Rooted in Science and Economics: How Regenerative Farming is Redefining Agriculture

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Agriculture Over Time

Agriculture takes many forms from wet-rice production in East Asia to cattle ranching in the Americas. In all cases, people are environmental engineers. They change or remove vegetation, re-route water, use fertilizers, and modify the soil. As the Mayans, Indus Valley Civilization, and the Roman Empire can attest to, the health of the agricultural system has decided the fate of civilizations. The United Nations (UN), World Economic Forum (WEF), and Stockholm Resilience Centre believe that global agriculture must change to prevent severe environmental and societal consequences.

Humans are estimated to have engaged in agriculture starting around 15,000 years ago as glaciers began to recede. Today's agriculture is generally divided into two approaches: traditional and conventional. Traditional farming relies heavily on manual labor, limited machinery, and low-tech methods passed down through generations. Conventional farming is more loosely defined but is focused on scalability, often including genetically modified crops (GMOs), greater reliance on machinery (even going as far as self-driving tractors), and heavy usage of synthetic fertilizers generally composed of nitrogen, phosphorus, and potassium.

But there is another type of agriculture that is taking hold on farms from California to India. One that connects us to our past and helps build a more sustainable future. Regenerative agriculture combines environmentally responsible and more resilient traditional methods with advanced technologies and data science. Whether the concern is climate vulnerability, food insecurity, environmental stewardship, or greenhouse gas emissions, the need for regenerative methods has never been greater than today. Regenerative agriculture can rebuild the fertility of tens of millions of acres and may be mankind's most effective path to fighting climate change and achieving global food security. This paper examines how regenerative compares to industrial/conventional agriculture, its adoption, how it can alleviate major global issues, and practical steps to expand regenerative agriculture.

Regenerative Vs Conventional

To understand regenerative agriculture's capabilities and limitations, we need to analyze it against conventional methods. Farmers and ranchers today face many of the same challenges as thousands of years ago: controlling pests, achieving reliable pollination, water availability and quality, erosion, maintaining soil nutrients, choosing the right fertilizers, and managing risks associated with extreme weather. It is how these variables are managed that separates regenerative from conventional farming and ranching.

Pest Management

Conventional industrial farming relies on a combination of synthetic pesticides (which includes fungicides, insecticides, herbicides, and similar substances), poisons, and mechanical traps to control rodents and destructive insects. If regenerative practices are not deployed, farmers are dependent on these methods or risk substantial crop losses. Modern pesticides have their drawbacks, but they are a driver of substantial increases in farming output (especially in the short- to medium-term) seen in many regions.

Pesticides, however, generally fail to discriminate between natural pollinators, such as bees and other insects. If the bee population is compromised when plants bloom, the pollination process, and therefore plant's yield, can be severely impacted. This damages not only the commercial crop but the local ecosystem. It also increases the farmer's reliance on imported pollinators, such as using European honeybees in the U.S. This materially increases operational risks and costs. The U.S. Department of Agriculture estimates annual economic losses caused by rodents alone in the U.S. at $19 billion. It's clear that steps must be taken, but rat and mice poison often destroy native species and can contaminate crops.

Source: aginfo.net. American Barn Owl.

Regenerative farming deals with these challenges by integrating a more diverse ecosystem of plants and animals like what occurs in nature. Natural predators normally control rats and mice. By introducing or encouraging owl populations, rodent populations are managed with less or no poison and their remains are recycled rather than left to spread disease. There are over 20 species of owls in the U.S. with their total population estimated in the millions. The Barn Owl is prevalent throughout most the U.S. and Mexico, and outside of a barn-like structure, doesn't need much besides prey, water, and darkness.

To take advantage of their natural abilities, owls prefer the removal of unnecessary light, perches so they can survey their hunting grounds, and water during the dry season. Owls are easy to attract in most parts of the country and are a much more cost-effective and sustainable way to deal with rodents. While not appropriate for every situation, utilizing owls instead of poison and mechanical traps is a concrete way to implement regenerative practices.

Pollination

Roughly one in three foods consumed today require pollination. Grains, like corn, use the wind. The rest depend on butterflies, beetles, bees, moths, or hummingbirds, and all these pollinators need foraging habitat and diverse nectar-supplying plant species. Conventional farming removes most or all these native habitats. The continual use of pesticides also kills many native pollinator species.

Out of necessity, 70-80% of conventional U.S. farms now rely on imported honeybees since those practices damage the local ecosystem, including the 4,000 native bee species. The importation of honeybees creates a waterfall of negative externalities. European honeybees are more aggressive and out compete native bee species. European honeybees are more susceptible to diseases and parasites, such as the fungal disease Nosema and Varroa mites, which they spread to native species. This makes the supply and quality, and therefore the cost, of European honeybees highly volatile.

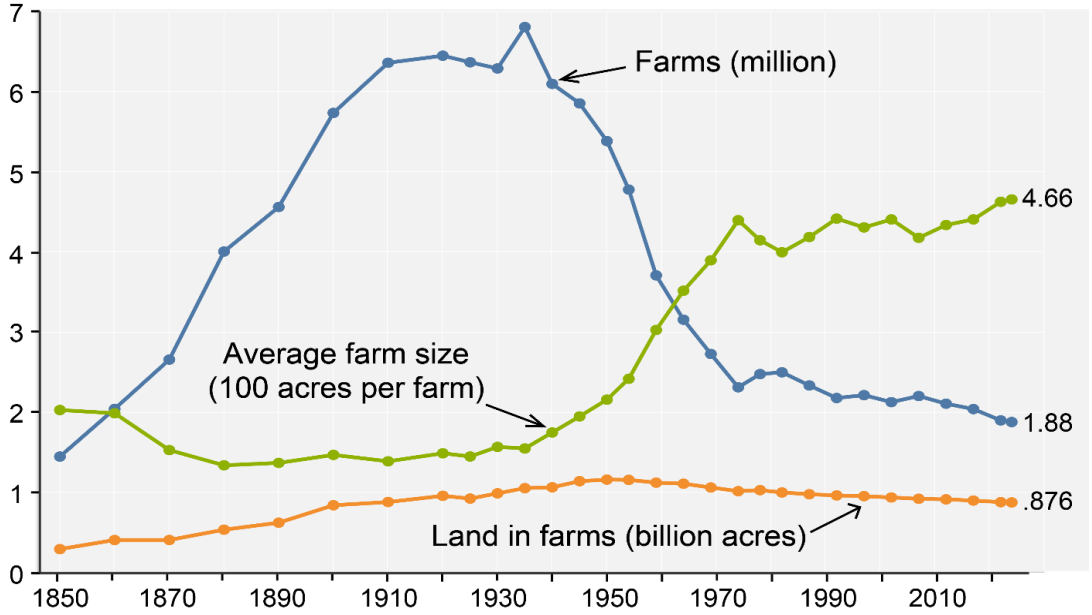
European honeybees are generalist pollinators and are not optimal for many crop types, such as tomatoes. If measures are not taken to support native pollinators, yields decline and the dependency on European honeybees increases.

Blueberries, apples, and almonds have short pollination windows. Farmers face fierce competition to obtain healthy fees at the right time, which drives up costs. Renting bees in California was $76 per colony in 2005. That rose to $157 by 2009 and is currently between $200 and $225 per colony. That roughly 200% increase in cost compares to a decline of approximately 42% for the price of almonds over the same period. Outside of regenerative farms, almonds are almost completely reliant on imported bees for pollination and have a short pollination of window of mid-February to early March.

This creates a dilemma for conventional farmers that's cited throughout this paper: when harvests are favorable, costs associated with conventional farming tend to rise proportionally and limit or erase profitability.

Farms, land in farms, and average acres per farm, 1850–2024

Million farms, billion acres, or 100 acres per farm



Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, Censuses of Agriculture (through 2022) and *Farms and Land in Farms: 2024 Summary* (February 2025).

This is a major contributor to the systemic decline in family farms over the past 100 years. From a peak of nearly seven million in the 1930s, there are now just 1.88 million farms in the U.S. Despite the population nearly tripling, farm acreage has declined by about 15% from the peak set around 1950. In a recent 2024 report by the nonprofit group Farm Bureau titled New Census Shows Alarming Loss of Family Farms, it states that rising supply costs were a primary driver of the loss of 141,733 family farms between 2017 and 2023 and the 20 million acres they managed. Most elements of regenerative farming reduce operational costs over time while improving the value of both the output and the land. Regenerative agriculture invests in the health of native pollinators by reducing the usage of chemicals, strategically growing native wildflowers that bloom in different seasons, and planting high-nectar and pollen-rich plants like lavender, clover, and sunflowers. Native pollinator populations also require clean sources of water and suitable habitat for the winter like brush piles. Diversifying pollinators, such as orchard and bumblebees, is another way to fortify sources of pollination. This necessitates an understanding of the local ecosystem and native pollinator species.

Source: CommonGood Capital. Regenerative Farm in California owned by Agriculture Capital.

In addition to improved risk management and lower expenses, studies have demonstrated substantial increases in crop yields by using native pollinators. For blueberries in Michigan and Maine, native pollinators (primarily bumble bees) result in 70% greater fruit yield. That is because bumble bees perform buzz pollination and honeybees, the type imported from Europe, do not. Another study showed 30-50% greater tomato production in both greenhouses and open fields. Almond farms in California experienced up to 60% more almonds per tree when native blue orchard bees were incorporated into the pollination process. The largest gain was to 200% higher watermelon yields by using native squash bees and bumblebees in California and Pennsylvania. Embracing native pollinators reduces operational risks and costs while increasing the volumes and quality of crops. These aspects of regenerative agriculture can change the financial and operational trajectory of a farm and potentially reverse the 100-year decline in family farms.

Water & Soil Management

In conventional farming, synthetic fertilizers and deep tilling are used for planting, which degrades the soil by releasing moisture and carbon back into the atmosphere. Heavy machinery compacts the soil and reduces its ability to absorb water and nutrients.

Conventional farming relies on flood irrigation or large-scale sprinkler systems. These are effective at delivering water to crops but lead to waste through runoff and evaporation. These practices also cause greater soil erosion and are a key driver behind synthetic fertilizers and herbicides entering the water system. Farms are often dependent on groundwater pumping. In drier areas like southern California and parts of Texas, both regions where large-scale agriculture occurs, this puts pressure on the same aquifers used for drinking water.

Regenerative farming uses methods to reduce water consumption. Drip irrigation, keyline design (landscaping that follows the natural flow of water), and rainwater harvesting are can be applied to many farms and collectively reduce water usage by approximately 50% compared to conventional flood irrigation. Regenerative farming also emphasizes "no-till" methods to keep the soil as intact as possible. Mulching and cover crops are also simple and cost-effective means of reducing evaporation and soil temperature.

Environmental Resiliency

Using more natural methods instead of flood-irrigation affects how plants grow. Regenerative farms build plants with deeper root systems to access underground moisture. Deeper roots better handle flooding, high winds, and extreme weather. This is a good illustration of how regenerative farming practices reduce risks. Droughts are common and devastating in many parts of the world, and regenerative farms with deep-rooted perennial crops can produce target yields with 40-50% less water than annual row crops.

In addition to requiring less water and experiencing less erosion due to flooding, the healthier soils that regenerative farming create have higher carbon content and beneficial microbial activity. This makes the soil more resilient against high temperatures and disease. The greater biodiversity from cover crops, natural pollinators, and crop rotations creates more hardy ecosystems.

Economics

One of the most important aspects of regenerative agriculture is the potential financial benefits to the farmer or rancher. This translates into a wide array of socioeconomic advantages. A family farm in the U.S. may use regenerative practices to improve its economics and allow it to transfer to the next generation. Globally, the adoption of regenerative farming may be the difference between not having enough food to eat and selling extra produce as supplemental income. India is recognizing this due to its huge dependence on farming for employment and hundreds of millions of citizens that live via subsistence farming.

In Sikkim, India, farmers facing declining soil fertility and increasing fertilizer expenses transitioned to organic and regenerative agriculture. This increased crop yields of pollinator dependent crops (native pollinators have started recovering) by more than 23% and reduced costs by 14-19% overall. Just as important is the fact that Sikkimese organic products now attract global export markets, thereby increasing revenue significantly.

In Andhra Pradesh, India, in what came to be known as the largest agroforestry program on earth, a campaign saw over 500,000 farmers adopt regenerative methods including cover cropping and composting. These simple measures increased yields materially and resulted in higher financial returns for farmers. Specific financial outcomes were not provided, but the elimination of chemical fertilizers and pesticides resulted in "significant savings" for farmers.

In the U.S., small farmers have saved over $150 per acre in input costs on average by eliminating synthetic fertilizers and pesticides. On an average farm of 500 acres, that's $75,000 annually and may improve the farm's profits by 50% or greater.

The Midwest U.S. is one of the most productive farming regions on earth. It is susceptible to erosion from heavy rainfall, however, which damages the area's row crops. It is simultaneously vulnerable to droughts. Farmers that switch to regenerative techniques have reported 20-30% higher water retention, which has markedly improved yields during both periods of heavy and below-average rainfall. Due to elevated and volatile fertilizer pricing in the U.S., many farmers opted for regenerative methods strictly for economic reasons. This is bolstered by efforts by many states to incentivize regenerative methods.

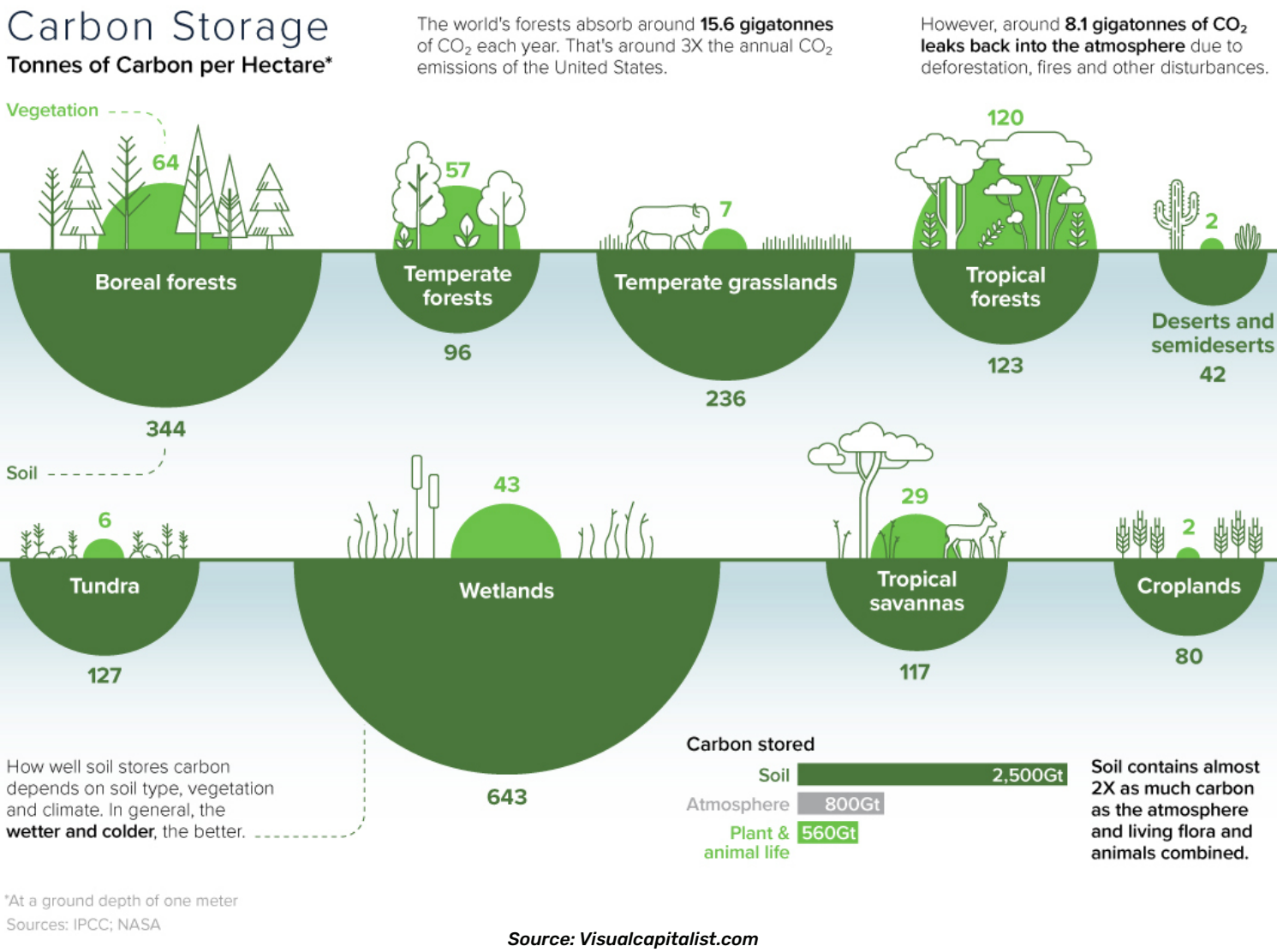
The Illinois Department of Agriculture's I-COVER program provides direct payments to farmers ranging from $61.13 to $105.40 per acre for implementing cover crops. On average and based on 2022 data, farmers in central Illinois generated a return on investment averaging $276 per acre for corn. As this demonstrates, regenerative practices can improve farm economics markedly, and adding in these incentive programs means that a dramatic increase in profitability is feasible.

Source: native.eco. Brazilian silvopasture operation.

Brazilian farmers added trees and livestock to land previously dedicated to growing crops in a practice known as silvopasture. The farmers realized the integration of livestock and trees not only improved crop yields, quality, and durability, but were also additional income streams. A study in Australia showed that traditional eucalypt plantations that added silvopastoral systems resulted in a land value of $560.10 per hectare compared to just $57.33 per hectare from conventional plantations. In addition to the multiple income streams, higher core crop yields, and increased land values, projects like the Native Palm Silvopasture initiative are targeting the sequester of over 900,000 tons of CO2 over twenty years. Current carbon pricing rates vary dramatically by nation with Uraguay the highest at $167 per ton of CO2 and global averages around $65 per ton. Using the average, this would provide the Native Palm Silvopasture $58.5 million in incremental revenue.

On the topic of carbon credits, there are compliance (regulated) and voluntary markets, each with their own dynamics. Compliance markets are government mandated using cap-and-trade or similar regimes. The European Union's ETS, California's Cap-and-Trade, and China's ETS are examples. These are driven by government climate goals. Voluntary markets are the result of many factors including investor pressure and personal interest. In all cases, organizations achieve their carbon goals by purchasing carbon credits to offset emissions through projects like reforestation, carbon sequestration, and methane capture.

The world's largest and most established carbon market is the EU Emissions Trading System (ETS). It focuses on power, manufacturing, aviation, and maritime industries. Carbon prices have remained over 80 Euros in recent years, which has been sufficient to reduce emissions. An important component is the adoption of a Carbon Border Adjustment Mechanism (CBAM). Without this, companies can offshore their carbon generating activities and still achieve their stated emission reduction goals. This common activity at least substantially reduces, if not eliminates, the practical benefit of the EU ETS. Germany, for example, has notoriously outsourced its carbon intensive aluminum, steel, and chemicals industries to countries like Turkey, India, and China to achieve its emissions reduction targets. The unfortunate result is that global greenhouse emissions may actually increase due to these activities in Germany face much stricter environmental and efficiency standards than where the operations are relocated to. It is anticipated that the adoption of frameworks like the CBAM by the EU and other regions will dramatically increase the demand for and value of carbon credits.



Source: Visualcapitalist.com

Although the atmosphere garners the most attention, it's the soil that retains most of earth's carbon. Unsurprisingly, soil has the largest capacity to absorb more carbon and can do so much more economically on average than other approaches. Studies have shown that carbon sequestration can occur meaningfully for decades. In one study focused on the U.S. state of Vermont, the implementation of rotational grazing alone by ranchers contributed to a meaningful predicted increase in carbon sequestration of 1,269 kilotons, or the emissions produced by approximately 285,000 motor vehicles annually. For context, that's more than half of the number of registered vehicles in Vermont.

Regenerative Agriculture Advancements

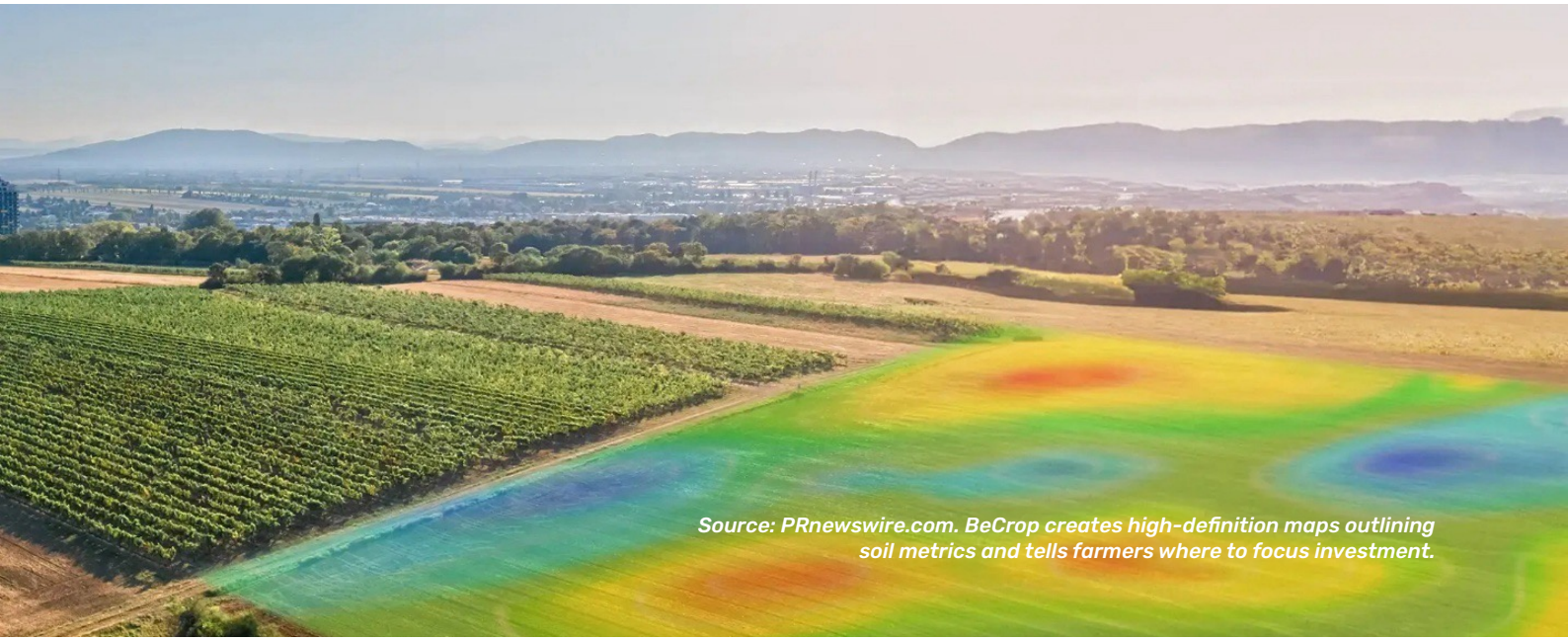
Prior to conventional farming methods becoming the norm in the 1950s and 1960s, farming was sustainable, or it failed. Integrating agriculture with the local ecosystem was necessary for success against unpredictable weather and pests and disease. The ability to import synthetic herbicides or fertilizers to force the local environment to comply with the farmer's objectives didn't exist. Organic fertilizers, such as animal waste, have always been around but don't create anywhere near the level of negative externalities.

Today, regenerative farming still relies on a healthy and mutually beneficial relationship with the local environment. But unlike in the past, it benefits from cutting edge data science and technology to improve decision-making cost efficiency.

Artificial Intelligence

Artificial intelligence ("AI") is working through every sector of the global economy and agriculture is no exception. AI tools analyze nutrient and microbial activity, as well as the structure and organic matter content of soils. This allows AI models to predict the timing of nutrient deficiencies and recommend precise solutions.

Biome Makers soil database has over 24 million microorganisms from samples across six continents and 56 countries. The company's AI tool uses its massive data set to help over 21,000 farmers and 2,000 agribusinesses. Syngenta, Bayer, and UPL are among the larger clients.



Source: PRnewswire.com. BeCrop creates high-definition maps outlining soil metrics and tells farmers where to focus investment.

As an example, a vineyard in California suffered from deteriorating soil health. Its yields declined as its irrigation needs and sensitivity to pests increased. After engaging with Biome Makers' BeCrop™ AI platform, specific cover crops and compost applications were recommended in addition to regenerative farming practices like no-till and rotational grazing. The vineyard implemented the recommendations and tested the soil six months lather. Water retention in the soil improved 30% alongside improved microbial diversity, nutrient cycling, and carbon sequestration. Not only was the vineyard's grape production restored, but the grapes were of higher quality and the lower dependence on synthetic fertilizers and herbicides reduced operational costs.

Drones & Sensors

Farmers have always physically assessed the health of crops. That often means no days away from the farm for months and a realization that plants won't be inspected as often as they should be. Drone technology and advancement in sensor technology are rapidly changing that.

Source: Technologyreview.com and PricewaterhouseCroopers.

Drones equipped with Normalized Difference Vegetation Index (NVDI) sensors evaluate plant health, soil quality, and biodiversity with accuracy, speed, and cost-effectiveness that was impossible just a few years ago. As an indication of the value add this creates, PricewaterhouseCoopers (PwC) estimated the agriculture drone market at $32.4 billion.

Drones communicate with farmers and provide guidance on how to deal with diseases and soil deficiencies before symptoms even appear. Taken together, the surveying and data collection lead to better decisions on cover cropping, composting, and water management.

Drones have other applications related to seeding and livestock management. DroneSeed, a Seattle-based reforestation company, deploys drones for optimal seeding with zero impact to the ground. GPS-enabled drones monitor livestock movements and capture critical information on pasture health. This helps ranchers know when and where to move livestock to maximize soil and animal health. Drones specializing in thermal imaging can detect moisture levels to alleviate dry or wet spots within a farm.

Autonomous Tractors and Robots

This is an area that regenerative and advanced conventional farming are embracing because of the cost and time efficiency gains. It's a testament to the idea that farmers navigate toward regenerative methods if they are educated on their economic and risk reduction benefits. John Deere's 8R Autonomous Tractor incorporates no-till farming and carefully evaluates its environment and farming needs to optimize pathing. This reduces compaction and seed waste as both primary and cover crops are planted at precise intervals and depths to maximize their germination rates. Other autonomous tractors are used in ranching to monitor grass regrowth, calculate carbon sequestration, and even guide livestock with GPS fencing.

Carbon Robotics' LaserWeeder uses lasers to destroy weeds allowing the farmer to avoid synthetic herbicides or tilling the soil. Third-party assessments show a reduction in weed control costs by up to 80% using the company's technology once hand labor, herbicides and machinery costs are accounted for. The company's rapid success has allowed it to develop five models to help more farm sizes and budgets. In many ways, autonomous capabilities are the potential key to unlocking regenerative farming at scale. They permit industrial capabilities and efficiencies while augmenting adaptation to the local environment that regenerative farming is founded on. The combination of artificial intelligence, robotics/autonomous vehicles, and data science enables a single farmer to not only effectively manage the complexities of a large regenerative farming application but do so with greater cost and time efficiency than would be possible with an army of volunteer consultants or laborers.

Regenerative Water Usage

We've already discussed how sensor and machine learning technology allow for better water management. There are a few additional ways that modern regenerative farming enhances water productivity. One is IoT-enabled drip irrigation. The "internet of things" concept combines widely available sensors with smart management. IoT-enabled drip irrigation allows for the precise application of water literally down to the drop to maximize water efficiency.

Strategic tree and shrub planting alongside crops is another proven mechanism to reduce evaporation and improve the soil's ability to retain moisture. Another method is utilizing charcoal made from organic matter known as biochar. Companies like Charm Industrial convert organic plant waste into this charcoal enhanced microbial activity, drought resilience, and water retention.

There are also various ways to recycle and reuse rainwater. Farmers can build systems that capture rainwater from roofs or land that naturally becomes flooded. Fungal networks are a hidden mechanism used in nature to distribute rainwater that is often compromised with conventional farming. Biome Makers' BeCrop AI mentioned previously has the capability to track fungal networks to optimize soil hydration. Regenerative water management can restore infertile land and add millions of acres of productive farmland back to the globally supply.

Integration with Animals

Ranching and farming have gone hand in hand for centuries. Rotational grazing promotes root development in grasses and improves the organic matter content of soil. These naturally improve water retention and drought tolerance. The likes of bison, horses, sheep, and cattle all strike a great balance of minimal compaction and aerate the soil with their hooves. This provides similar benefits to industrial tilling without most of the side effects. It also helps with seed germination and water infiltration. Cattle can be introduced to a corn field after harvesting to reduce surface waste, recycle unharvested plant matter, and clean fields. Nutrients are then returned to the soil in the form of waste from the animals. Similar practices can be applied to wheat and barley after they are harvested. Soybeans and peas can be inter cropped with grasses ideal for grazing. The livestock consumes these crops and then recycles the nutrients, like nitrogen, back into the soil to the benefit of the commercial crops. Ranchers and farmers around the world, from Brazil to Australia, are increasingly recognizing these benefits.

Source: Wikipedia. Integrated rice-fish farming.

It's not only livestock that form symbiotic relationships with agriculture. Fish farming creates nutrient-rich waste and benefits the natural ecosystem in nature. When concentrated, however, fish waste becomes problematic. Combining aquaculture (fish farming) with agriculture restores the same balance found in nature. Plants benefit from the nutrient rich fertilizer produced by the fish and the plants filter the water. If the fish farm is densely populated, excess nitrogen and phosphorus can cause algae blooms and spread disease and parasites. When part of an agriculture system, however, the waste product can be periodically harvested via filtering and distributed to nearby farmland and maintain the balance for both farm types.

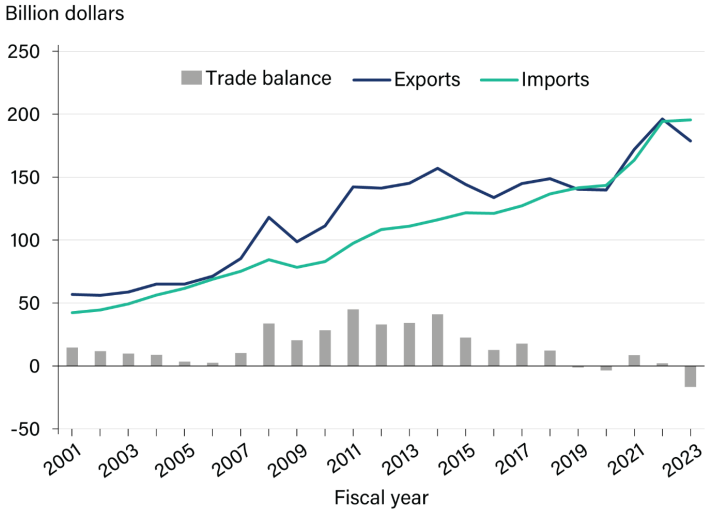
In applications like rice-fish farming, fish, typically tilapia or carp, spend their entire lives in the rice fields. In addition to generating natural fertilizer, they control pests and aerate the water. Approximately 50% of the world's fish come from fish farms, and that percentage is rising. A modest increase in aquaculture would markedly lower global fertilizer consumption and reduce the price of both fish and the crops they support.

Global Agriculture Landscape

Now that we have a strong grasp on regenerative and conventional farming, let's evaluate what extent regenerative practices are in place or changing in popularity globally. This will help us understand the potential benefits and feasibility of expanding regenerative practices, as well as where to focus investment or policies to have maximum impact.

The U.S. is the single largest exporter at over $190 billion in agricultural products in 2023. It produced 35% of the world's supply of corn and 34% of all soybeans. The industry contributes about $1.4 trillion to U.S. GDP. A McKinsey survey found that 90% of U.S. farmers know of sustainable farming practices but adoption varied. Roughly two-thirds have introduced reduced or no-till practices. No-till farming has increased in popularity by about 50% from 2017 to 2023. Mirroring the efforts used to achieve this is a good starting point for the adoption of more regenerative practices. Despite many areas in the U.S. facing water shortages, only one third utilize controlled irrigation.

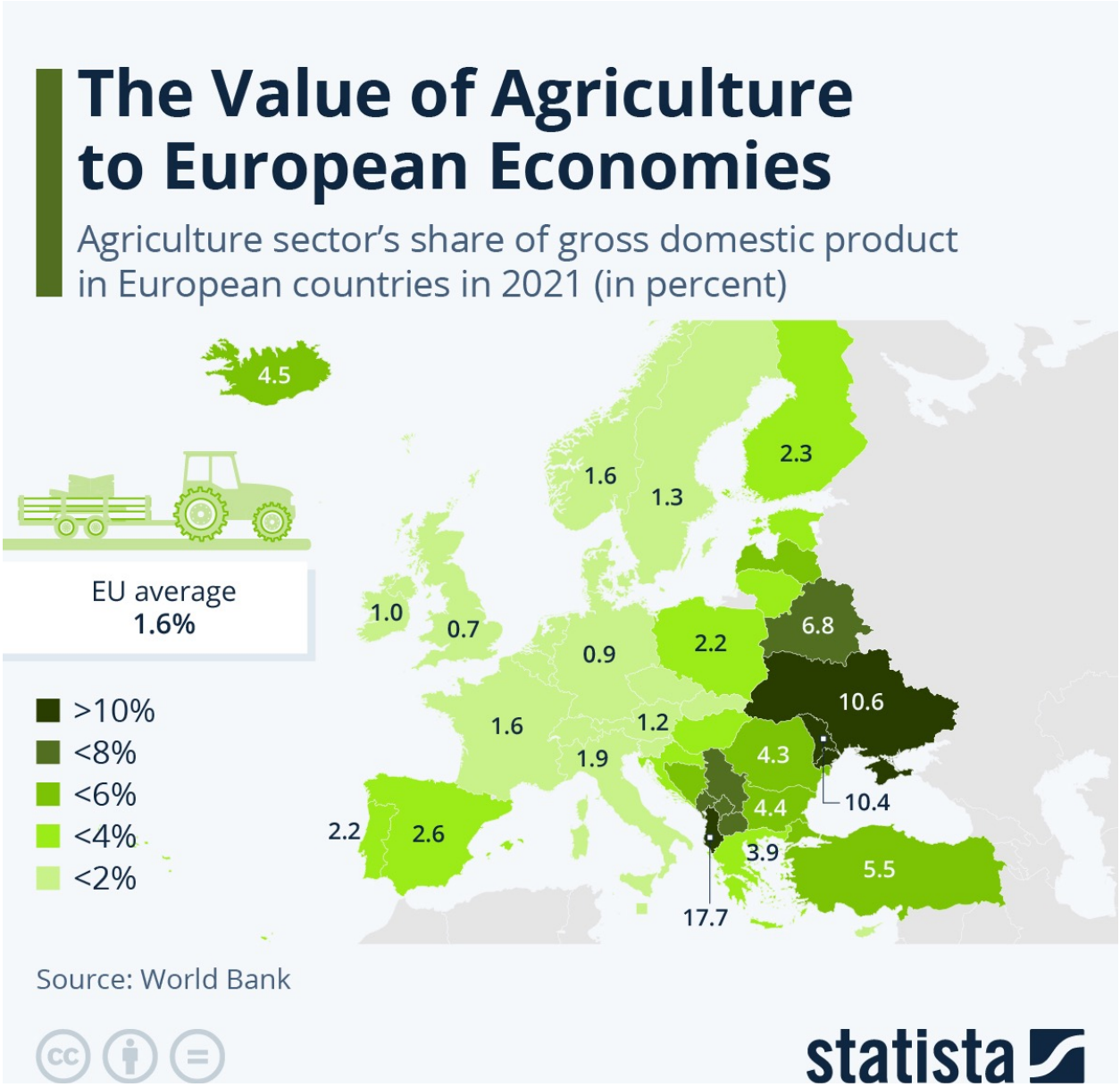
U.S. agricultural trade, 2001–23



Note: Values are not adjusted for inflation. The trade balance is equal to the value of exports minus the value of imports. When the balance is negative, imports exceed exports.

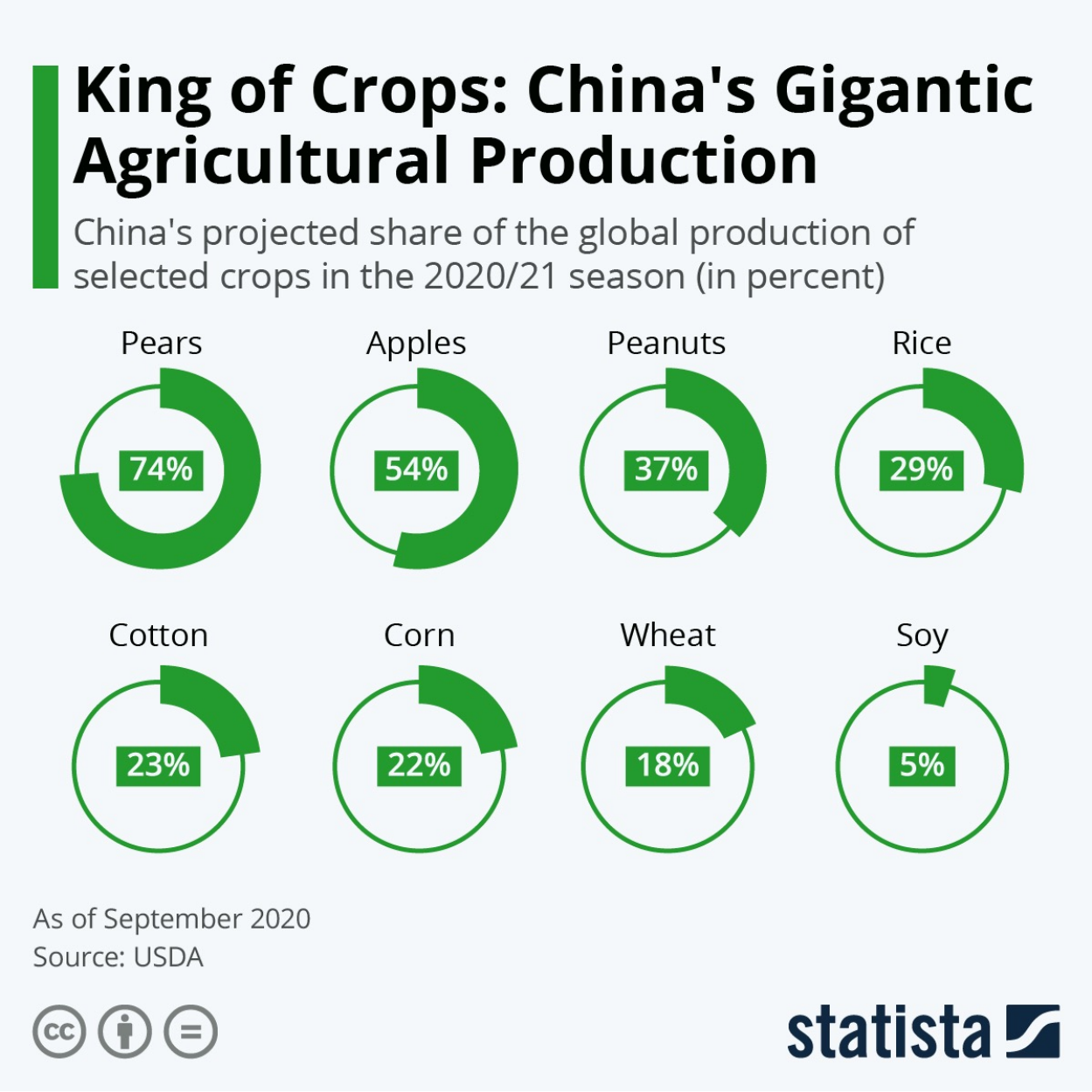
Source: USDA, Economic Research Service using data from U.S. Department of Commerce, Bureau of the Census.

Over one million honeybee colonies (primarily European honeybees) are imported to the state of California each year. Certain crops, like almonds, have a very high reliance on imported bees. A substantial portion of U.S. agriculture depends on imported bees. Aggregating reports suggest 60-65% of U.S. farms and 30-35% of ranches utilize at least one regenerative agriculture technique. These are far higher than 10 years ago but indicate huge potential in the U.S. in terms of yield, environmental management, and quality of production.

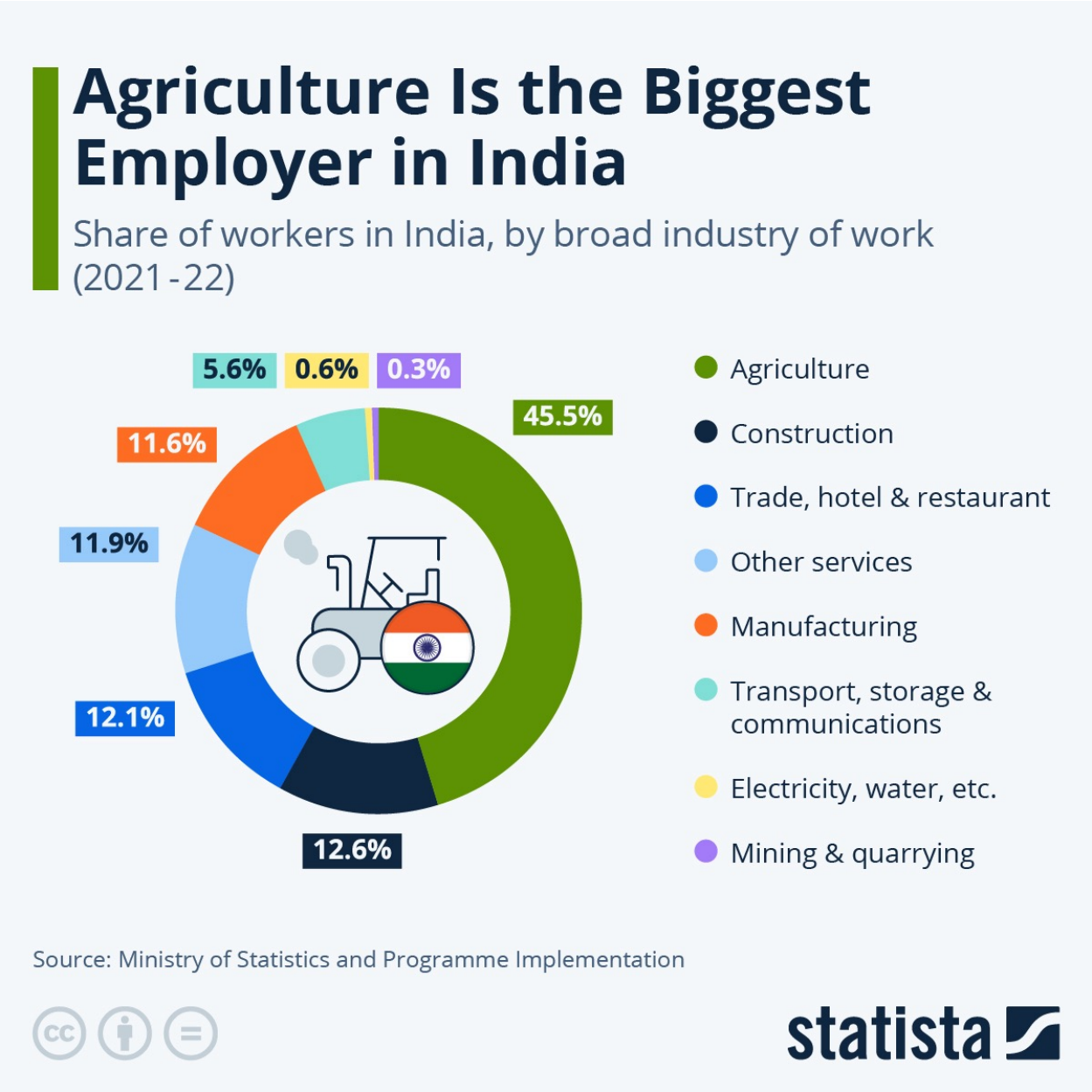


The combined European Union (EU) is also a major exporter and responsible for 15% of global agricultural production with wheat, dairy, pork, wine, and fruits the major categories. Creating standardized reporting methods and regenerative practices is even more difficult in the EU compared to the U.S. given the number of agencies and nations involved.

The EU's Farm to Fork strategy is targeting 25% organic farming by 2030 compared to 10.5% in 2022. Organic farming overlaps with regenerative agriculture by focusing on soil health and eliminating synthetic herbicides and pesticides. Reports out of the EU indicate the market for regenerative agriculture is anticipated to grow by 14.1% from 2023 to 2029. The World Economic Forum calculated that if 20% of EU farmers implemented regenerative practices, global greenhouse gas emissions would be markedly positively impacted, and the continent's soil health would improve proportionally. Like the U.S., the foundation is laid for regenerative agriculture in Europe, but it is currently underutilized.



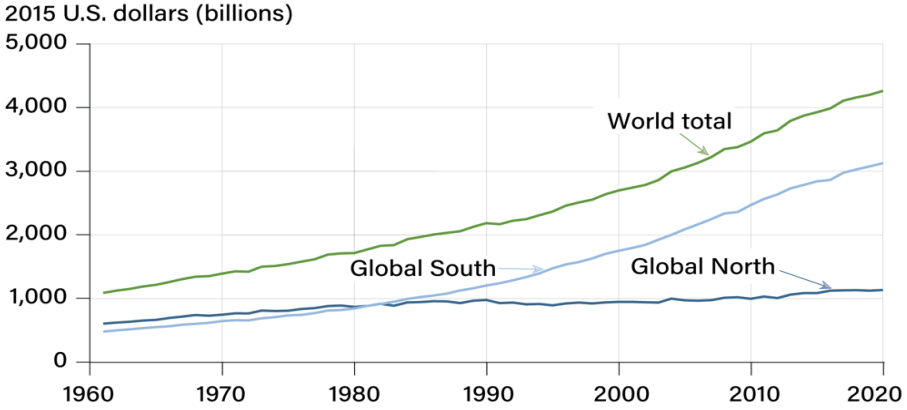
China is the world's largest agricultural producer at 25% of all output. Most is consumed internally so the specifics of China's agricultural sector are not as well understood. Its agriculture industry is less sophisticated and still working toward widespread mechanization. Outside of a few smaller areas like Hong Kong and the Loess Plateau, regenerative practices are limited. This challenge is magnified by over 100 million Chinese farmers that need education, resources, and infrastructure development suited for their specific environments and crops. Nonetheless, the market for regenerative agriculture in China is anticipated to grow by 16.4% annualized through 2034.



India 's agricultural sector is 17-18% of GDP and employs roughly 50% of its workforce. The health and trajectory of India's agriculture may be the most important in the world. Specializing in staple crops such as rice, wheat, and maize, the nation also produces the cash crops tobacco, tea, coffee, spices, and cotton. The nation's geography, not unlike the U.S., is diverse enough that each region is known for different products. India faces unique challenges that regenerative farming is adept at solving. For one, India is dependent on monsoons, or seasonal climate patterns mostly originated from the Indian Ocean, for water. Agriculture productivity is among the lowest in the world due to a low rate of mechanization, low technological adaptation, and degrading soil quality. To make matters worse, over 60% of India's irrigation is dependent on diminishing groundwater resources.

The government has taken measures to try to support the farmers including subsidies for fertilizers and electricity, insurance regimes, and minimum support prices (MSP). While a small portion of Indian farms are organic or sustainable today, the trend is increasing rapidly. The National Mission on Sustainable Agriculture (NMSA) encourages organic farming, water conservation, and soil health improvement, all key elements of regenerative farming. The Padhan Mantri Krishi Sinchayee Yojana (PMSKY) is focused on water issues to improve irrigation efficiency and promote water conservation. To mitigate the damage caused by synthetic fertilizers, India's Soil Health Card Scheme provides detailed information to farmers about their soil health and recommended interventions. This is critical to moving India's disparate farming system, which includes over 118 million agricultural households. As noted earlier in the paper, India is home to numerous remarkable demonstrations of regenerative agriculture's promise. Technological innovations and continued government support and guidance are needed to keep India moving toward regenerative. It is clear that India recognizes that regenerative agriculture is essential.

Value of world agriculture output shifted from Global North to Global South, 1961–2020



Note: Values are represented in purchasing power parity dollars, which means that a given quantity of agricultural product will have the same purchasing power. The Global South consists of Africa, Latin America and the Caribbean, and Asia except high-income countries of East Asia. The Global North consists of Canada, the United States, Europe, Australia and New Zealand (Oceania), and high-income countries of East Asia.

Source: USDA, Economic Research Service (ERS) using ERS October 2022 International Agricultural Productivity data.

South America includes several major agricultural producers including Argentina, Brazil, and Chile. Argentina is a leader on the continent with the widespread implementation of no-till farming and crop rotation. Brazil's track record is mixed with notable improvements in agroforestry systems, regenerative livestock management, and organic farming. This is offset by continued destruction of the Amazon rain forest. Chilean vineyards are utilizing regenerative practices at a growing rate. While not as far along as North America or Europe, South America is making significant progress in regenerative farming and leading in the integration of livestock and farming.

Africa is a giant continent made up of 54 nations with a complex set of challenges and environments. It has the highest employment in agriculture at up to 70% of the population in many areas. Mechanization is low and comparable to rural India and China. Soil degradation is a major concern across Africa with excess erosion and desertification negatively impacting millions. Cover cropping, crop rotation, and composting are being used to augment soil health but less frequently compared to other markets. Agroforestry, the practice of integrating trees with crops and livestock to improve biodiversity, is much more universal. Tanzania, Kenya, and Ethiopia are leaders in this area and have minimized desertification and improved crop yields. Initiatives to incorporate regenerative farming are in effect at the most granular and regional levels.

Farmer field schools provide critical community-level engagement and operate in Kenya, Uganda, and Tanzania. The Great Green Wall Initiative aims to alleviate desertification in the Sahel region, which includes parts of Chad, Senegal, Mali, and Niger. The objective is to restore 100 million hectares (247 million acres) using sustainable and regenerative farming.

Access to resources like the right seeds, tools, and compost, and techniques are the major hurdles for rural African farmers. Another challenge is that much of the farmland is communal or has uncertain ownership. Many African export markets like the U.S. and Europe are willing to pay a premium for sustainably produced crops. This has encouraged adoption in East Africa and Southern Africa due to their production of coffee, cocoa, and tea shipped to these markets.

The methods employed by Africa in all areas, from energy to agriculture, will have an outsized impact. Most population growth through 2050 will occur on the continent, and historic levels of infrastructure and economic development will be needed. The fact Africa has most of the unused arable land is a major catalyst with estimates of up to $1 trillion in agriculture exports possible by 2050. Agriculture imports are currently a major drain on the continent's foreign exchange reserves. The extent Africa incorporates regenerative practices will influence its environment and human development as well as the world's.

Environmental and Human Impact of Conventional Vs Regenerative Farming

Human and Land

Regenerative practices can materially impact farmers' lives. The health issues caused by synthetic pesticides and herbicides are massive and difficult to quantify. Long-term exposure to many pesticides (including those sold in the U.S. like Roundup) are linked to higher rates of leukemia, breast cancer, prostate cancer, and other cancers. Many synthetic herbicides interfere with human endocrine systems. This has been shown to contribute to developmental delays in children and during pregnancy, compromised thyroid function, and reduced fertility in both men and women. Chronic exposure is tied to neurological disorders including but not limited to Parkinson's disease, peripheral neuropathy, and cognitive deficits. Respiratory and immune system problems are also common.

In nations like India and China where hundreds of millions of people are involved in near daily farm labor, the human, social, and financial cost of synthetic pesticides and herbicides on people is nearly incalculable. Much of it falls on children as they are more sensitive to exposure. But the cost of conventional farming practices goes far beyond the people directly engaged in it. Many chemicals used by these synthetic products bio-accumulate in the food chain. They do not naturally decompose on normal timelines, and therefore affect the entire food system, wildlife, livestock, and water supplies. Wealthier regions can afford activated carbon or reverse osmosis to treat water contaminated by pesticides and herbicides, but not poor rural areas where most farming globally occurs.

Many people in these regions boil water to make it drinkable, which is ineffective against most pesticides. Some countries, mainly in North America and Europe, have bans and enforcement measures that have removed highly toxic pesticides from general use. India, China, and Brazil, three of the largest agriculture producers in the world, are all still using banned pesticides like DDT, paraquat and glyphosate. The main reasons cited for this are lack of enforcement, lower cost, and lack of education leading farmers to underestimate their danger. Until a more economical method is available to these farmers, such as through regenerative farming, it is unlikely that their widespread use will diminish.

Atmosphere

Urea, ammonium nitrate, and ammonium sulfate are common nitrogen-based synthetic fertilizers. The production of these chemicals is energy intensive. Globally, the production of these fertilizers alone is responsible for approximately 1.2% to 2.0% of global greenhouse gas emissions. In 2020, the International Fertilizer Industry Association (IFA), a promoter of the industry, stated the sector was responsible for 2% of global C02 emissions. Natural gas is the primary feedstock of many synthetic fertilizers, including ammonia.

Carbon dioxide is at least beneficial for plants and harmless to humans. Synthetic fertilizers also release significant amounts of Nitrous Oxide (N20). Nitrous oxide can result in negative health effects long-term and is roughly 300 times more effective at trapping heat than C02 over a 100-year period. To put the amounts and impact into context, a 2021 study published by Nature Communications estimated that nitrogen fertilizer use is comparable to 2.5 billion metric tons of C02 emissions annually. Added together, agriculture is responsible for approximately 5% of all global emissions.

Regenerative Capabilities & Solutions

One of the most powerful but complex benefits of regenerative agriculture is carbon sequestration. While there are natural limits, they align surprisingly well with mankind's needs. To start, the soil organic carbon (SOC) capacity varies primarily based on their texture and mineral composition. For example, clay has higher capacity to store carbon because of its fine particles and rigidity. Sand is the opposite because the particles are larger, and stability is lower. The depth of the soil is also a major factor, and one that can be improved through cover cropping, no-till practices, and reducing erosion.

While there is a maximum carbon sequestration any soil can sustain, it's quite high at one to three metric tons annually per acre at the beginning of a soil restoration program. This falls over a five to 20-year timeline depending on the depth and makeup of the soil. If regenerative farming was applied globally, 10 to 30 billion metric tons of carbon could be sequestered annually for the foreseeable future. Global carbon emissions from human activities are estimated at 36-37 billion tons annually. This includes fossil fuel emissions, cement production, deforestation, and all the major contributors. If the carbon credit market continues to develop, farmers from Africa to Alabama could obtain a valuable secondary income for decades by applying regenerative farming practices.

China is the largest emitter globally by a wide margin and is responsible for nearly a third of all greenhouse gas emissions. The U.S. is next at 15-17%, followed by India and the European Union at roughly 8% each. Interestingly, this mirrors the list of the largest agricultural producers. Over 60% of both agricultural output and global greenhouse gas emissions come from the same four sources.

This creates a unique opportunity. For India and China, environmental, social, and economic concerns related to the hundred million small farmers in each nation can be alleviated, and in some cases eliminated, by adopting regenerative farming. Both nations are making a concerted effort to embrace the practices and have had at least modest success. Roughly 80% of Indian farmers use at least one regenerative practice, but much more work is needed before the majority are adopting integral regenerative practices across the core areas of water management, no-till, reducing synthetic fertilizers/herbicides, and improving soil health. While China has announced measures by the Food and Agriculture Organization (FAO) toward sustainable initiatives, such as restoring 9.33 million hectares of degraded land by the end of this year, data on regenerative farming's popularity or success in China is limited.

Domestic and international support for rural Chinese and Indian farmers is likely to have a dramatic positive impact on global greenhouse gas emissions, several of the world's largest and most important river systems and improve the health and financial position of hundreds of millions of small farmers.

Like China and India, the U.S. and Europe fall into similar positions when it comes to regenerative agriculture practices and potential. Both regions have an array of government programs and non-profits focused on the topic, but adoption of comprehensive regenerative systems remains tepid. Since environmental regulations on aspects like pesticides are readily enforced, the primary benefits to transitioning to regenerative agriculture are revitalizing unproductive land, improving resiliency to droughts and extreme weather, reducing costs, and improving overall profitability. Based on surveys of farmers and the research of non-profits, the primary roadblock for farmers of all sizes is the upfront investment in equipment and time. Expanding regenerative agriculture quickly requires a market-based solution to these hurdles, which is what we'll explore next.

How to Invest in and Expand Regenerative Agriculture

Regenerative agriculture is financially accretive versus conventional methods, but there are barriers slowing its adoption. These can be divided into financial, practical, and structural. Cover cropping, high efficiency irrigation, rotational grazing, and reduced tillage often require investment into new equipment and infrastructure. Another cost is the period between the end of fertilizer heavy farming and when the soil is rehabilitated. This takes at least one season and may impact up to three years of output. Many farmers can't afford to invest in new machinery and infrastructure or absorb one to three years of lower yields, much less both simultaneously. This is when specialty financing or strategic partnerships are crucial. Loans designed specifically for the needs of regenerative farming transitions now exist through firms like MAD Capital. Others, like Agriculture Capital, absorb the greatest financial cost by acquiring the land and leasing it to regenerative farmers.

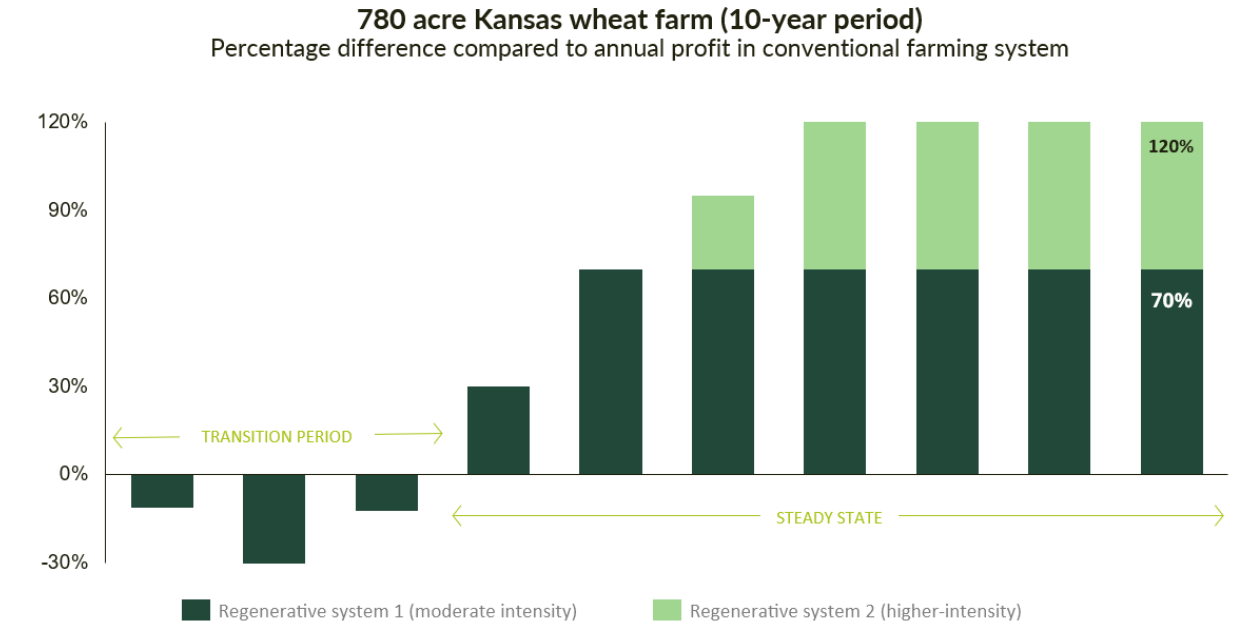
Tied to this are subsidy structures largely favoring conventional monoculture operations. This applies to the Farm Bill and USDA. Government agencies and traditional lenders alike often view regenerative practices as riskier, particularly if there is not a concrete plan for overcoming the aforementioned period of potentially lower yields. Similar constraints apply to the insurance market, with some insurers biased against regenerative farms.

Next, the knowledge gap for conventional farmers to go regenerative should not be underestimated. A 2024 McKinsey survey revealed that 90% of U.S. farmers were aware of sustainable farming practices but most lacked the knowledge to implement them effectively. Maximizing regenerative practices requires a deep understanding of soil biology, the local ecosystem, and skills to adapt to changing environmental conditions. Farmers, especially those that are less tech savvy, may struggle to make the regenerative transition without significant institutional support. Traditional agriculture education is focused on conventional methods, compounding the information deficit faced by so many farmers and ranchers.

Lastly, there are market limitations. Unlike Certified Grassfed beef or USDA Organic classifications, none exists for regenerative farming. This means consumers cannot discern between products made from conventional or regenerative farming, and this eliminates the potential for a price premium. Even in the case of regenerative farmers and ranchers who embrace the Certified Grassfed or USDA Organic labels, it's often three years after all systems are in place before the farmer or rancher can begin marketing their products as such and capture the premium.

Another market limitation concerns to a key component of the farmer's return profile. The increased value of the farm or ranch land isn't monetized until years after the transition at minimum, and in the case of a multi-generation family farm, it may not be realized during the farmer's lifetime. Financial and subsidy systems that recognize the increased value of regenerative farmland could augment the industry's expansion significantly. We'll illustrate the mechanics of the value creation next.

Regenerative farmer profit vs. conventional farmer profit at a representative



Source: Agriculture Capital

Regenerative techniques on a typical Kansas wheat farm generated a meaningful positive return on investment around the start of year four. Given many farmers only partly apply regenerative practices, the graph shows both moderate and more comprehensive adoption. A moderate application of regenerative farming generated a 70% higher yield compared to conventional techniques in perpetuity once stabilization was reached around year five. A complete regenerative system, which creates even healthier soils and enjoys even lower operating expenses, shows a 90% increase in profitability by year six and stabilizes around a 120% increase compared to conventional farming.

Keep in mind that these illustrative financial gains do not include the increased value of the land, monetization of carbon credits, or government programs subsidizing regenerative activities. This is already more than enough delta to improve the outlook for struggling family farms all around the world.

But the farmer needs to be able to absorb the one-to-three-year investment period and obtain the knowledge and tools necessary to implement regenerative farming techniques. These are the hurdles that investors and policymakers should focus on. Careful integration with the local ecosystem must be part of the solution. Rodale Institute offers online and in-person programs on regenerative organic farming. Kiss the Ground, Savory Institute, and the USDA's Natural Resources Conservation Service (NRCS) are other organizations that provide free or low-cost education on regenerative farming. Many agriculture focused universities, such as Iowa State, UC David, and Texas A&M University offer professional research on all critical elements of regenerative farming at no cost. USDA's Environmental Quality Incentives Program (EQIP) provides funding for farmers implementing the key components of regenerative agriculture.

These resources help fill the education gap but may fall short on the financial end. Farmers can implement regenerative practices over multiple crop cycles to maintain reasonable levels of revenue and profitability during the transition. Another option is to partner with an institutional farm investor that understands the process.

Private vs Public Funds

Agriculture Capital, for example, has managed over $1 billion in regenerative agriculture projects and is a pioneer in regenerative data collection and assessment. Its latest investment fund is designed specifically to expand the amount of land using regenerative practices while seeking to capture the long-term financial benefits versus conventional methods. It works with farmers looking to expand their regenerative agriculture footprint but lacking the resources to do so. Farmers engage in a lease structure with Agriculture Capital that recognizes the one-to-three-year investment period to realize the net financial gains of regenerative methods. Farmers and Agriculture Capital share in the success of the farm or ranch, further aligning interests. And critically, Agriculture Capital has the local ecosystem and soil knowledge to help the farmer or rancher implement regenerative techniques quickly and optimally. Agriculture Capital's approach is designed to overcome all the major challenges faced by farmers looking to expand or improve their regenerative operations. Private funds, like Agriculture Capital, benefit from the one-to-one relationship between capital raised and farmland acquired. It also permits institutional scale and expertise when it comes to qualifying for and monetizing carbon credits that an individual farmer cannot duplicate.

Outside of private funds such as Agriculture Capital's, investors have limited options. There are two farmland specific publicly traded real estate investment trusts (REIT): Farmland Partners (FPI) and Gladstone Land Corporation (LAND). Farmland Partners discusses soil quality and water availability but doesn't disclose specific information regarding regenerative practices. Gladstone Land's ESG report states that several tenants have initiated regenerative practices with the main objectives of earning carbon credits and sequestering carbon. Like Farmland Partners, Gladstone Land Corporation does not quantify the impact or scope of its

regenerative activities. Gladstone Land does provide some information on properties that grow organic produce, such as 417 acres producing strawberries and vegetables in Duette, Florida.

While investing in the shares of publicly traded companies may provide indirect benefits to the company, it's minimal. Farmland Partners and Gladstone Land Corporation are not meaningfully growing their portfolios. It's also unclear if they are focused on regenerative farming to any degree. Gladstone Land Corporation had 89,000 acres under management in 2020 compared to 103,000 acres as of its last quarterly filing approximately five years later. Farmland Partner's acreage has decreased by about 10% over the same period. Buying shares in these two farmland REITs in the past five years has not resulted in more regenerative farming.

Outside of private and public investment funds, individuals can also acquire farmland themselves. This is impractical for all but a small percentage of people and requires considerable resources. The average acre of farmland is $5,586 per acre as of 2023, but more productive regions are a multiple of that. Then comes the full-time job of running a farm and implementing a regenerative system, which would likely require engaging a qualified third party. The other option is leasing the property to a regenerative farmer or rancher, which are difficult to source and comes with its own set of underwriting challenges. This method has a similar effect of investing in a private farmland fund but with considerably more work and risk, especially in terms of geographic and crop diversification.

Conclusion

Regenerative agriculture has been developed for millennia. Billions of tons of annual synthetic fertilizer and herbicide usage, global efforts to reduce carbon dioxide in the atmosphere, and hundreds of millions of farmers struggling to making a living from Indiana to India indicate it's time for another regenerative farming renaissance. New technologies and government support make it an even better potential solution to many of the world's greatest problems.

Synthetic pesticides and herbicides disturb, and in some cases destroy ecosystems around the world. Human health is also a major casualty. Despite having among the strictest bans on the more dangerous chemicals, the Journal of Environmental Health Perspectives estimates that 20,000 cancer cases each year in the U.S. are linked to occupational pesticide exposure. Globally, where banned chemicals are used regularly and populations are much higher, the figure is likely in the millions. That also excludes the toll on the local community via contaminated water and food that is not actively working on farms or ranches.

Most nations involved in global greenhouse gas reduction efforts are not anticipated to contribute the majority going forward. Expensive and often limited measures in the West to reduce greenhouse gas emissions, which often classify offshoring polluting industries like steel making to developing nations as reductions, are not sufficient to reach climate goals set by the U.N. and similar organizations. Without involving the likes of India, China, and Africa, plans to stabilize greenhouse gas emissions and atmosphere levels are in vain. By embracing market-based solutions and improving both the lives and finances of farmers, regenerative farming can incorporate the world's greatest polluters into the solution. Based on current technology and constraints, transitioning to regenerative farming has the capacity to improve environmental conditions on the land and in the air at least on the level of renewable energy. And unlike renewable energy, it does not require trillions of dollars in investment to replace the old system.

One mega-watt hour of solar electricity offsets 0.5 to 1 metric ton of carbon dioxide, or about 0.85 on average. The typical residential solar system requires an investment of roughly $1,825 to offset one ton of carbon, which drops to around $1,400 for the highest quality dual-axis, 96-cell panel commercial solar farm. Large-scale regenerative farming can sequester the same amount of carbon for $30 to $50 and do so for roughly the same period as a solar panel's lifespan. Cover cropping, the easiest and likely most common regenerative practice, is the most cost efficient and sequesters a ton of carbon for about $10 in many areas. If a small fraction of the capital allocated to renewables and other green projects were directed toward cover cropping initiatives, we'd likely see at least ten times, and potentially 100 times

more carbon sequestered compared to commercial solar, which is among the most efficient renewable energy sources. This is all while improving the resiliency and yield of millions of acres of farmland and improving the health of hundreds of millions of the poorest and most vulnerable populations. But regenerative farming cannot power homes or factories, which is why we at CommonGood Capital invest in both and believe private institutions, governments, and investors should consider doing the same.

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