenerative agriculture has to be a place-based, customized, systems approach, there are certain interlinked practices that are part of most regenerative systems.

These practices alone do not signify regeneration—they are a starting point, not the end point. At a minimum, regenerative agricultural practices that support soil carbon sequestration include:

1. Diversifying crop rotations
2. Planting cover crops, green manures, and perennials
3. Retaining crop residues
4. Using natural sources of fertilizer, such as compost
5. Employing highly managed grazing and/or integrating crops and livestock
6. Reducing tillage frequency and depth
7. Eliminating synthetic chemicals

Regenerative agriculture is focused on outcomes and practices that ensure outcomes: these interlinked practices support soil life and minimize erosion by retaining biomass from a wide variety of living and dead roots, shoots, and microbes, which work together to sequester carbon [8,26].

While most of the practices that enable soil carbon sequestration are associated with regenerative farming systems, they are "best management practices" that can be adapted to any type of farm. However, supporting soil life is not as easy as just adding one practice; the synergies from interlinked practices in an overall system are the key to the biodiversity that sequesters soil carbon [27].

Soil Carbon Sequestration

Soil carbon sequestration means maximizing atmospheric carbon dioxide removal and minimizing soil carbon losses.

For soil carbon sequestration to occur, all of the soil organic carbon sequestered must originate from the atmospheric carbon pool and be transferred into soil organic matter through plants, plant residues, microbial residues, and other organic solids [28].

Soil organic matter, while highly variable, is comprised of about 50% percent soil organic carbon [29].

Photo: Brittany App, Tablas Creek Farm

Carbon Cycle Institute's Carbon Farming Practices

- Mulching/compost application
- Residue and Tillage Management
- Anaerobic Digester
- Multi-Story Cropping
- Windbreak/Shelterbelt Establishment
- Silvopasture Establishment
- Forage and Biomass Planting
- Nutrient Management
- Tree/Shrub Establishment
- Forest Stand Improvement
- Contour Buffer Strips
- Riparian Restoration
- Riparian Forest Buffer
- Vegetative Barrier
- Windbreak/Shelterbelt Renovation
- Alley Cropping
- Riparian Herbaceous Cover
- Range Planting
- Herbaceous Wind Barriers
- Critical Area Planting
- Forest Slash Treatment
- Filter Strip
- Grassed Waterway
- Hedgerow Planting
- Cross Wind Trap Strips Conservation Cover
- Wetland Restoration

BIODIVERSITY BELOW GROUND

Soil life is exceptionally complex, comprised of a vast community of microscopic bacteria, fungi, protozoa, and nematodes, as well as meso- and macrofauna like arthropods, earthworms, springtails, spiders and insects.

There are billions of these organisms in just one teaspoon of healthy soil. The soil community builds carbon stores through its interactions underground with the soil physical structure, living roots and decomposing organic matter, and aboveground with plants, animals, weather, people and their farming practices.

The abundance and composition of soil life is heavily influenced by the farm system. To harness soil carbon sequestration and its co-benefits, farmers choose interlinking management strategies that increase biodiversity above and below ground. A systematic review of over 50 international studies found nearly 60% more biomass from soil microorganisms in organically managed farm systems versus conventional [30]. The soil life in the organic systems were also over 80% more active than in conventional systems [30]. This is not surprising, as most organic systems, and all regenerative systems, are built on interlinking practices designed to increase biodiversity and support soil health.

Recent research underscores the predominant role of soil microbes in building soil carbon stores. Contrary to previous thought, it's not the recalcitrant plant material that persists and creates long term soil carbon stores, instead it's the microbes who process this plant matter that are most responsible for soil carbon sequestration [31,32]. Stable soil carbon is formed mostly by microbial necromass (dead biomass) bonded to minerals (silt and clay) in the soil. Long term carbon storage is dependent on the protection of the microbially-derived carbon from decomposition. This protection takes place in soil pores in a specific size range of 30-150 micrometers, which are created by roots from diverse polycultures—not from monocrops [33].

This means that to enable soil carbon storage, farmers should focus on encouraging diverse carbon inputs to create pore structures and feeding soil microbes, both of which are achieved with a wide variety of plant roots. These roots help microbes build biomass that becomes necromass-mineral amalgams that store carbon over very long time periods [34].

Feeding soil life to encourage biodiversity and abundance means managing the farm so that there are living roots in the ground for as much of the year as possible. Roots aid soil health by directly feeding microbes with their exudates including sugars, amino acids, and organic acids, by creating the right kind of soil structure to protect carbon, and by partnering with mycorrhizal fungi to store carbon and cycle nutrients [33,35]. As leading soil ecologist Francesca Cotrufo, PhD of Colorado State University says:

> *"It's becoming very clear that in order to regenerate soils, we have to have continuous and diverse inputs, and that mostly comes from living roots."*
>
> —(Cotrufo Interview)

Farmers must also manage microbial carbon use efficiency by applying high-quality plant inputs. When processing plant inputs, microbes simultaneously use carbon for growth and maintenance. Carbon use efficiency is the proportion of a carbon input that microbes assimilate relative to the carbon lost, or respired, out of the system as carbon dioxide [36]. Soil has a conservative carbon to nitrogen ratio of about 10:1. This means that for soil carbon sequestration to occur, every 10 units of carbon require one unit of nitrogen. This explains why high carbon inputs are, counterintuitively, not associated with proportional gains in soil carbon. Applying diverse but low quality (high C:N ratio) inputs (e.g. high proportion of sawdust or woodchips) or cover crops (e.g. cereal only) results in low carbon use efficiency, which causes a larger proportional loss of carbon. These high carbon to nitrogen ratio inputs also put microbes under stress, resulting in nitrogen mining from existing soil organic matter. To avoid this, farmers should include high quality (low C:N) inputs such as legume cover crops and manure, vegetable based, or worm compost, which are more efficient in building carbon.

Plants rely on available nutrients provided by the soil. This nutrient cycle depends on rapid carbon matter turnover by microbes, resulting in particulate organic matter (POM), which does not store carbon over long periods [34]. Managing agricultural soil to increase biodiversity and soil life abundance below ground results in organic matter buildup that stores carbon for the short and long terms. Both types of organic matter are needed for proper ecosystem function, nutrient retention and cycling, and food production.

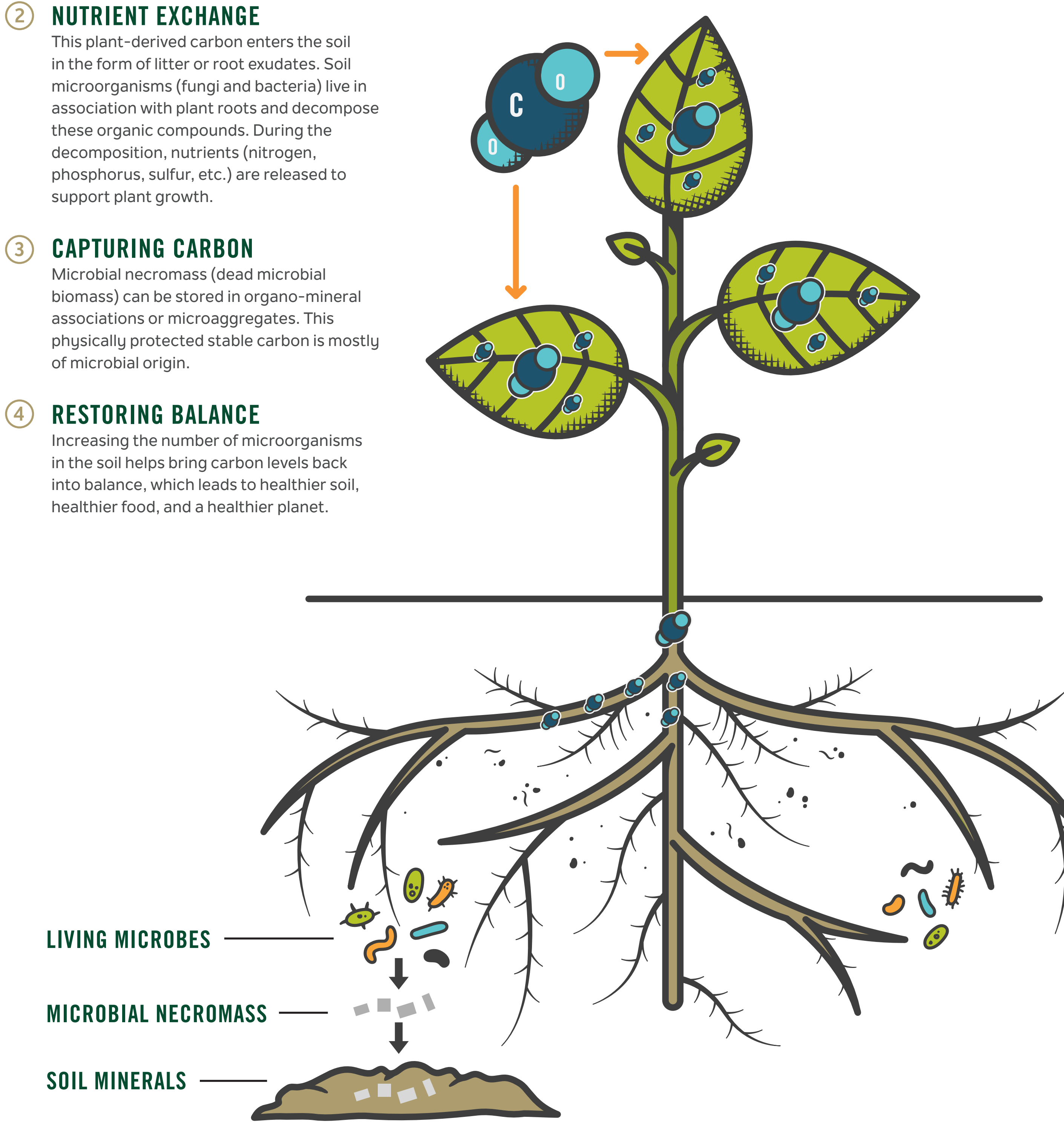
CARBON SEQUESTRATION - HOW IT WORKS

① PHOTOSYNTHESIS
During photosynthesis, plants convert carbon dioxide (a gas) into sugar (carbohydrate molecules).

② NUTRIENT EXCHANGE
This plant-derived carbon enters the soil in the form of litter or root exudates. Soil microorganisms (fungi and bacteria) live in association with plant roots and decompose these organic compounds. During the decomposition, nutrients (nitrogen, phosphorus, sulfur, etc.) are released to support plant growth.

③ CAPTURING CARBON
Microbial necromass (dead microbial biomass) can be stored in organo-mineral associations or microaggregates. This physically protected stable carbon is mostly of microbial origin.

④ RESTORING BALANCE
Increasing the number of microorganisms in the soil helps bring carbon levels back into balance, which leads to healthier soil, healthier food, and a healthier planet.



NITROGEN

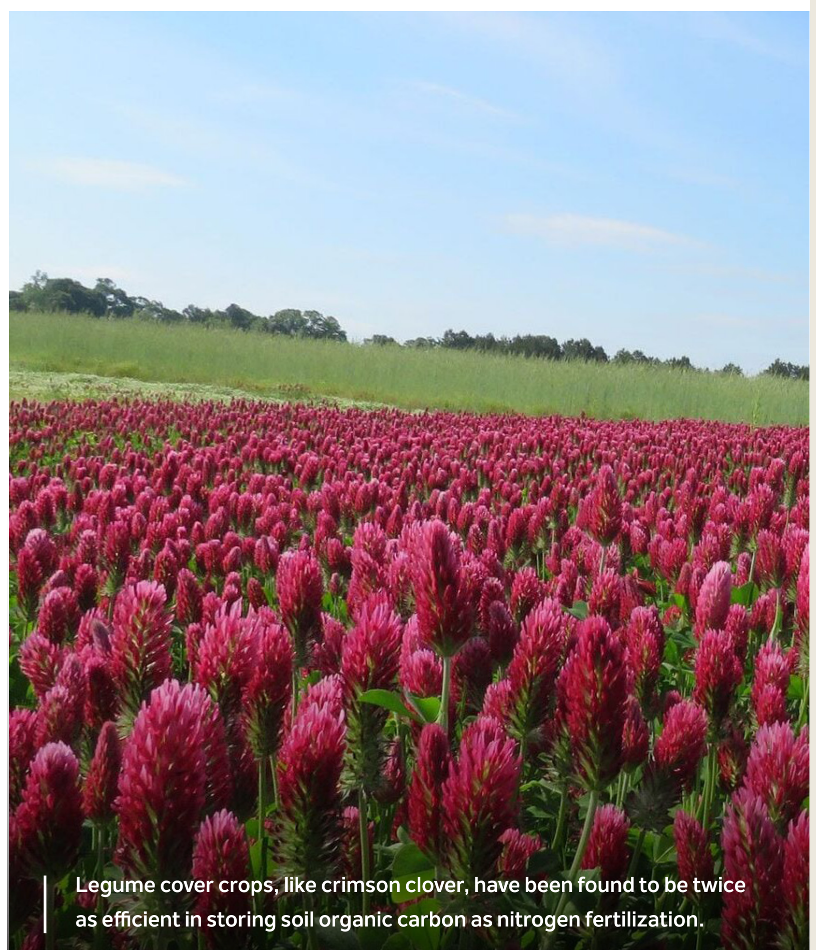
Carbon does not cycle alone. The type of nitrogen used in an agricultural system is linked to the carbon storage capability of that system. Long-term studies demonstrate that providing crop fertility with composts or manures results in increased soil carbon storage, while the use of synthetic fertilty sources results in the loss or no change in soil carbon [37,38]. Organic nitrogen sources support soil carbon sequestration by feeding the microbes responsible for carbon storage. Synthetic nitrogen sources encourage the dominance of bacteria that quickly turn ammonia into nitrate, which is easily respired or otherwise lost from the soil [39–41].

> *When compost replaces synthetic nitrogen, plants grow more roots.*

Reduction of fertilizer nitrogen losses is vital. Less than half of the 109 million metric tons of fossil-fuel-based nitrogen fertilizer used each year is assimilated into crops, the rest is either leached into groundwater creating marine dead zones, or lost as potent nitrous oxide greenhouse gas emissions [42]. In addition, the industrial production of nitrogen fertilizer directly contributes two to three percent of all global greenhouse gas emissions; and the acidification of agricultural soils due to synthetic nitrogen also contributes another two to three percent of emissions [43].

When compost replaces synthetic nitrogen, plants grow more roots, fixing more atmospheric carbon in the process [44]. **Legume cover crops have been found to be twice as efficient in storing soil organic carbon as nitrogen fertilization** [45]. In a multi-decade field experiment comparing soil carbon sequestration and fertilization, organic fertilization significantly improved the capacity of soil organic carbon storage in comparison to chemical fertilization [46]. In a cropping trial of wheat and maize, organic compost led to the formation of long-term carbon storage at the rate of .38 metric tons of carbon per hectare per year, compared to .23 for industrial fertilizers [47]. After 34 years in Rodale Institute's Farming Systems Trial, the organic manure system had between 18 to 21% higher soil organic carbon levels than the conventional system [48]. In this long-term trial, the soil carbon sequestration rate was highest in the first 15 years [17].

Regenerative systems can provide the nitrogen needed for soil carbon sequestration by including nitrogen-fixing legumes and/or trees in the farm plan, making synthetic nitrogen fertilization unnecessary. Legumes planted as cover crops, forage, or cash crops in regenerative systems work with rhizobium, a soil bacterium, to fix atmospheric nitrogen which feeds plants and microorganisms. This nitrogen fixing relationship supports carbon storage while reducing nitrogen losses and environmental damage that comes with synthetic fertilization [49]. Ectomycorrhizal fungi, those associated most with trees, work with bacteria to control the amount of nitrogen available, keeping the soil community in a balance that suppresses carbon respiration and increases soil carbon storage [50–52]. Farmers can encourage atmospheric nitrogen fixation by inoculating legume or tree crops with nitrogen-fixing rhizobia bacteria or ectomycorrhizal fungi.



Legume cover crops, like crimson clover, have been found to be twice as efficient in storing soil organic carbon as nitrogen fertilization.

SPECIAL INSERT: FARMING SYSTEMS TRIAL

RODALE INSTITUTE'S FARMING SYSTEMS TRIAL – EST. 1981

North America's longest-running side-by-side comparison of organic and conventional agriculture.

Rodale Institute has been comparing various grain cropping systems, side-by-side, for more than 40 years. The Farming Systems Trial, divided into 72 plots on 11 acres at Rodale Institute's headquarters in Kutztown, PA, have proven that regenerative practices, including cover cropping, crop rotation, and composting, lead to increased soil health and carbon storage, while producing competitive yields, using less energy, and being more profitable for farmers.

Learn more at RodaleInstitute.org/FST.

Results at a Glance

The FST has shown that, in comparison with conventional methods, organic systems:

- **PRODUCE** competitive yields with a good management plan
- **YIELD** up to 40% more in times of drought
- **EARN** 3-6x greater profits for farmers
- **IMPROVE** soil health and build soil organic matter over time
- **USE** 45% less energy
- **RELEASE** 40% fewer carbon emissions
- **LEACH** no atrazine, a toxic chemical, into waterways

The Systems

CONVENTIONAL SYNTHETIC

This system represents a typical U.S. grain farm. It relies on synthetic nitrogen for fertility, and weeds are controlled by synthetic herbicides selected by and applied at rates recommended by Penn State University Cooperative Extension. GMOs were introduced in 2008.

ORGANIC LEGUME

This system represents an organic cash grain system. It features a mid-length rotation consisting of annual grain crops and cover crops. The system's sole source of fertility is leguminous cover crops and crop rotation provides the primary line of defense against pests.

ORGANIC MANURE

This system represents an organic dairy or beef operation. It features a long rotation of annual feed grain crops and perennial forage crops. Fertility is provided by leguminous cover crops and periodic applications of composted manure. A diverse crop rotation is the primary line of defense against pests.

Each system is further divided into two: tillage and no-till, for a total of 6 systems.

FUNGI

Fungal to bacterial ratios are ecologically important for carbon storage and overall farm system sustainability [53–55]. Soils with higher fungal to bacterial ratios are characterized by higher carbon use efficiencies [53]. The two groups of beneficial soil fungi important for soil carbon sequestration are the decomposers—saprotrophic fungi—and the root-associated, or mycorrhizal fungi [56]. Increases in plant abundance, plant diversity [57] and organic fertility sources [58–60] increase fungal biomass and fungi to bacteria ratios.

Many plant species directly depend on these fungi for growth and survival.

Ninety-percent of all plants live in symbiosis with mycorrhizal fungi [35]. These fungi are particularly important for soil carbon sequestration. Mycorrhizal fungi receive a significant portion of the plant belowground carbon as their only energy source, in return, they provide up to 80% of a plant's nitrogen and phosphorus [61]. Mycorrhizal fungi also provide soil and plants other important benefits, such as resilience from drought and stresses through their mediation of soil physical structure and water [62–65]. So many plant species directly depend on these fungi for growth and survival that researchers have suggested "the role of the symbiosis in global nutrient cycling is significant" [61,66].

Mycorrhizal fungi secrete a protein called glomalin; this particular fungi-root partnership and its glomalin are largely responsible for creating persistent, stable soil aggregates that protect soil carbon from being lost as atmospheric carbon dioxide [67,68]. This initial shorter-term stabilization provides the time for organic matter to create bonds with metals and minerals, the resultant organo-mineral or organo-metal complexes can remain in the soil for millennia [26,34].

Since mycorrhizal fungi need root-partners to survive, farming strategies that include perennial plantings, trees on edges, reduced tillage, and plants with long, fibrous root systems, encourage the long-term stabilization of soil carbon [57,67,69,70]. Long-term systems trials comparing organic and conventional systems find higher levels of mycorrhizal fungi in organic systems [71-73], presumably due to greater plant diversity through longer crop rotations and the use of cover crops and green manures. Promising effects have been shown for inoculation of soils with fungi, especially in cases where frequent or deep tillage has destroyed the native population [22,74]. Mycorrhizal fungi can be introduced through inoculations that are easily prepared on-farm [74,75] and could be a strategy to accelerate carbon sequestration and regeneration of degraded soils.

BIODIVERSITY ABOVE GROUND

An abundance of biodiversity above ground results in greater soil health and soil carbon sequestration below ground [25,76].

A lack of life above ground—bare soil—disables photosynthesis and encourages erosion. Losing soil to wind and rain decreases agricultural productivity and nullifies any hope of shifting agriculture from a climate problem to a climate solution.

Another sign of a poorly designed system is a monoculture—one type of crop covering a vast landscape. Monocultures and simplistic crop rotations require chemical inputs to control weeds, insects, and diseases and to provide fertility. These inputs destroy soil biology and exacerbate soil carbon loss.

In general, systems based on organic management principles foster biodiversity. Recent research comparing more than 60 crops grown in conventional and organic systems worldwide found that organic systems fostered significantly more biodiversity, both in abundance and in species richness [77,78]. Any farm, whether certified organic or not, can borrow from organic models to introduce a set of practices that regenerate soil life by focusing on biodiversity above and below ground.

DIVERSIFY CROPPING

Only nine crops account for nearly 70% of worldwide agricultural land use: sugar cane, maize, rice, wheat, potatoes, soybeans, oil-palm fruit, sugar beet and cassava [79]. These crops are often produced in monocultures or narrow cash crop rotations, like corn-soybean rotations. Growing just one or two types of crop makes a farm prone to devastation from pest outbreaks or extreme weather, which are becoming more common with the climate crisis. Increasing biodiversity above ground by growing diverse crops in rotation, cover cropping, strip-cropping, inter-cropping, multi-story cropping, and integrating crops and livestock leads to resilience from these kinds of shocks while aiding soil carbon sequestration.

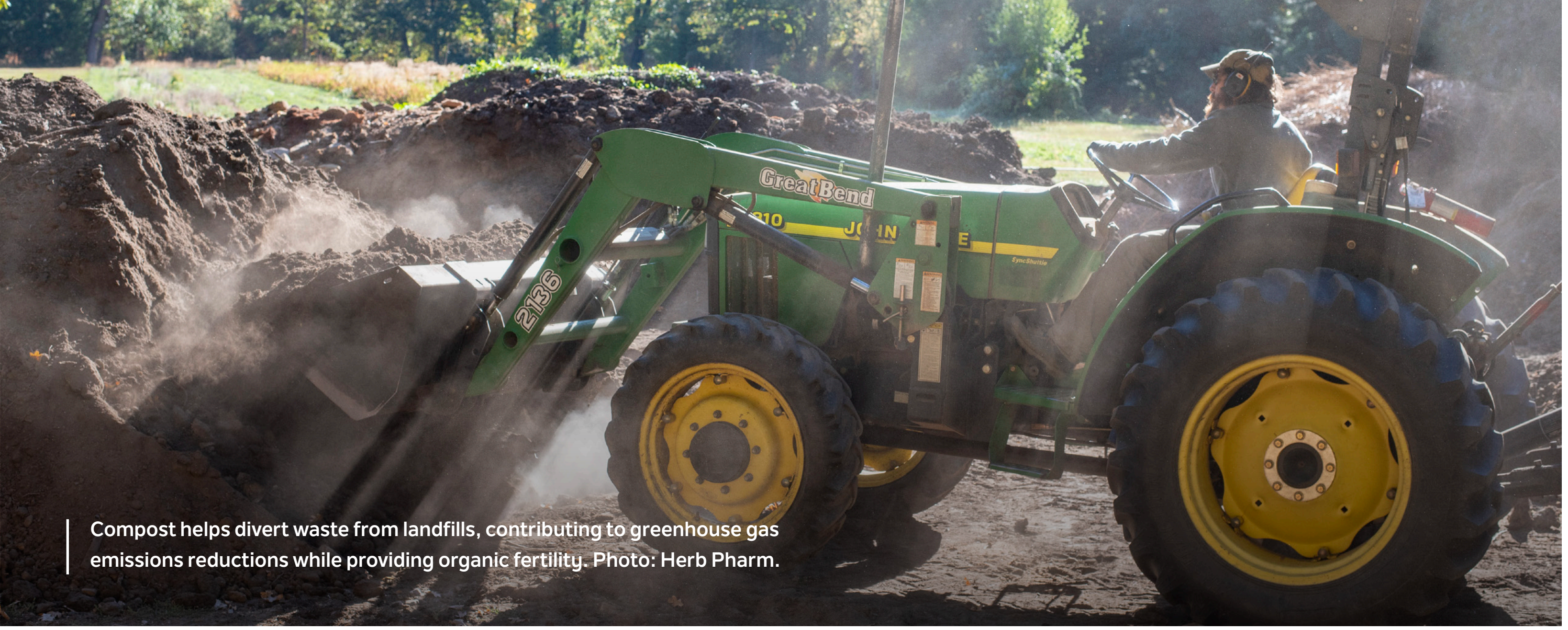
Cover crops are equally important for large and small-scale systems.

Moving crop rotations away from monoculture with fallow towards polyculture with no fallow increases soil biodiversity and sequesters carbon [30,80,81]. For instance, switching a wheat-fallow rotation to a wheat-sunflower or wheat-legume rotation was found to increase soil organic carbon stocks significantly [80] and a continuous barley system more than doubled soil carbon stocks compared to a barley-fallow system [82]. Integrating seeded grass species as cover crops, living mulches, or in rotation increases soil carbon due to the deep, fibrous root systems of these perennials [80,83]. Both enhanced cash-crop rotations and introducing cover crops result in continuous cover, which increases soil microbial biomass and soil carbon by ensuring available energy and root hosts for bacteria and fungi [81,84,85].

Diversifying with cover crops is more effective than no-till in sequestering carbon. In a 30-year trial of maize cover cropping in Brazil, the effect of a legume cover-crop on soil carbon stores was greater than the effect of not tilling the soil [86]. Similarly, in Rodale Institute's Farming Systems Trial, differences in soil carbon were not impacted by tillage intensity but differed significantly between organic and conventional systems [87]. Soil organic carbon (SOC), microbial biomass carbon (MBC), active carbon (PoxC), and water extractable carbon (WEC) were all higher in the Rodale's organic manure system compared to the conventional system, while SOC and MBC were higher in the organic legume system than the conventional system. Both organic systems include diverse cover crops and green manures with the manure system including a multi-year, mixed perennial hay crop and composted manure as additional inputs. The conventional system is a corn-soybean rotation using standard chemical inputs with no cover crops. After ten years of continuous no-till the conventional system had the lowest soil organic carbon levels in all six Farming Systems Trial systems, including its tilled conventional counterpart, suggesting that no-till alone, in the absence of cover crops and diverse crop rotations, does not sequester carbon. No-till farming limits the speed by which soil carbon loss and soil degradation occur, but it does not sequester carbon.

A meta-analysis of worldwide studies found that cover crops are nearly as effective as afforestation of cropland for sequestering carbon, while also reducing nutrient leaching, wind and water erosion and pest pressure [16]. Cover crops are equally important for large and small-scale systems. Cover crops and green manures are a critical component for regenerative tropical agriculture where smallholder maize systems interplanted with legumes can sequester almost six metric tons of carbon per hectare per year [21]. Importantly, "sequestering that carbon is a free by-product of doubling and tripling their own [smallholder's] agricultural yields" [21].

Apricot Lane Farms, in Moorpark, California, grows an assortment of grasses, nitrogen-fixing legumes, native weeds, and flowers under 75 varieties of organic and biodynamic certified fruit trees.



Compost helps divert waste from landfills, contributing to greenhouse gas emissions reductions while providing organic fertility. Photo: Herb Pharm.

MULCHES AND COMPOST

Diverse crops also play a significant role in soil carbon sequestration when their plant and root residues are retained rather than removed or burned [81,88–90]. These residues fuel the soil food web, constructing more complex biochemical structures that serve as forerunners to building soil organic matter [34,77]. Residue removal, whether of the main cash crop or a cover crop, has become common for the production of biofuel, but this practice depletes soil organic matter [91]. Retaining crop residues as a mulch prevents erosion, inhibits weed growth, moderates soil temperatures, reduces soil water evaporation, provides organic matter that is cycled by earthworms, and protects soil from extreme weather events.

The benefits of compost can accrue quickly.

In addition to retaining residues as mulch, compost made from plant residues and/or manure increases soil biodiversity and microbial biomass which improve soil structure, nutrient cycling, and disease suppression [18,92-96]. Compost is highly efficient in building soil carbon by both feeding microbes and directly forming organo-mineral associations [96]. The benefits of compost can accrue quickly: after only one application of plant-based compost, soil organic carbon and aggregate stability can increase significantly in the following years compared with non-amended soils [97,98]. In a 10-year trial, fields amended with composted dairy manure sequestered more than two metric tons of carbon per hectare per year, while the paired conventional farming system lost carbon [18].

Using only small amounts of fungal rich plant-based compost to inoculate soils can result in substantial carbon sequestration and soil health improvements [22,99,100]. For instance, a single application of compost to grassland soils increased soil carbon in labile and physically protected pools over subsequent years [100]. Compost also helps divert waste from landfills, contributing to greenhouse gas emissions reductions while providing organic fertility [101].

However, relying on compost, especially composted manure, to promote carbon sequestration in cropland soil may be difficult because of limited supplies and the economic and environmental costs of transportation [101,102]. This is especially relevant in limited resource smallholder agriculture when livestock is not present [21]. In addition, carbon inputs originating outside of a farm and transported considerable distances are difficult to attribute carbon sequestration values when considering the amendments' full lifecycle. Therefore, on-farm and local waste stream composting that recycle nutrients naturally should be promoted. For instance, incorporation of manure and crop residues in integrated crop-livestock systems sequesters carbon, improves soil function and mitigates erosion [103-105]. Farmers can select appropriate amendments from a range of on-farm or locally available mulches and composts to support soil life and soil organic matter in a way that adds carbon to the system, rather than redistributing it.

REDUCING TILLAGE

Plowing clearly affects soil life—it breaks up aggregates, destroys fungal networks, increases water trans-evaporation, increases the breakdown of organic matter, and can lead to wind and water erosion. Tilled, exposed, and eroded soils allow formerly stable soil carbon to be released as a greenhouse gas [106,107]. Switching from deep, regular tillage to reduced tillage programs improves soil structure, reduces carbon dioxide emissions and contributes to increases in soil organic carbon [108,109].

There is growing evidence that conventional no-till alone does not sequester carbon.

The interlinking effects of regenerative practices are highlighted by the highly variable outcomes researchers record in tillage experiments. **There is growing evidence that conventional no-till alone does not sequester carbon, but must be part of a systems approach**, especially when considering the entire soil profile rather than the surface soil [110]. For instance, after seven years comparing conventional industrial maize systems under reduced and conventional tillage, the reduced tillage system resulted in more carbon dioxide and nitrous oxide emissions [111]. A review of more than 30 studies found no difference in annual soil organic carbon stocks between tilled and untilled plots [16]; and an experiment testing conservation tillage with cover cropping on soil carbon sequestration potentials in conventional systems, found no benefit of reduced tillage in soil carbon storage [112]. No-till systems can best reverse the trend of soil organic carbon losses when they are part of a systems approach to regeneration that includes cover cropping, enhanced crop rotations, and reduction or elimination of synthetic inputs [90, 91]. Soil improvements occur when conventional, no-till farming practices are replaced with organic farming methods, even though some tillage is used in organic systems [113]. Soil carbon and nitrogen were higher after nine years in an organic system with reduced tillage compared with three conventional no-till systems, two of which included cover crops [113]. Any soil carbon gains achieved under conventional no-till may be countervailed by the greater nitrous oxide emissions from synthetic nitrogen fertilization in these systems [114,115].

Regenerative organic reduced tillage systems depend on heavy cover cropping for weed suppression [116]. Coupled with the benefits of organic management in general, organic reduced tillage has been shown to increase soil organic carbon by nine percent after two years and more than twenty percent after six years [116,117]. A recent review of reduced tillage in organic systems found that using inversion tillage to only a shallow depth results in significantly higher soil carbon stocks, and while weed abundance increased, yield was not necessarily affected [118].

Rodale Institute's roller crimper, shown here, rolls cover crops into a weed-suppressing mulch in an organic no-till system.

GRAZING MANAGEMENT

Regenerative grazing couples the sequestration potential of highly managed grazing systems to enhance the large natural sink capacity of perennial pasture and woodlands [5,25,104,119]. Grazing lands account for more than 70% of the global agricultural land area (there are 1.4 billion hectares of arable cropland versus 3.3 billion hectares of meadows and pastures) [79]. Thus, grazing lands may provide the greatest potential to sequester carbon through regenerative agriculture if managed properly to regenerate soils, providing a massive carbon sink with many co-benefits for ecosystems, ruminant livestock and ranchers.

Livestock itself is not the problem, it's the way we have chosen to raise livestock that creates the problem.

However, livestock production is increasingly "landless" [79]. Even in places previously known for grass-fed production, such as Brazil and Argentina, deforested land that once held extensive pastures for cattle are now being turned into conventional soybean cropland to feed cattle held in crowded lots [120]. These conventional livestock production systems contribute an estimated 7–18% of global greenhouse gas emissions [23].

But livestock itself is not the problem, it's the way we have chosen to raise livestock that creates the problem. Levels of greenhouse gas emissions from beef production are dependent on the type of grazing system [23,122], or lack of grazing. With appropriate grazing management, ruminant livestock can increase carbon sequestered in the soil that more than offsets their greenhouse gas emissions, and can support and improve other essential ecosystem services [121, 122].

Regenerative grazing is an umbrella term encompassing many forms of management intensive grazing such as adaptive multi-paddock (AMP) grazing, holistic grazing management, and mob grazing. While these systems do have differences, their commonality is in the frequent, calculated movement of high densities of ruminants with decisions made based on the herd size and qualities of the available forage. Critically, this highly managed movement of the herd allows forage to recover between grazing (Teague interview), mimicking large herds found in nature, allowing soil organic carbon to increase even at stocking rates thought to be detrimental to soil health in set-stocking systems [122, 123].

Regenerative grazing can also be employed in integrated crop-livestock systems. The careful management of grazing in these systems is critical to increasing soil organic carbon. In a nine-year study of cover crop grazing, Brazilian researchers found greater stocks of soil organic carbon and nitrogen under moderate and light grazing intensity (20–40 cm height) than for ungrazed or higher intensity grazing [124]. Similar conclusions about intensity have been made by other researchers investigating integrated crop-livestock systems [105,125,126]. The addition of rotational grazing to a cash crop rotation can provide multiple benefits beyond the increased carbon storage, including increased soil glucosidase activity, available calcium, magnesium, nitrogen, soil pH, and an increase in the carbon to nitrogen ratio [127].

Researchers have also found reduced methane emissions from cattle in regenerative systems.

In addition to managing grazing activity, more diverse pasture grass mixes, and those that include legumes, better sequester carbon than less diverse pastures [128]. Researchers have also found reduced methane emissions from cattle in regenerative systems, suggesting this may be due to the increased diversity of pasture grasses in theses systems [121]. In general, shifts in grazing management present a great potential for agricultural mitigation of the climate crisis, besting even policies aimed at reducing deforestation or targeting crop production practices [129].

SYSTEM COMPLEXITY

Regenerative agriculture is a knowledge-intensive, systems-based approach grounded in ecological thinking. It is not simply reducible to a handful of practices, instead it's guided by principles and outcomes. Even within organic systems growing the same crops and using the same tillage, management choices like cover crop type and frequency and the use of compost, have significant effects on soil health over the long-term [85]. Researchers studying nine different vegetable systems, some organic, some conventional, over almost twenty years found that only one of those systems—an organic corn-tomato-cover crop and manure system—increased soil organic carbon along the full soil profile [102].

The potential and rate of soil carbon sequestration for any farming system depends on many interacting factors [85,130,131] including: existing and historic soil organic carbon content, climate and landscape position, and length of growing season [See Sidebar for more factors].

This complexity means that farmers can best create regenerative systems when they draw from a basic ecological literacy to make management decisions for their particular farm's context.

"Globally, farmers risk becoming passive customers of the agroindustry, in which a declining ecological literacy translates into an increased reliance on purchased synthetic inputs." [132]

Longer more complex rotations, including cover crops, perennials, and trees, ensure there are diverse living roots in the soil for as much of the year as possible—an important principle for regenerative agriculture. Reintroducing highly managed livestock, retaining crop residues, reducing tillage and adding composts or microbial inoculants can further amplify soil health.

These synergistic practices combine to form regenerative systems that promote biodiversity above and belowground. The suite of practices that make an appropriate system for any one farm will differ, but the menu of regenerative practices is broad and substantiated enough now that every farm can implement some management changes that help move agriculture from a climate crisis problem, to part of the solution.

Carbon Sequestration Factors

- existing and historic soil organic carbon content
- climate and landscape position
- length of growing season
- soil type, depth, and water holding capacity
- the main cash crops or livestock
- type and rate of fertilizer used
- available soil nitrogen
- use of insecticides, fungicides, and herbicides
- cover crop types and rotation
- tillage intensity
- type and frequency of compost applications
- use of irrigation
- prevention of land use change once carbon is stored and many other management choices.

Photo: Alexandre Family Farms

WHERE *is* REGENERATIVE FARMING *in the* MARKETPLACE?

In recent years, a number of nonprofits and brands have been developing definitions of regenerative agriculture, product labeling and certifications, and measurement systems to track outcomes.

While the term "regenerative" is currently vulnerable to greenwashing, these initiatives are attempting to develop criteria—and transparency—to help consumers identify regenerative products in the marketplace:

Regenerative Organic Certified™

Regenerative Organic Certification

RegenOrganic.org

Regenerative Organic Certification, a new high-bar label led by the Regenerative Organic Alliance (and backed by brands and nonprofits such as Rodale Institute, Patagonia, and Dr. Bronners), requires organic certification as a baseline, while adding additional criteria for soil health, animal welfare and social fairness such as:

SOIL HEALTH	ANIMAL WELFARE	SOCIAL FAIRNESS
• Builds Soil Organic Matter	• Five Freedoms:	• Capacity Building
• Conservation Tillage	1. Freedom from discomfort	• Democratic Organizations
• Cover Crops	2. Freedom from fear & distress	• Fair Payments for Farmers
• Crop Rotations	3. Freedom from hunger	• Freedom of Association
• No GMOs or Gene Editing	4. Freedom from pain, injury or disease	• Good Working Conditions
• No Soilless Systems	5. Freedom to express normal behavior	• Living Wages
• No Synthetic Inputs	• Grass-Fed / Pasture-Raised	• Long Term Commitments
• Promotes Biodiversity	• Limited Transport	• No Forced Labor
• Rotational Grazing	• No CAFOs	• Transparency and Accountability
	• Suitable Shelter	

ROC Star Farms

The first Regenerative Organic Certified products hit shelves in 2020. The certification is for food, fiber, and personal care products.


Photo: Savory Institute

LAND to MARKET™

Savory Institute's Land to Market Program

savory.global/land-to-market

Ecological-Outcome-Verification (EOV) is the outcome-based science protocol inside of Savory Institute's Land to Market regenerative program. It is intended to give a voice to the land in the marketplace. The scientific protocol evaluates a comprehensive aggregate of environmental health indicators including: soil organic matter, soil carbon, soil water holding capacity, water infiltration rates, and biodiversity. The protocol utilizes a mix of quantitative and qualitative data and photographic records that work synergistically to account for changes in ecosystem services. EOV employs a variety of indicators that help producers make management improvements, alongside other empirical indicators that have value in the marketplace. As of July 2020, through Savory's global network of Hubs, over 2 million acres have been measured by EOV.

SOIL CARBON INITIATIVE

Soil Carbon Initiative

SoilCarbonInitiative.org

The Soil Carbon Initiative (SCI), created by The Carbon Underground, is an outcomes-based, scientific, agricultural standard designed to help farmers and supply chains measure improvements in soil health and soil carbon. The SCI creates a framework that calls all who touch the soil to address the climate crisis by building soil health and increasing soil carbon sequestration through better soil health. The SCI does not dictate practices, so no matter the underlying agricultural system (organic, regenerative, non-GMO, conventional), the SCI can measure soil health and soil carbon. The outcomes-focus allows supply chains to use SCI to measure the results of customized soil health programs.

Farmers demonstrate commitments annually by submitting evidence of learning/teaching about soil and ecosystem health, and of actions taken to improve ecosystem and soil health. The actions are aligned to five principles of soil health:

1. Minimize Soil Disturbance
2. Maximize Crop Diversity and On-Farm Biodiversity
3. Keep the Soil Covered
4. Maintain Living Roots Year Round
5. Integrate Livestock


Coconut Farmer in Sri Lanka. Courtesy of Serendipol, Ltd., Dr. Bronner's sister company and supplier of Regenerative Organic Certified Coconut Oil.

LOCKING CARBON UNDERGROUND

Regenerating soils while sequestering carbon can happen quickly, but trapping carbon in the soil for long periods of time is a more time-consuming process.

Since the carbon cycle is dynamic and the study of soil is inherently complex, the factors influencing retention time of carbon in soil are actively being researched [34,133].

All soil carbon is in flux and the degree to which it is protected in undisturbed soil aggregates protected from decomposers and respiration largely determines how long it is held in soil [26].

Carbon is more likely to be protected deeper in the subsoil at one to two meters.

Carbon locked in mineral-associated organic matter (MAOM) has a saturation point, but is stable over millennial time periods, while particulate organic matter (POM) cycles more quickly to provide plant nutrients each season but may be able to accrue carbon indefinitely [134]. Soil structure plays a critical role in the stability of soil carbon [33, 135, 87], which can be improved by crop management and diverse types of plant roots growing for as much of the year as possible.

Carbon is more likely to be protected deeper in the subsoil, at one to two meters [5,136–140]. And yet, it remains rare that soil carbon is measured below plow depths of 30 to 40 centimeters [16] meaning it is likely that current data sets underestimate soil carbon stocks. Recent results from paired organic and conventional vegetable and grain systems found significant differences in the deeper soil profiles [48, 87, 102]. If soil had not been measured below 30 centimeters, almost 60% of the soil organic carbon in the organic system would not have been accounted for [102]. Conversely, the shallow measurement depth would have suggested that carbon was gained in the conventional system, when in fact the deeper measurements revealed an overall loss of carbon in that system [102].

This is important as reduced tillage systems that once were assumed to have lost soil carbon compared to no-till, rather may have redistributed carbon to below the plow level and out of reach of most soil sampling [28]. Beyond 30 centimeters in the soil profile, the age of carbon increases, much of it persisting for thousands of years [141].

Both rapid and stable carbon sequestration under the conditions encouraged by regenerative agriculture are possible. Additions of fresh organic matter can, under the right circumstances, be effectively sequestered rapidly. After only one application of compost and cattle manure, soil organic carbon levels were significantly higher in the ensuing years, even after accounting for the carbon in the amendments [97,99]. Two years after conversion from a degraded conventional row crop system to regenerative grazing, dairy farms in the Southern US began sequestering carbon at a rate of 4.6 metric tons of carbon per hectare per year. This increased to a very high 9 metric tons a year before the researchers saw a plateau and decline in the rate of sequestration after six years [24]. Similarly, in tropical soils, results suggest that two years of organic system management may significantly and consistently enhance microbial biomass carbon [142].

These results suggest that stable soil carbon can be built quickly enough to result in a rapid drawdown of atmospheric carbon dioxide upon transition to regenerative agricultural systems.

Photo: Savory Institute

Rodale Institute's Farming Systems Trial has proven that organic systems (right) can outperform conventional systems (left) during times of drought.

THE QUESTION *of* YIELDS

Crop yields are often touted as the reason why we cannot scale up organic and regenerative systems, but evidence does not support this claim.

Meta-analyses of refereed publications show that, on average, organic yields are lower than conventional [143,144]. But the yield gap is most prevalent when practices used in organic mimic conventional [145], that is, when the letter of organic standards are followed using an input mentality akin to conventional chemical-intensive agriculture. Regenerative systems are based on a holistic approach to farming that aims to improve soil health, they are not simply replacing conventional chemicals with organic-approved chemicals.

Actual yields in well-designed regenerative organic systems, rather than agglomerated averages, have been shown to outcompete conventional yields for almost all food crops including corn, wheat, rice, soybean and sunflower [18,72,143]. Researchers have found that "adoption of organic agriculture under agroecological conditions, where it performs best, may close the yield gap between organic and conventional systems" [144,146].

In 2016, Rodale Institute's organic no-till with manure system produced 200 bushels of corn per acre—a record-breaking yield for the organic system and well above the county average and the conventional corn yield that same year (140 bushels per acre). Over a forty-year period there has been no statistical difference in yield between the organic and conventional systems within that trial [17,147].

It has been noted that the organic yield gap also arises, in part, due to a lack of varieties adapted for organic systems [31]. Conventional seeds, and the chemical systems they are locked in, have benefitted from immense R&D funding by private corporations and their university researcher partners, whereas ecological plant breeding for organic production has not [148-150].

Importantly, yields under organic systems are more resilient to the extreme weather accompanying climate change. As found in the long-running Rodale Institute Farming Systems Trial, during drought years, yields are 30% to 100% higher in the organic systems [151,152]. Crop resilience in a changing climate is an important economic co-benefit because "climate-resilient soil can stabilize productivity, reduce uncertainty, and produce an assured yield response even under extreme weather conditions" [5].

A strong evidence base has been building that shows regenerative systems bring a wide range of traditionally under-valued benefits that are equally as important as yields [2,77,146,153]. When compared to conventional industrial agriculture, regenerative systems improve:

- Biodiversity abundance and species richness
- Soil health, including soil carbon
- Pesticide impacts on food and ecosystem
- Total farm outputs
- Nutrient density of outputs
- Resilience to climate shocks
- Provision of ecosystem services
- Resource use efficiency
- Job creation and farmworker welfare
- Farm profitability
- Rural community revitalization

THE MYTH OF A FOOD SHORTAGE

There is no global food shortage. Nor are we on a trajectory for a global food shortage. World food production has been steadily rising, currently providing 2,900 calories per person per day, 22% more than is needed [154].

The continued use of the trope that 'we will soon need to feed nine billion people' as justification for seeking ever greater yields is duplicitous. **Hunger and food access are not yield issues.** They are economic and social issues which, in large part, are the result of inappropriate agricultural and development policies that create and reinforce hunger [155]. We currently overproduce calories. In fact, we already produce enough calories to feed nine billion people. However, we do it in a manner that degrades soils and harms the environment, putting our health and future food production at risk.

> *Over 40% of the current global harvest is wasted each year.*

Worldwide hunger and food access are inequality issues that can be ameliorated in part by support for small-scale regenerative agriculture, both urban and rural [156]. For those smallholder farmers for whom yield is a matter of eating or not eating, regenerative agriculture with few inputs is the best means of increasing yield as documented across tropical regions for more than 50 years by development agronomists [21].

Just over 55% of world crop production is eaten directly by people [158]. Calorie availability could be increased by 70% by shifting crops away from animal feed and biofuels to direct human consumption [157]. If livestock were raised on pasture instead of competing for arable land suited for human food production, "a 100% shift to organic agriculture could sustainably feed the human population in 2050, even with a yield gap" [158]. What's more, over 40% of the current global harvest is wasted each year, largely before it ever reaches consumers [159].

It's clear we need to make environmentally conscious food choices, but we also need to focus resources on solving food waste, returning ruminants to pasture, and curtailing the use of fertile land for fuel production. When we take a holistic perspective on the food system, we see that yields alone mean little. **Regenerative agriculture absolutely can feed the world. And it can do it while stabilizing the climate, regenerating ecosystems, restoring biodiversity, and enhancing rural communities.**

TAKING ACTION

We need to reduce greenhouse gases in the atmosphere now.

This requires strong policy action that can support the total transformation of our energy and transportation sectors. At the same time, we know that the terrestrial carbon pool is a massive reservoir that's been drained by intensive agricultural practices. We can refill that reservoir by recarbonizing farm and rangeland soils.

Farmers have led the revolution in regenerative agriculture, and many need little more than knowledge, experience and support to switch practices. However, beyond a certain eyes-to-acres ratio [160], taking a new approach may be more difficult. Large-scale conventional, industrial farming is locked in a system that needs more than the farmer's will to shift. It's a system built on high capital expenses, proprietary inputs, seeds purposefully designed to work only in tightly controlled chemical regimes, and on scales reliant not on eyeballs and acres, but by satellites geolocating across miles. The great capital expenses involved produce low-priced commodity crops. The only way these systems work is through externalization of costs and sheer scale coupled with support from government agricultural policies and entrenched interests of large agribusiness corporations. To recarbonize, we need to support place-based, customized regeneration for all farms, including large scale operations.

In the past five years, there has been an explosion of attention on regenerative farming, carbon farming, soil carbon sequestration and soil health. Among several international initiatives, the "4 per 1000" launched at COP21 in 2015 galvanized many governments to support soil carbon sequestration as part of their climate change strategies. The voluntary program draws attention to "an annual growth rate of 0.4% in the soil carbon stocks in the first 30-40 cm of soil, would significantly reduce the CO_2 concentration in the atmosphere related to human activities." In the U.S., a bill introduced in early 2020, the Agriculture Resilience Act, would have the country join the 4 per 1000 initiative, and lists a comprehensive set of regenerative agriculture policy support measures.

Policymaker, farmer, or eater—everyone can do something to support shifting the food system from industrial to regenerative.

WHAT CAN EATERS DO?

Put the Pressure On!

1. ***Put pressure on supply chains.*** We need to take away the social license for food companies to use food and fiber products and ingredients that degrade ecosystems. Tell food manufacturers that ecologically destructive supply chains are a time bomb about to explode for their brands. Let them know it's no longer ok to produce food at the expense of humanity's future. Demand food and fiber products that are sourced from farms employing regenerative practices.

2. ***Give policymakers hope.*** We need to approach governmental leaders with regenerative strategies. Many of them buy into the green revolution myth that we can sustainably intensify conventional agriculture. They know the soils of their states and nations are being destroyed, but they don't see an alternative. Tell them there is a better way, show them this report and others like it. Let them know you support their actions to shift agriculture from the problem side of the climate equation to the solution side.

3. ***Start a conversation.*** Ask your grocer, school, workplace, local hospital, and other institutions and organizations you frequent to carry products from farms practicing regenerative agriculture. If they can't talk to the producer directly, tell them to look for third-party verified labels like Regenerative Organic Certified, Land to Market, Real Organic Project, and the Soil Carbon Initiative.

4. ***Buy regenerative.*** When possible, buy from brands who source food stocks and ingredients from regenerative farms. Let them know you appreciate their sourcing practices. Or better yet, buy directly from regenerative farms. Many regenerative farms that sell to the public are proudly transparent about their practices. But remember that most farms, especially large-scale ones further from metropolitan areas, are not set up to sell directly to the public—shopping alone is not going to shift this.

WHAT CAN FARMERS DO?
Grow This Movement!

(1) ***Grow the community.*** The regenerative agriculture movement is farmer-led; if you don't know of a group nearby, join a regional, national or international organization for farmer-to-farmer learning about organic, regenerative, agroecological, holistic grazing, or syntropic agroforestry, among others. If you already frequent these circuits, consider creating a Carbon Farm Plan or becoming certified to a more stringent standard that goes beyond organic, such as Regenerative Organic Certified, Real Organic Project, Land to Market (for graziers), or Soil Carbon Initiative. You can also set up a local or regional group to regenerate at the landscape scale, organize a Regeneration Alliance, or start or join a food policy council where diverse constituents make a path for a regenerative food system that is adapted to the local context.

(2) ***Experiment, observe, share.*** As a farmer-led movement, experimentation on real farms is critical. When you shift management practices based on what you are learning, observe and measure changes in soil health and biodiversity, and then share those results with others. Whether informally talking to your neighbors, hosting field-days, posting on social media, collaborating with researchers, or speaking at conferences and other meetings, when you experiment, observe and share your farm's regeneration story, you inspire others, provide data for researchers and policymakers, and enhance the benefits to your farm, community, and the greater food system.

(3) ***Measure outcomes.*** Regenerative systems provide a wide host of beneficial outcomes that society values. High total farm outputs, nutrient density, resilience to extreme weather, ecosystem services like reduced runoff or fertilizer use, and job creation are a few [2]. In addition, farms can track the buildup of soil organic matter where testing services are available and affordable. In general, 50% of soil organic matter is soil organic carbon [29]. For some regions, testing soil carbon sequestration may be feasible in the near future with affordable soil sensors and other accurate soil carbon measurements [140]. There are also many no-cost observations to determine soil health impacts related to management changes, including biodiversity observations, soil aggregation and water infiltration tests. You can obtain or design a soil health card to record observations and track your farm's progress.

WHAT CAN POLICYMAKERS DO?
Defund Soil Destruction!

(1) ***Learn from constituents.*** Regenerative agriculture is a farmer-led and consumer-supported movement the world over, it does not have the lobbying power of industrial agribusiness. Prioritize actively building relationships with this movement. Even in unlikely places, there are passionate people working to shift the food system from a climate problem to a climate solution. Find these constituents; they may be regenerative farmers, natural food store and co-op buyers, sustainable agriculture organizations, or even university researchers. Build the relationships that will keep you informed about regenerative agriculture locally and globally.

(2) ***Support regenerative, organic, and regenerative organic agriculture.*** Policies that support regenerative agriculture recognize and reward farmers for building soil organic matter. These policies are best focused on supporting and rewarding positive outcomes. There are a wide range of policy options, from direct cost-sharing for cover crops to facilitating farmer-to-farmer peer learning, funding organic research, creating local or regional food policy councils and integrated landscape initiatives, and much more. The current complexity of precise outcome measurements means that it may be more feasible to support systems of interlinked practices, such as those proposed in the U.S. Agriculture Resilience Act, than to reward outcomes.

(3) ***Defund soil destruction.*** Policymakers can shift soil destructive policies in many ways. Start by rethinking commodity-based subsidies and support, crop insurance, biofuel mandates, government procurement programs, government funding for chemical-intensive research, and agribusiness corporate mergers. Consider how a Healthy Soil Act might be introduced to give soil rights [5]. Be vigilant to the global political power of industrial agribusiness corporations; their consolidation is a serious threat to shifting the food system to regenerative approaches [161].


Photo: Rodale Institute

SOIL HEALTH *for a* LIVABLE FUTURE

The climate crisis is a monumental opportunity to change course.

Now is the time to create a future that embraces life, a future bent on encouraging health, a future where healthy soil, clean air and clean water is available to all. In so many ways, a fundamental restructuring of how we cultivate our food is at the heart of this shift; we need to cooperate with nature. The tired era of sustainability is over. We turn now to regeneration. Regenerative agriculture is our best hope for creating a future we all want to live in, and a future our children will be happy to inherit.

Regenerative agriculture is aligned with forms of agroecology practiced by farmers concerned with food sovereignty the world over. Choosing farming practices that create regenerative systems can increase soil carbon stocks, decrease greenhouse gas emissions, maintain yields, improve water retention and plant health, improve farm profitability, and revitalize traditional farming communities while ensuring biodiversity and resilience of ecosystem services.

Soil carbon sequestration through regenerative agriculture is a human-scale remedy to global warming that's ready for implementation now. Farmers are already leading the evolution to regenerative systems. But we need to scale up and out, to make regeneration possible on conventional farms, on smallholder tropical farms, on orchards and ranches the world over in ways that make sense for each place.

This shift is going to take all of us working together—farmers, eaters, and policymakers—to create widespread societal support for moving to regenerative systems. We need to put positive pressure on supply chains, get better at measuring and sharing on-farm progress, and defund soil destruction.

Robert Rodale urged us toward this vision of regeneration in 1985:

> ***My hope is that the period of sustainability will not be sustained for more than 10 or 15 years but that we will move beyond that to the idea of regeneration, where what we are really doing with the American Land is not only producing our food but regenerating, improving, reforming to a higher level the American landscape and the American Spirit [162].***

Nearly 35 years later, the specter of the climate crisis has provided an unparalleled opportunity to harness cutting-edge technological understanding, human ingenuity and the rich history of farmers working in tandem with the wisdom of natural ecosystems to arrive at a stable climate. It's time now to heal our land and ourselves.

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