Regenerative Agriculture Guide

INTERNATIONAL COTTON ADVISORY COMMITTEE

2025

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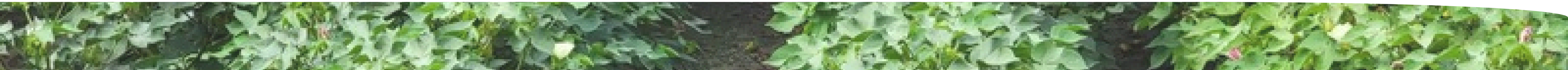
Website www.icac.org

Executive Summary

Regenerative Agriculture includes farming practices that improve soil health and the resulting ability of soil to indefinitely support profitable crop production. This guide is designed to convey the basic practices and benefits of Regenerative Agriculture to a broad audience working in the cotton industry. There are many benefits to farmers and the community. Farmers benefit from: enhanced water and nutrient uptake by roots; reduced fuel, chemical and labor cost; and avoiding soil loss from tillage. For the surrounding community, soil health improves air and water quality by reducing dust and downstream flooding, siltation, and eutrophication. Both farmers and the community benefit from the ability of soil health to improve the profitability of farming, to sequester carbon, and to make our food, feed, and fiber supply more resilient to adverse weather.

The cotton industry has a history of connecting farmers to the textile industry and textile consumers. Many of the Regenerative Agriculture practices have been widely adopted by cotton farmers due to their cost savings and pest management benefits. This is especially true in industrialized farming communities but lagging where resources are sparse. Adoption can be further stimulated with educational and financial support from governments, NGOs, and textile consumers. Cotton farmers are ideally suited because of their commitment to continual improvement in both fiber quality and farming practices (a key tenant of Regenerative Agriculture). As climate change increases in severity, Regenerative Agriculture will play an expanding role in protecting crop yields and sequestering carbon. Many future innovations will facilitate further adoption by both well-resourced and limited resource cotton farmers.



INTRODUCTION

Regenerative Agriculture (RA) is a movement in sync with the global need to protect our food, feed, and fiber supply from climate change. Regenerative Agriculture is also a contemporary label applied to established farming practices that aim to improve soil health and farm efficiency. By focusing on soil health, Regenerative Agriculture clarifies the alignment of environmental stewardship with production cost efficiency and climate resilience. A common theme in the Regenerative Agriculture discussion is that previous farming practices degraded the soil's ability to sustain long-term crop production and that regenerating or reinvigorating the soil towards a pre-farming, indigenous, state will be beneficial. Although mechanized agriculture with its plows, discs, and cultivators has fed billions of people who previously turned over sod, broke clods, and hoed weeds, it has also compacted and stripped soil of its organic material.[1.2]

Because of soil's critical role in water, nutrients, and diseases there has been extensive research that incorporates new science and technologies towards the improvement of soils and farming practices. [2,3]

Much of this research has been conducted under diverse banners (pathology, mycology, soil physics, etc.). Regenerative Agriculture is useful terminology to communicate this research as a systems approach that farmers naturally adopt as they protect their crops from abiotic and biotic threats. And, is useful terminology to align with the broader discourse on Regenerative as a component of sustainability.[4]

Some Regenerative Agriculture frameworks and certifiers have extended Regenerative Agriculture to include diverse social and farming programs that are important to the quality of farm life but are tangentially associated with soil health (worker safety, gender equity, organic, animal welfare, etc.). However, common to most Regenerative Agriculture frameworks are three farming objectives: minimize soil disturbance, maintain permanent soil cover, and grow diverse crops.[5,6]

Since farming practices must be tailored to individual farm communities, farmers, or even individual fields, there is no one-size-fits-all approach to these Regenerative Agriculture objectives. Instead, the challenge is to understand, evaluate, and apply appropriate tools for specific conditions. This Regenerative Agriculture guide seeks to convey some of the basics of Regenerative Agriculture to a broad audience and explain why it is gaining importance in both the farming and consumer communities.

Three forces are converging to create the interest in Regenerative Agriculture. The consumer demand for sustainable products pressures the agricultural industry to adopt and document farming practices that enhance long term environmental sustainability.[7,8]

The second force is the advancement of science in understanding the complex field environment and in creating cost-efficient tools to deliver this science to farmers of all scales and resources.[9]
And a third force is the recognition that Regenerative Agriculture farming practices can help adapt to and perhaps mitigate some climate change adversity.[10,11]

These forces apply equally to cotton as to other crops, but due to cotton's close connection with consumers and its historic early adoption of innovative farming practices, these forces converged early in the cotton community. Cotton is different from all other major crops. It is an industrial input to a diverse and complex manufacturing industry that must deliver ever-improving textiles for a fickle global consumer. Over the past 100 years, the cotton community has learned how to link the justifiably cautious farming community to the rigid tolerances of the textile machinery that feed the ever-changing demands of brands and retailers. Examples of these linkages include: plant breeding for new spinning technologies, farming practices that maximize fiber quality while minimizing fiber contaminants and defects, fiber premiums based on whiteness to allow just in time dyeing, individual bale testing (HVI) to compensate farmers based on multiple physical metrics, and algorithms that utilize HVI testing to create blends of ~100 bales in the textile mill.

Thus, it is no surprise that many of the Regenerative Agriculture discussions for cotton are more advanced than in other crops which have simpler processing and less engaged consumers. Because of cotton's historic cooperation between farming, merchandizing, processing, and consumers, the cotton industry leads other commodities in pan-industry initiatives such as sustainability, traceability, and now Regenerative Agriculture. Thus, other commodities will benefit from this Regenerative Agriculture guide as a tool to anticipate their own future.

The potential for Regenerative Agriculture practices to deliver the dual benefits of environmental protection and economic prosperity remains largely untapped within many cotton production regions since almost all farmers are resource limited. This guide attempts to lower the risks and costs to farmers who want to adopt Regenerative Agriculture practices thereby ensuring cotton's reputation as a leading environmentally beneficial textile fiber.

Regenerative Agriculture

Definitions

There is no common accepted definition of Regenerative Agriculture in cotton, or across agriculture. This poses challenges for brands, retailers, and consumers who want a clear communication tool to encourage Regenerative Agriculture for its environmental outcomes. However, this lack of a common, static definition reflects the rapid growth in our knowledge about soil health, microbiomes, and carbon sequestration potential.[12]

It avoids misguided maladaptation metrics such as limiting irrigation capability.[13]

In addition, cotton is uniquely unsuited to preplant prescriptions. Cotton farmers make many agronomic and pest management decisions during the growing season, unlike grain growers. The cotton plant is highly adaptable and grown across a wide range of soils, latitudes, and moisture levels. These unique features of cotton and its cultivation limit prescriptive programs. Cotton farmers benefit from having the expertise and tools to tailor each field and each day to the evolving weather and pest conditions.

There are many definitions of Regenerative Agriculture, some of which are listed on the next page.

REGENERATIVE AGRICULTURE DEFINITIONS

From Rhodes 2017:

Regenerative Agriculture has at its core the intention to improve the health of the soil or to restore highly degraded soil, which symbiotically enhances the quality of soil, water, vegetation, and land-productivity.[14]

From Schreefel 2020:

An approach to farming that uses soil conservation as the entry point to regenerate and contribute to multiple provisioning, regulating, and supporting ecosystem services, with the objective that this will enhance not only the environmental, but also the social and economic dimensions of sustainable food production.[15]

From American Society of Agronomy, Crop Science Society of America, and Soil Society of America 2021:

Regenerative agriculture, which includes carbon sequestration as a central tenant, encompasses important strategies for sequestering carbon and increasing resilience. Such strategies include reducing disturbance, keeping the ground covered, increasing biodiversity, and tightening nutrient cycles, among others.[16]

REGENERATIVE AGRICULTURE DEFINITIONS

From O'Donoghue 2022:

Any system of crop and/or livestock production that, through natural complexity and with respect to its inherent capacity, increases the quality of the product and the availability of the resources agriculture depends upon, soil, water, biota, renewable energy, and human endeavor.[17]

From CSIRO 2023:

Regenerative Agriculture is an agricultural and transdisciplinary approach that integrates local and indigenous knowledge of landscapes, as well as their management, with established scientific knowledge. It combines a range of adoptable principles with context-specific practices, focusing on soil conservation as the initial step to restore soil health, enhance ecosystem functions, and promote improved socioeconomic outcomes.[18]

From SAI Platform 2023:

Regenerative agriculture is an outcome-based farming approach that protects and improves soil health, biodiversity, climate, and water resources while supporting farmer livelihoods.[19]

REGENERATIVE AGRICULTURE DEFINITIONS

From Aid by Trade Foundation 2024:

Actively creating co-benefits in interaction between nature, people, society, and the economy to bring agricultural systems into a better state than they are currently in.[20]

From CottonConnect 2024:

Regenerative agriculture is a holistic, outcome-based farming approach. It focuses on practices that help to improve soil health, encourage biodiversity, promote water efficiency and reduce greenhouse gas emissions whilst also supporting farmers to diversify their incomes and become more resilient to climate change.[21]

From the Soil Health Institute 2024:

The foundation of Regenerative Agriculture is management systems that improve soil health.[22]

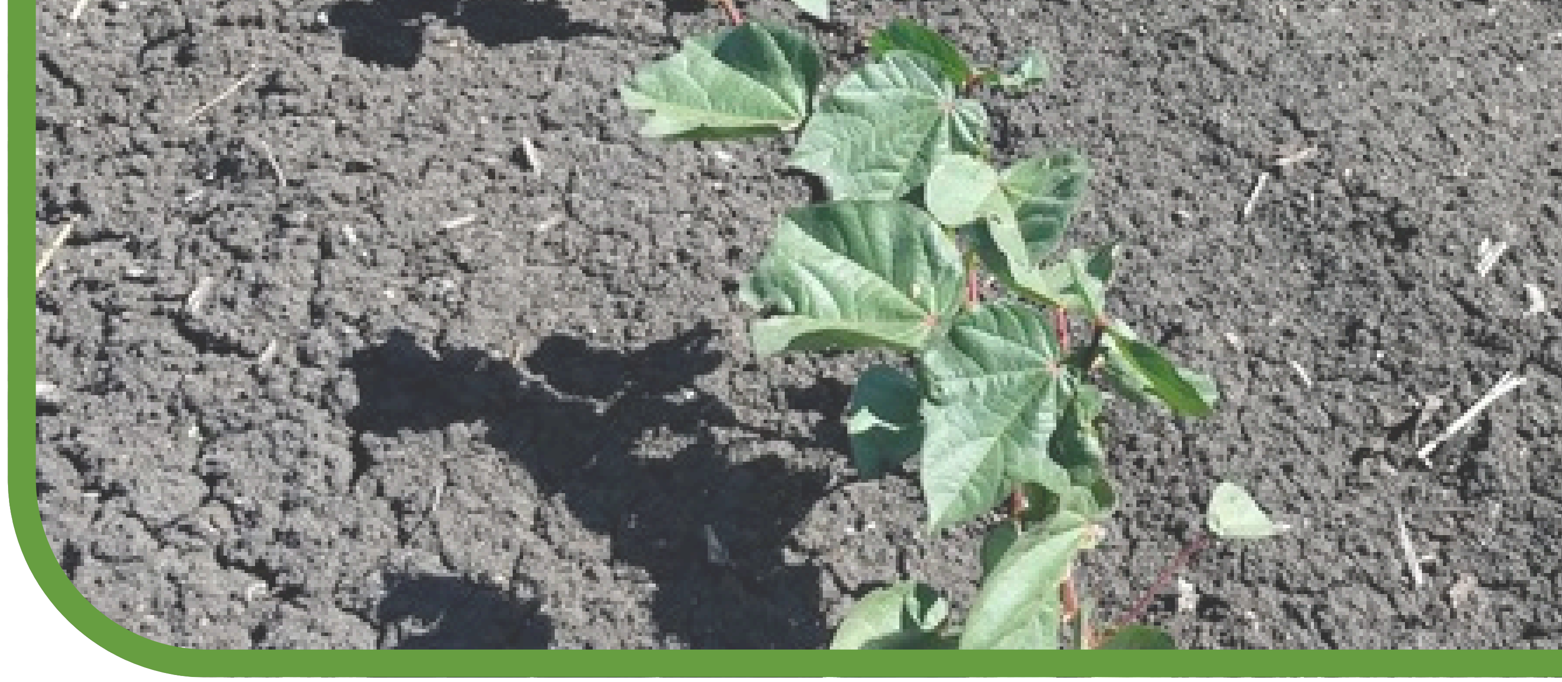
REGENERATIVE AGRICULTURE DEFINITIONS

From Nature Sustainability 2024:

Regenerative Agriculture describes maintaining and improving resources through continuous renewal of the complex living system, having in mind that there is no 'waste' in nature.[23]

Although more than 25 practices have been promoted as a component of Regenerative Agriculture in cotton[24], the backbone in these 10 definitions above is improving soil health (or the ability of soil to indefinitely support profitable crop production). The many on-farm and off-farm benefits are the justification for the focus on soil health. For farmers, soil health enhances water and nutrient storage and uptake by roots. Soil health also reduces farm fuel and chemical costs and soil loss associated with tillage. For the surrounding community, soil health improves air and water quality by reducing dust and downstream flooding, siltation, and eutrophication. Both farmers and the community benefit from the ability of soil health to improve the profitability of farming, to sequester carbon, and to make our food, feed, and fiber supply more resilient to adverse weather.

Why
Regenerative Agriculture?



Recognition of soil in farming's success has expanded beyond its chemical and physical contributions. In the 1970s, chemistry quantified the soil's availability of macro and micronutrient chemicals and recommended fertilizer rates. Physics elucidated how gas, water, and chemicals moved through soil. Agricultural engineers designed irrigation systems that uniformly applied water and tillage implements that created a homogenous, loose medium for root growth. Soil biology in the 1970's agriculture focused on minimizing pathogens and nematodes with broad spectrum biocides.

Regenerative Agriculture improves upon the agricultural science of the 1970's by combining chemistry, physics, and biology into a holistic understanding of how healthy soils lead to on-farm and off-farm benefits. A uniform, homogenous, loose, and sterile soil medium is no longer recognized as optimum. While science is still investigating what is optimum, natural environments are used as guides for the direction agriculture should pursue to optimize soils. Natural environments have weathered millennia of droughts, floods, pests, freezes, and extreme heat by being organismally and spatially diverse. Thus, Regenerative Agriculture's theme of regenerating or reinvigorating soil is a good starting model for agricultural resilience.[25]

Science is refining this model because society's goal is not to return cultivated land back to its natural state that only provisioned a low density of hunter gatherers. We need healthy soils that support high productivity and land sparing for modern society. The science of biology has been especially helpful in understanding the role of soil microorganisms in healthy soils. Due to the incredible microbial diversity in each gram of soil and the heterogeneity of soil when not disturbed, the soil biology science of Regenerative Agricultural is in its infancy.[26]

The common Regenerative Agricultural objectives (minimize soil disturbance, maintain permanent soil cover, and grow diverse crops) that lead to soil health provide tangible economic benefits. Reducing tillage saves fuel, equipment, and labor costs. Diverse cropping better ensures an economic return when markets and weather are volatile. Live roots prevent loss of costly nutrients from leaching. Soil fungi increase the root uptake of expensive fertilizers. Soil bacteria create nitrogen nutrients that further reduce fertilizer expense.[27,28]

Surface residue and macropores capture and infiltrate valuable rain. Environmental benefits also accrue. Air and water pollution from dust and runoff is reduced. Downstream dams and deltas are less vulnerable to siltation and eutrophication. Fossil fuel emissions are reduced from no-till and improved fertilizer efficiency. Soil carbon sequestration can be enhanced.[29,30]

However, the biggest driver for Regenerative Agriculture is climate change.[31,32]

The practices associated with Regenerative Agriculture help address the agricultural threats from climate change - extreme rainfall events both droughts and deluges, hotter days and nights[33] and risk of occupational heat-related illness.[34,35]

When soils are left undisturbed with macropores and surface residue they better absorb rainwater, slow surface water flow, and store soil water for later use by roots. Soils with surface residue also absorb less sunlight heat during the day, staying cooler for surface roots and beneficial microbes[36], and release less radiant heat to the canopy at night.

Regenerative Agriculture
Practices

A wide diversity of farming practices can advance Regenerative Agricultural objectives (grow diverse crops, minimize soil disturbance, and maintain permanent soil cover) but several have broader applicability and ease of adoption. Top on this list is crop rotation and the related use of cover crops.

- Growing diverse crops
- Minimizing soil disturbance
- Maintaining permanent soil cover

Growing Diverse Crops

Growing diverse crops has provided benefits to farmers around the world since agriculture began.[37] Genetic analysis of plant and animal remains from early farming communities catalog a wide diversity of food and feed species.[38]

Since each crop or animal species has unique susceptibility to pathogens and adverse weather, building a food supply based on just a few species was and still is risky. This is true for individual farm families, farming communities, and the global population.[39] Crop diversity emulates the success of natural plant diversity. Natural environments contain mixed stands of plant species because of their greater resiliency and utilization of resources.[40,41]

If conditions turn unfavorable for one species, another proliferates. If trees do not capture all the sunlight an understory shrub will. Maintaining a mixture of food plants in a field requires gardening-level hand labor. Most commercial farmers operate at a larger scale. Even at the lowest density, 1 hectare of cotton exceeds 10,000 plants, thus plant diversity is easiest to achieve with crop rotation. Crop rotation is common on small farms since family nutrition derives from crops other than cotton. Crop rotation is also preferred on medium and large farms to diversify farm income and provide agronomic benefits[42]. Cotton is ideally suited to crop rotation. Cotton enhances subsequent crops by allowing effective weed control and suppressing diseases of rotational crops.

Unlike delicate and bushy vegetables, cotton's woody stem allows close cultivation; cotton also tolerates a diversity of herbicides (WSSA Groups # 1, 2, 3, 4, 5, 7, 9, 10, 12, 13, 14, and 15)[43] to control a diversity of weeds in rotation crops.

Since cotton is genetically unrelated to all other crops (except okra) cotton in a rotation suppresses many diseases. Cotton benefits from prior crops that add root mass and crop residue. There are environmental benefits from cotton rotations since most rotation crops are shallow rooted and leave excess soil nitrogen that cotton is highly adapt at utilizing before the nitrogen contaminates water or air. Since cotton has a deep tap root and yield of quality fiber benefits from depleted soil nitrogen at harvest, cotton can be utilized to remove excess soil fertilizer left after corn.

Another practice that introduces plant diversity to a field is cover crops. Cover crops planted after cotton harvest are a form of rotation and introduce plant diversity to a field. Common cover crop species bring diversity to a field since they are typically grasses, legumes, or mustards. Interseeding (aka relay planting) entails seeding a different plant species before the cotton is harvested. Wheat and cover crops can be seeded prior to cotton harvest which provides multiple benefits. Interseeded plants get a jump start in heat units. They pull moisture and nitrogen from the soil speeding boll opening and lint fluffing and firm the soil in preparation for harvest labor or machines.

For cotton farmers, crop rotation is the preferred source of the soil health benefits from plant diversity. It is common at all farm sizes, resources, and climates and it supports financial security and resilience. Crop rotation enhances soil health by disrupting disease and insect pest cycles, adding fibrous roots and surface residue when rotated to a grain, adding organic nitrogen when rotated to a legume, and adding antimicrobial compounds when rotated to alliums or brassicas. When annual rainfall falls below 50 cm, farmers without access to irrigation have fewer crop rotation options, other than winter small grains since the only summer annual crop with the cotton plant's tolerance of drought is sorghum.

Minimizing soil disturbance

Minimizing soil disturbance is the next most common Regenerative Agriculture objective for farmers to achieve. Farms are independent businesses where harvest value must exceed cost over the long term. Cost saving has been the incentive for minimizing soil disturbance. Soil is heavy (weighs approximately 50% more than water per volume) so moving soil requires draft animals or tractors. With 10 to 20 tractor passes per year in mechanized agriculture, farmers have experimented with eliminating tractor passes or combining operations in one pass. This has been called reduced tillage or minimum tillage and was often facilitated by herbicides instead of cultivators, disk opener planters instead of seed bed tillage, or strip tillage instead of mold board plows and subsoilers.

Considering that native soils experience zero tillage, it is easy to understand why reducing tillage regenerates soils.[44] The linkage with soil health is also clear. Every tillage pass exposes the soil to oxygen which allows bacteria to decompose organic matter. Every tillage pass disrupts the macro pores from dead roots and earthworms where water can infiltrate rapidly. Every tillage pass mixes leaves and stems with deeper soil leaving the surface vulnerable to erosion and baking. Every tillage pass disrupts the soil microbiome, especially the delicate mycorrhizal fungi hyphal networks.[45,46]

Many growers on the reduced tillage path eventually eliminate tillage and adopt zero-tillage or no-till for cost savings in labor, equipment, and fuel. Cotton is ideally suited to both reduced tillage and no-till because cotton seedlings can be established without seed beds and weeds can be controlled without tillage.

Maintaining permanent soil cover

Maintaining permanent soil cover is the more challenging Regenerative Agricultural objective in cotton. Cotton requires more heat units to mature than corn, wheat, or legumes and has zero economic value if lack of heat units or an early freeze prematurely halts fiber development. These other crops still have economic value as animal feed, even when immature. Thus, the 5 to 7 months required for cotton maturation often leaves few warm, sunlit months to grow a double crop. Double cropping cotton is rare outside of the tropics. Small grains are one of the few options to maintain soil cover after cotton harvest AND generate income from grazing or grain. As a result, non-harvested cover crops are the common solution to maintaining soil cover after cotton harvest outside of the tropics. Many annual plant species are useful cover crops that protect soil from rain and wind erosion, adding organic matter to the soil, and nourishing the soil microbiota. Additional benefits include nitrogen fixation, soil compaction loosening, weed germination suppression, rainwater infiltration, and soil nutrient retention. However, none of these benefits from cover crops include income from harvesting a second crop.

In the tropics, second crops are common where rain or irrigation permits. Crop rotation occurs more than once a year since a new crop is often no-till planted right after a mature crop is harvested.[47]

Maintaining permanent soil cover in the tropics through multiple crops per year provides the same benefits as cover crops with the added income from harvesting a second crop.

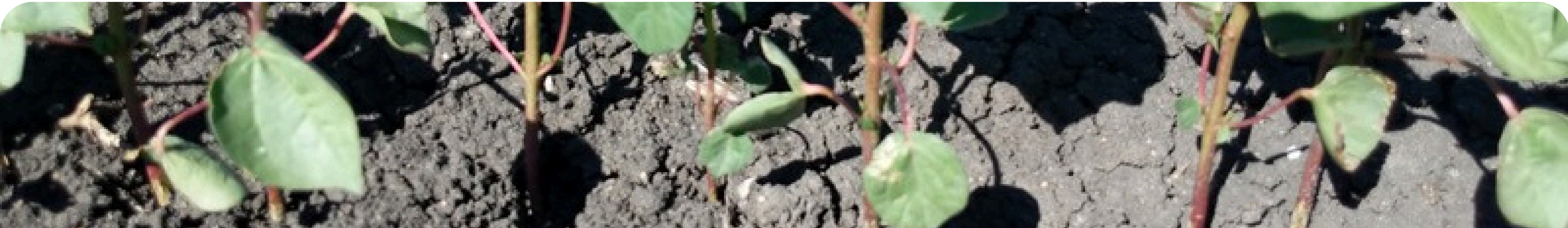
Regenerative Agriculture versus Traditional Farming

Traditional cotton production practices have been developed and honed for specific fields, handed down from one generation to the next. Adjustments are made as younger generations take charge or new technologies improve profitability. Many traditional farmers already practice Regenerative Agriculture, without the name, for the purpose of lowering cost and stabilizing income. Regenerative Agriculture practices lower input costs through eliminating some or all tillage (costs of fuel, labor, and tillage equipment are substantial) and more efficient use of scarce or expensive inputs (rainwater, pesticides and fertilizers). The Regenerative Agriculture objective of diverse crops also has a clear farmer benefit where markets, weather, and pests are volatile. The impact of Regenerative Agriculture practices on the other side of the profit equation (yield, quality, and price) is less clear.[48]

When fields are converted from full tillage to no-till, stand establishment can be challenging due to the surface residue which delays soil warming, surface compaction which requires specialized planters, and live plant tissue which provides a “green bridge” for insects to move from cover crop roots and leaves to seedling cotton. The impact of Regenerative Agriculture practices on fiber quality is also unclear. On the one hand, drought stress is often reduced from Regenerative Agriculture practices in marginal rainfed cotton which usually improves staple length and fiber uniformity; on the other hand delayed stand establishment can lead to delayed fiber maturity.

A key driver for support of Regenerative Agriculture from textile consumers are off-farm environmental benefits. Regenerative Agriculture practices that maintain resources on the field also translate to less impact off the field. These include nitrogen and phosphorus fertilizers, pesticides, floodwater, and soil particles in the air and water. Although traditional agriculture also aims to keep valuable resources on the field and in the plants, Regenerative Agriculture calls out and elevates the importance of our shared environment. Another key driver for Regenerative Agriculture supporters is the goal of sequestering carbon in the soil. Farm productivity invariably improves with elevated soil organic carbon because of improved soil tilth, water and nutrient holding capacity, and a robust soil microbiome.

Broad adoption of some Regenerative Agriculture practices cannot be driven solely by on farm profitability, especially maintaining permanent soil cover with cover crops[49,50], and the record keeping required by various certifying organizations. Some farm communities need support from the benefits to our shared environment that motivate textile consumers. With locally tailored and agronomically sound linkages between limited term consumer investments and Regenerative Agriculture practices the farm transformations can be durable, handed down from one generation to the next, and evolve as new technology unfolds (see next two sections). Regardless of whether farmers label themselves Regenerative and seek certification, the cotton industry has an opportunity to acknowledge the already widespread adoption of Regenerative Agriculture practices.[51,52]



Can We Expand Regenerative Agriculture Adoption?

Adequately resourced cotton farmers have readily adopted Regenerative Agriculture practices for their on-farm benefits. The challenge to further adoption lies primarily in less resourced farm communities. They have limited access to modern farm machinery, safe and reliable crop protection products, and the knowledge necessary to adapt new practices to their local conditions (weather, soil, pests, markets, infrastructure, finances, labor, etc.). This limitation is compounded by the focus of indigenous knowledge on perennial and diploid cottons. Only in the last 200 years has Upland tetraploid cotton been grown worldwide as an annual.[53]

Paths to increased

Crop Rotation

While there are many benefits of crop rotation in a cotton system[54], increasing adoption requires creating the opportunity for farmers to profitably rotate crops. This includes post-harvest infrastructure and markets for the rotational crops, specialized harvesters, and new knowledge about pest control and fertilization. Larger farms are less dependent on the existing post-harvest infrastructure and markets than smaller farms because they can individually or collectively install the necessary processing facilities and establish new markets. To enhance adoption by small and medium farms, greater investment in post-harvest infrastructure and markets is needed. With all size farms, experience with locally tested and well adapted rotational crops is critical to lower the agronomic and pest risks. Pest risks with novel crops are often underappreciated since they occur to both to the rotational crop and to cotton from the new crop establishing new pests or becoming a weed.[55]

A reliable seed supply is needed. Farmers planting a new crop need to be aware of the half dozen critical agronomic or horticultural steps to ensure success. Initial success with a new crop builds confidence and local knowledge. While initial failure leads to generations of skeptical farmers. Local knowledge supported by robust science can expand the weed and disease suppression benefits of rotation that further increase adoption.

Paths to reducing Tillage

Most farming practices are refined and improved incrementally over decades. Testing an innovation for only 1 or 2 years may fail to uncover severe consequences of a change in long established practices. However, some farming changes have been abrupt; no-till adoption was accelerated across North and South America with two innovations - cotton stand establishment without a seed bed and weed control without cultivation. These two innovations (combined with savings in labor, fuel, and tillage equipment) can power rapid adoption of reduced tillage around the rest of the cotton world.

Compared with grain crops, cotton stand establishment is more difficult because cotton emerges slowly pulling its seed leaves above the soil. Planting too deep delays emergence extending the vulnerability to crust forming rains and soil borne diseases and insect pests. Planting too shallow risks desiccation before the root establishes in moist soil. Historically, cotton seed beds of small soil particles were created to allow optimum seed depth and placement. The availability of disc opener planters and predictably vigorous seed facilitated the adoption of reduced tillage and no-till. Disc opener planters slice through surface residue to place seed in moist firm soil. Although disc opener planters can establish a stand with low vigor cotton planting seed under warm conditions, high vigor cotton planting seed takes advantage of these planters' ability to establish a cotton stand under the cooler temperatures often experienced when surface residue delays spring soil warming.

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The second innovation that spurs adoption of reduced tillage (especially no-till or zero-till) is cotton-safe herbicides that collectively control all weeds of concern. Weed seed germination inhibitors (premergence herbicides) have been successfully used in no-till fields that were free of perennial weeds. The introduction of cotton-safe foliar herbicides, with GMO tolerance to glyphosate, glufosinate, and auxin herbicides expanded the no-till opportunity into fields infested with perennial weeds. Instead of cultivating weeds by uprooting and desiccating them, premergence herbicides prevent weed seed germination and foliar herbicides control perennial and escape weeds.

Besides cost savings from reduced tillage and farm innovations (planters, herbicides, seed vigor) farmers realize another encouragement to minimizing soil disturbance. Once a farmer starts no-till the benefits compound annually, providing a strong incentive to put additional fields into no-till. The first year of no-till cotton, the key farm benefits are cost savings and blowing sand protection. In most cases, subsequent years bring additional benefits of drought tolerance, nutrient efficiency, and weed seed deterioration.

Paths to increased Permanent Cover

The cost of planting and managing cover crops is not trivial considering that no direct income is generated. Some seed mixtures can cost $100 per hectare, plus seeding, plus terminating their growth to prepare fields for crop planting. Local research into specific cover crop species and cultivars is needed to allow successful adoption, along with a cover crop seed supply and locally relevant knowledge about cover crop agronomy. An infrastructure around cover crops is needed to increase adoption. These cost impediments to cover crop adoption can be lessened or balanced with other savings. For example:

- Farm-saved wheat seed at reduced rates (30 kgs per hectare) is the preferred cover crop in the Southwest U.S. [56]
- Early season cotton nutrition without starter fertilizer is enhanced with a legume/cereal cover crop mix in high-rainfall sandy soils [57]
- Utilization of surface applied manure increases with cover crops [58]
- Emergence of small-seeded weeds is delayed with high residue cover crops, saving herbicide costs [59]

Farms starting a cover crop program are encouraged to start with low-cost seed of only a few, perhaps just 1, locally adapted species that is planted while warmth and soil moisture allow early cover crop growth. The optimum cover crop termination date in relationship to cotton planting, usually with an herbicide, is an important decision that should be adjusted for local conditions. The general rules are useful starting points: The date should be early enough to allow the cover crop to dry down before planting. This avoids a green bridge for soil borne and foliar insect pests to move from the cover crop to the seedling cotton and allows planters to slice through the dry, brittle plant residue. The termination date should be even earlier if rainfall could be insufficient to replenish soil moisture for cotton stand establishment. [60]
A later termination date accumulates more cover crop biomass which is critical where weed germination needs to be suppressed. [61]

Support for Regenerative Agriculture

The current adoption of Regenerative Agriculture practices in well-resourced countries has been driven primarily by inherent benefits to farmers (profits from higher yields and cost savings). Off-farm support has also contributed, for example with subsidized cover crop seed or drip irrigation.[62] The outreach of agronomists and soil scientists at numerous research and demonstration stations has been hugely influential. Unfortunately, there has not been sufficient support for resource limited cotton farmers, especially in limited resource countries. To reach the point where Regenerative Agriculture practices are self-sustaining for these farmers will likely require off-farm support – at a minimum in locally relevant expertise and demonstrations, preferably in infrastructure that delivers planting seed, planters, crop protection products, etc. and ideally in an engine of self-sustaining local innovation and investment to create the necessary components and knowledge for Regenerative Agriculture into the future.[63]

Although external funds can facilitate resource limited farmers in their adoption of Regenerative Agriculture practices, it is essential that short-term funding that supports RA practices will be more suitable for resource-limited farmers than just environmental outcomes which inherently are more costly to verify.[64]

Local agronomic and pest management expertise can design paths to Regenerative Agriculture adoption that rapidly build self-sustaining production practices to lock in the Regenerative Agriculture gains when external funds dry up. Examples of locally tailored short term grants to facilitate new adoption include the Climate Smart Agriculture in the U.S.[65]

Carbon sequestration and carbon pricing are potential funding sources for launching Regenerative Agriculture practices in limited resource farming communities. The sequestration opportunity in these countries derives from the low soil organic carbon typical of warm soils tilled frequently for weed control.[66] The recent discrediting of forest-based carbon credits[67] and carbon certification agencies[68,69,70] will intensify the technical and policy scrutiny of all plant-based carbon sequestrations which may favor the more stable agricultural sequestration. Unlike forest sequestration where trees can be cut or burned which reverses sequestration, agricultural sequestration from no-till should be less vulnerable to deliberate reversion. Farmers who initiate no-till practices are incentivized to continue because: 1) no-till benefits increase over years, 2) no-till farmers sell their tillage equipment, and 3) the labor savings from no-till allows more hectares per manager and thus higher income. Multiple carbon sequestration certification strategies are developed based on practices such as no-till (which is remotely verifiable) or soil carbon content (which is not now remotely verifiable).[71] Carbon pricing has recently been shown effective at reducing carbon emissions.[72] Besides sequestration, Regenerative Agriculture practices such no-till and fertilizer use efficiency lower the carbon intensity of farming.

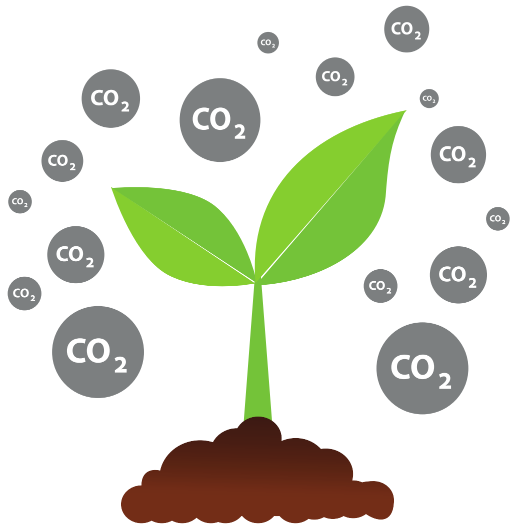
The textile consumer base is another potential funding source to facilitate adoption of Regenerative Agriculture practices in resource limited cotton farms. Cotton has a small but durable organic textile market where purchase decisions are based on environmental impact of cotton production, not the perceived safety of consuming organic foods. Some research shows that consumer brand loyalty is strengthened with the brands support for Regenerative Agriculture.[73] Direct connections from cotton's customers to the farmers who grew the cotton are challenged by the convoluted textile supply chain. Yarn spinners maintain uniform quality while minimizing their raw material cost by blending ~100 individually selected bales together, usually sourced from multiple outlets. For this reason, accurate traceability in the cotton textile industry is challenging and expensive. The desire of brands and retailers to connect customers with Regenerative Agriculture certification programs is laudable but challenged by the lack of globally accepted Regenerative Agriculture standards, numerous certification programs, and their diversity of requirements. Considering the need to adjust Regenerative Agriculture practices to individual countries, communities, farms, and crops, any global Regenerative Agriculture standard will need flexibility.

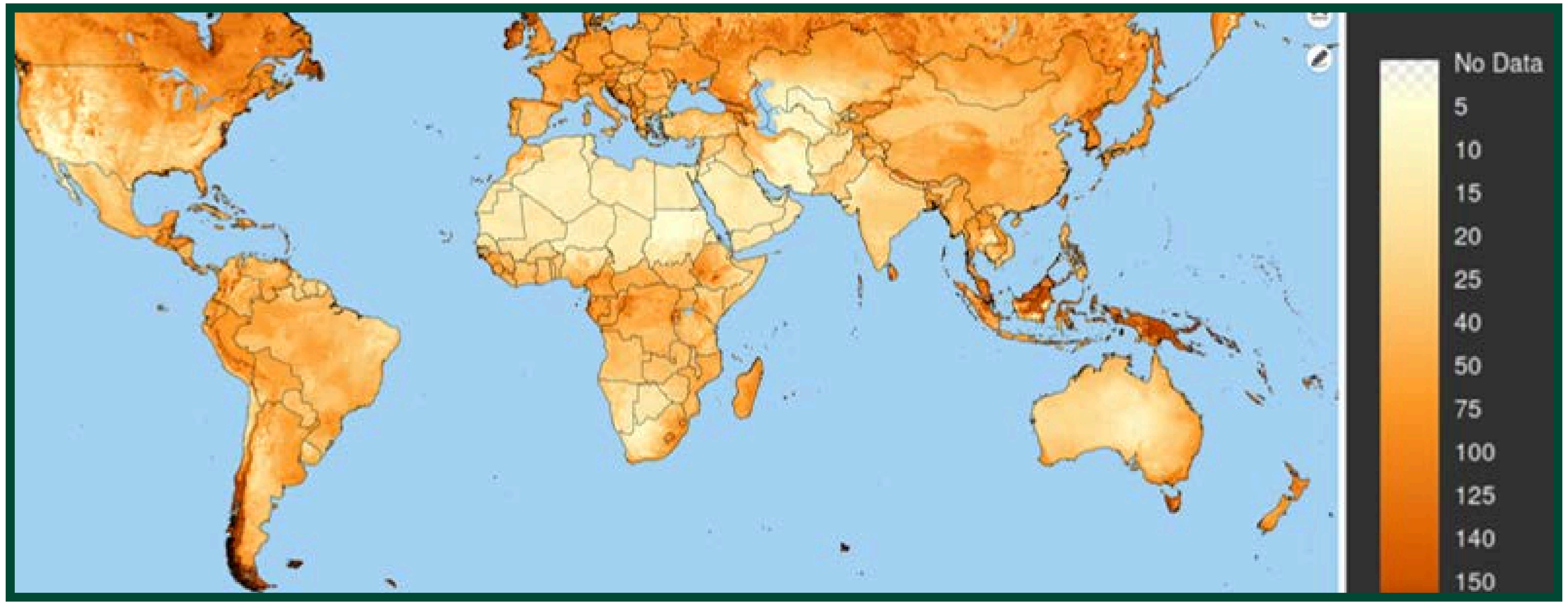
Regenerative Agriculture & Carbon Sequestration

Since cotton is one of the most drought and heat tolerant crops, the soils where cotton is grown are generally low in soil organic matter. Soils in colder and wetter climates have higher organic matter because rainfall increases plant biomass and microbial degradation is suppressed in cold soil. The FAO soil organic carbon map (in units of tonnes per hectare) shows this clearly.[74]

This low starting point for carbon sequestration offers opportunities for the cotton industry not available to other agricultural and forestry products, permanence of sequestration and additionality of sequestration. South Asia has the highest potential agricultural carbon sequestration of any other region 1.28 t/C/ha/yr.[75]

Considering the convolution of the cotton textile supply chain, incentives to producers for carbon sequestration are easiest conveyed through credits and collaboration[76] instead of consumer textile purchases targeted at a limited number of bales.





Permanence of carbon sequestration

The urgency of climate change has elevated in the last five to ten years as heat waves and floods have impacted communities and conversations. This immediacy has elevated the short lived Green House Gases (methane and nitrous oxide) which have a higher impact per molecule on global warming than carbon dioxide and fortunately degrade more rapidly (half-life of 10 years). Methane especially, required satellite technology to detect super emitters in the petroleum extraction and conveyance industry.[77]

Over the last ten years 47 percent of the growth in global warming from Green House Gases is estimated to come from methane.[78] Cotton is ideally suited for short term biogenic carbon sequestration[79] because cotton textiles contain ~1.5 kgs of CO_2 for every kg of fiber grown. Compared with food and feed crops, garments in closets keeps carbon out of the atmosphere, where as animals and humans return most of the food/feed carbon in 1 to 3 years.

Additionality of carbon sequestration

Most of the world's cotton is grown with some Regenerative Agriculture practices. The most common is crop rotation since it delivers immediate benefits to farmers who rely on their crops for family sustenance, to farmers who wisely hedge the fickle markets and weather with crop diversity, or to farmers who recognize the overwhelming benefits of plant diversity for crop productivity. The other practices of reduced tillage and permanent soil cover require technology to easily control vegetation. Of the major world crops, cotton is uniquely vulnerable to weed competition during the first 2 to 3 months of growth.[80,81]

Its slow leaf area expansion during cool springs combined with its lack of true leaves in the seed results in the requirement that competing vegetation from cover crops or weeds be robustly suppressed during this period. The global expansion of vegetation control technology will create an opportunity for many other countries to follow the example set by Brazil in rapidly adopting zero-tillage production.[82]

Another opportunity for Additionality comes from the expansion of mechanized harvesting in cotton. When cotton transitions from multiple hand picking to machine harvesting there is a need to curtail soil nitrogen as bolls open to allow a once-over harvest. Since nitrogen fertilizer production and emissions represent most of the Green House Gas emissions from cotton production,[83] reducing excess soil nitrogen will offer additional climate change benefits. Both vegetation and mechanization technologies have been permanent once adopted in cotton producing countries.[84]

Regenerative Agriculture beyond Practices to Improve Soil Health

Some Regenerative Agriculture frameworks have included farming objectives beyond the key Regenerative Agricultural objectives of grow diverse crops, minimize soil disturbance, and maintain permanent soil cover. Since all farming practices interact with each other to some degree, an argument can be made that many more practices should be included in Regenerative Agriculture. This section will discuss practices and their linkages to Regenerative Agriculture that are commonly included in Regenerative Agriculture frameworks. For more detail, the ICAC SEEP document of March 2024 covers this in detail.[85]

Livestock integration

Early agriculture relied on domesticated animals to convert indigestible plant cellulose into food. Thus, from an indigenous viewpoint the integration of animals is the earliest state that agriculture can be regenerated back to. But modern science also supports the benefits of livestock for soil health in cotton farming. Livestock grazed on rotational plants (crops and cover crops) provide multiple soil benefits: physically incorporates urine and manure into the soil, suppresses some weeds, and augments the soil microbiome. Livestock also require daily labor that is not available on many farms.

Soil Amendments

The linkages between Regenerative Agriculture and soil organic matter are strong. Sod busting tillage with plows released nutrients accumulated over millennia in the soil organic matter leading to a short-term fertility boom as the organic matter decomposed. Increasing soil organic matter to that pre-farming level on a large scale is not currently feasible but would be highly beneficial to help mitigate climate change. Adding organic amendments, even those that decompose rapidly such as fresh manure, have immediate soil health benefits. Organic amendments that decompose slowly (composts, biochar, etc.) can have short- and long-term benefits for farming and carbon sequestration. Where crop residue is not burned for fuel, on-farm production of organic amendments is feasible even in limited resource farms.[86]

Reduce Fertilizer

Regenerative Agriculture practices that lead to healthy soils invariably are more efficient with fertilizers. Globally, soil health improves nitrogen use efficiency in agriculture by 22%.[87] Surface residues promote root and beneficial fungal growth in the topsoil where fertilizers are applied. Higher soil organic carbon feeds biological N fixation. Thus, when farmers improve the soil health, they often can reduce their fertilizer input for a few years. However, nutrients are removed in cottonseed thus soil fertility declines unless replenished with manure or fertilizer and legumes (which only supply N) to balance the nutrients removed from the field. When soils are nutrient depleted, further fertilizer reductions will not contribute to the benefits from Regenerative Agriculture.[88,89]

Where soils have built up excessive nutrients from manure or fertilizer, reducing future fertilizer input is economically and environmentally sound. Excess nitrogen in manure or fertilizer can contaminate surface and groundwater with nitrate and pollute the air with the potent greenhouse gas, nitrous oxide.[90] Excess soil nitrogen also inhibits biological soil conversion of dinitrogen gas to ammonia by diazotroph bacteria (N-fixing microorganism) especially in low soil organic carbon soils typical of cotton fields.[91] Diazotroph bacteria are commercially used to supplement synthetic fertilizer N needs in corn[92] and being tested in cotton.[93] Excess phosphorus in manure or fertilizer can flow off farms and stimulate algal blooms in fresh and ocean waters.[94] Of 11 major crops, cotton was the only crop with a phosphorus use efficiency (P in the harvest divided by P in fertilizer + manure) greater than 100%.[95] In some countries, cotton's PUE exceeded 200% thus cleaning the soil of excess P left from previous crops. Cotton's high PUE likely derives from its high seed phytate content combined with it growth in warm neutral soils where soil P extraction is added by mycorrhizal fungi. Potassium is a natural component of clay particles which release and absorb K over decades of farming. Reducing excess K fertilizer use has near term economic benefits for farmers and long-term soil health benefits from reduced salinity.[96]

Reduce Water

Similar to fertilizer inputs, irrigation water inputs can often be reduced when Regenerative Agriculture practices lead to healthy soils. This is especially true in rainfed regions where rainfall infiltration improves. But like fertilizer, the blanket objective of reducing water inputs risks yield loss in some years. In cotton a small amount of irrigation water (10 cm) during the first 2-4 weeks of bloom can alleviate a yield robbing drought or a delayed harvest.[97] Improving water use efficiency is a beneficial objective regardless of rainfed or supplemental irrigation or reliant on season long irrigation.

Continuous improvement

Continuous improvement is a highly logical component of Regenerative Agriculture. Science is uncovering new tools and insights to better manage crops. Farmers are adapting and sharing Regenerative Agriculture practices. Climate change is throwing new obstacles into the highly complex machinery of food, feed, and fiber production. Because successful farms must adapt to changing climatic, ecological, and market realities, continuous improvement and flexibility are central to sustaining regenerative outcomes

Reduce Pesticides

Many Regenerative Agriculture frameworks include a reduction in pesticides that is analogous to a reduction in fertilizer or irrigation water. Substantial reductions in pesticide toxicity have already occurred over the last 50 years. Short chain, halogenated hydrocarbon soil fumigants were common for nematode control. These broad-spectrum biocides were highly disruptive of soil health, for example eliminating mycorrhizal fungi. Now Host Plant Resistance and crop rotation are sufficient for control of common nematodes.[98,99]
Insect control has transitioned from broad spectrum toxicants such as chlorinated hydrocarbons, organophosphates, carbamates and pyrethoids applied in the air above entire fields to pest specific insecticides, bioinsecticides, and seed treatment insecticides. Transgenic bioinsecticides, such as Bt cotton, only express their toxicants within the plant tissue thus targeting them to plant feeding insects. Seed treatments reduce environmental exposure compared with foliar applications because they are applied below ground at low rates (4% of labeled foliar rates for the same pests) and to less than 1% of the soil.[100]
Broad spectrum insecticides are still used in cotton production, but the next generation RNAi insecticides are becoming available to growers.[101] These offer insect species specificity and thus unprecedented mammalian and non-target safety. The one pest category where reductions in pesticide use has been challenging is weeds. With the transition to the regenerative agriculture practice of zero-till and no-till has come a greater reliance on herbicides to control weeds instead of tillage, especially glyphosate. Herbicides and fungicides are inhibitors of essential biochemical pathways and thus not without impact on microorganisms with similar metabolism, especially when tested in laboratory conditions. However, when tested under field conditions with optimum fertilization or in comparison with alternative tillage operations, the impact on soil microorganism of the common pesticides,[102,103] can be minimal.

Reducing the use of broad-spectrum, mammalian toxic pesticides in cotton that are applied by hand clearly brings environmental and human benefits.[104] The goal of reducing human exposure is paramount and requires regulation, training, and personal protection equipment (PPE). The reduction of pesticides for environmental benefits is highly farm and pest specific since numerous challenges of reducing pesticides can also be cited. Below label pesticide rates contribute to resistant pests (weeds, fungi and insects). Limiting herbicide mode of action to just one was a major contributor to herbicide resistant Amaranth pigweeds. A delayed insecticide application for square feeding insects, such as mirids, risks delayed crop maturity and fiber quality loss. A missed insecticide application that allows boll feeding insects to strip the plant just before harvest can render the other crop inputs wasted. While generally beneficial for farmers and society, blanket objectives of reducing inputs of fertilizer, water, and pesticides require careful evaluation of each specific application.

Deforestation and Biodiversity

The clearing of forests for agriculture led to a widespread loss of terrestrial biodiversity[105]. Further loss of forests compounds this damage with: additional species extinction, rainfall disruption, loss of ecological services, and zoonotic pandemics - just to name a few. Agricultural innovation can help minimize deforestation with increased productivity.[106] Although not immediately impacting cotton products, the European Union has approved biodiversity regulations on "Deforestation-free Products"[107] that impact seven other agricultural products. Due to the increased global concern surrounding deforestation[108] and biodiversity, some Regenerative Agriculture certifications for the developing world include avoiding further deforestation and some certifications for the developed world include reforesting previously deforested land.[109] Both are practical for farmers since the remaining forest near their farmland is likely less productive land and some previously deforested land has subsequently been found to be less productive. Compared to the relatively simple carbon metric and credits (CO_{2e} emitted into a shared atmosphere), proposed biodiversity metrics and credits entail a substantially elevated level of complexity due to the global diversity of species and environments.[110]

Social Welfare

Some Regenerative Agriculture certifications include social benefits of worker safety and rights, education, living environments, profitability, and economic resilience to extreme weather events. These benefits extend beyond the farm since modern agriculture requires knowledgeable and motivated farmers to maintain our food, feed, and fiber supply despite the challenges of climate change. Commercial cotton farming in the 1970's was largely scripted from one year to another. A standard regime of pesticides, irrigation, and tillage could to a large degree be replicated (almost to the week) across all the fields from year to year. Static production practices have now entirely disappeared and replaced with IPM, irrigation scheduling, and long-term cropping decisions when tillage is no longer an option. Besides satisfying basic human rights, the broad range of social welfare benefits is essential to educating and retaining the farmers who can invest their time and expertise in making the critical site-specific decisions of Regenerative Agriculture.

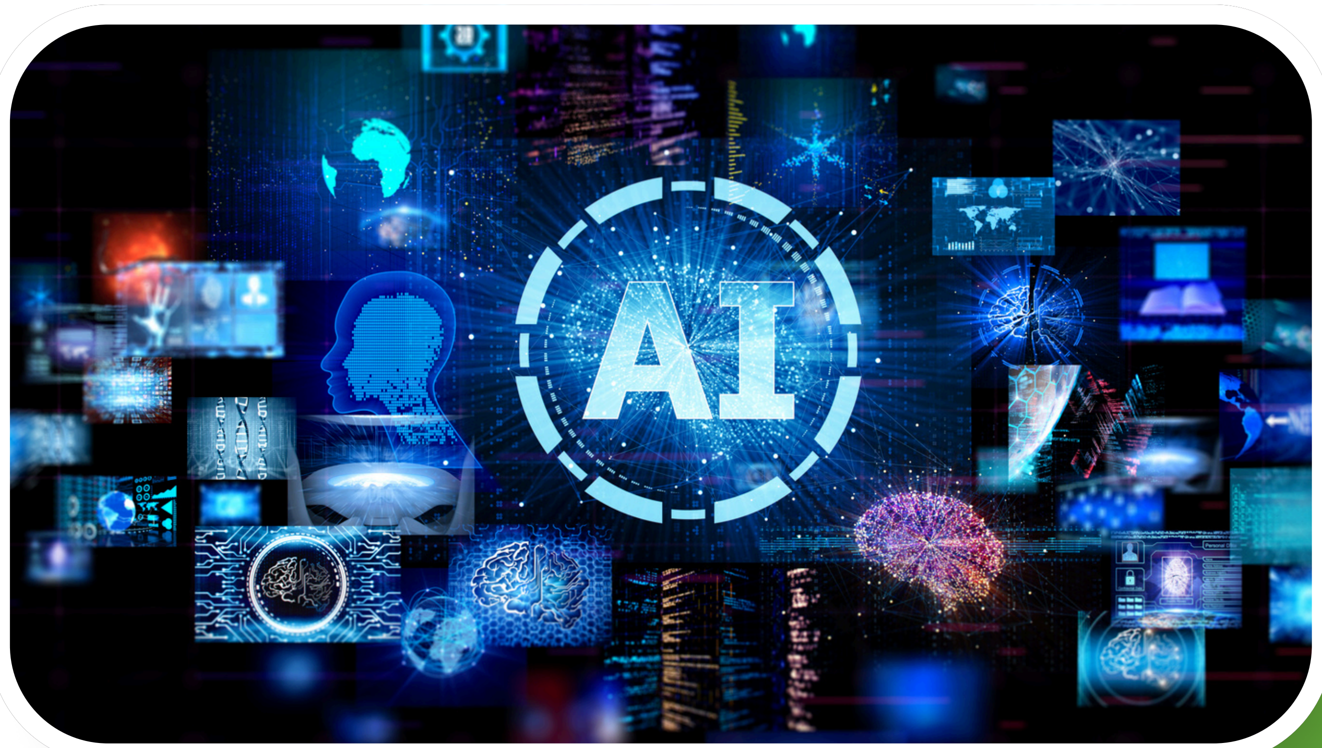
Regenerative Agriculture Future Directions

The definitions of Regenerative Agriculture focus on outcomes not prescriptive or prohibited practices. This is a plus for the expansion and durability of Regenerative Agriculture because it emphasizes the journey instead of a static prescription. It allows national, provincial, and farm level modifications/adjustments that accommodate farm realities. It encourages an open discussion on the benefits of new technologies and unforeseen future science. Although the name “Regenerative Agriculture” may be obsolete in 5 to 10 years, the objectives will likely persist. Several new technologies that can augment current Regenerative Agriculture practices include:

Regenerative Agriculture Practices

DIGITAL TOOLS

(Artificial Intelligence) enable Regenerative Agriculture and consumer support.[111] The Regenerative Agriculture objectives (minimize soil disturbance, maintain permanent soil cover, and grow diverse crops) can be readily monitored remotely. This provides farmers with raw data that can feed into AI prediction and advisory models,[112] while providing consumers with verification tools.



PRECISION APPLICATION

tailors pesticides, fertilizers, and soil amendments[113] to the soil and crop needs. Current weed control technologies both detect and apply herbicides as needed. Similar capabilities will be developed for spray drones. These technologies can be adapted to the range of field sizes and are especially useful with Regenerative Agriculture no-till where timely and precise herbicide application is essential.

Regenerative Agriculture Practices

GENE EDITING

enables inherited modifications to a crop without the full acceptance challenge of GMOs, in some countries. Since the medical community has accepted gene editing for intractable diseases, such as sickle cell anemia,[114] the agricultural acceptance and investment of gene editing has been spurred. Recent examples offer breakthrough improvements in photosynthesis and yield.[115]

RNAI PESTICIDES

can be designed to avoid non-target impacts and still provide the performance that farmers need.[116] Recent breakthroughs in RNAi design and formulation have led to commercial products with in-plant and pesticidal delivery.[117,118] The specificity offered by RNAi products should augment the biodiversity improvements in Regenerative Agriculture and offer reduced regulatory timelines.[119]

Regenerative Agriculture Practices

ORGANIC AMENDMENTS

deliver benefits from recycling nutrients and organic carbon from plant waste. With the need to improve soil health and nutrition on farms without economic access to fertilizers there is a growing interest in composting methods that deliver tailored benefits. Traditional aerobic composting concentrates plant waste nutrients. Anaerobic composting with heat creates a high pH and recalcitrant product, biochar, for acid soils. Anaerobic fermentation with inoculated microbes creates a low pH nutrient dense product, bokashi, for alkaline soils.[120]

PLANT BREEDING

is customizing root architecture for Regenerative Agriculture,[121,122,123] especially feed crops in no-till soils, which have stratified nutrients but also the potential for deeper root exploration. Cotton roots are already highly plastic and can adapt to their soil environment. But, considering that early plant selection is typically conducted in traditionally managed breeding nurseries there may be opportunities to develop varieties better suited to long term Regenerative Agriculture fields.[124]

Regenerative Agriculture Practices

SOIL MICROBIOMES

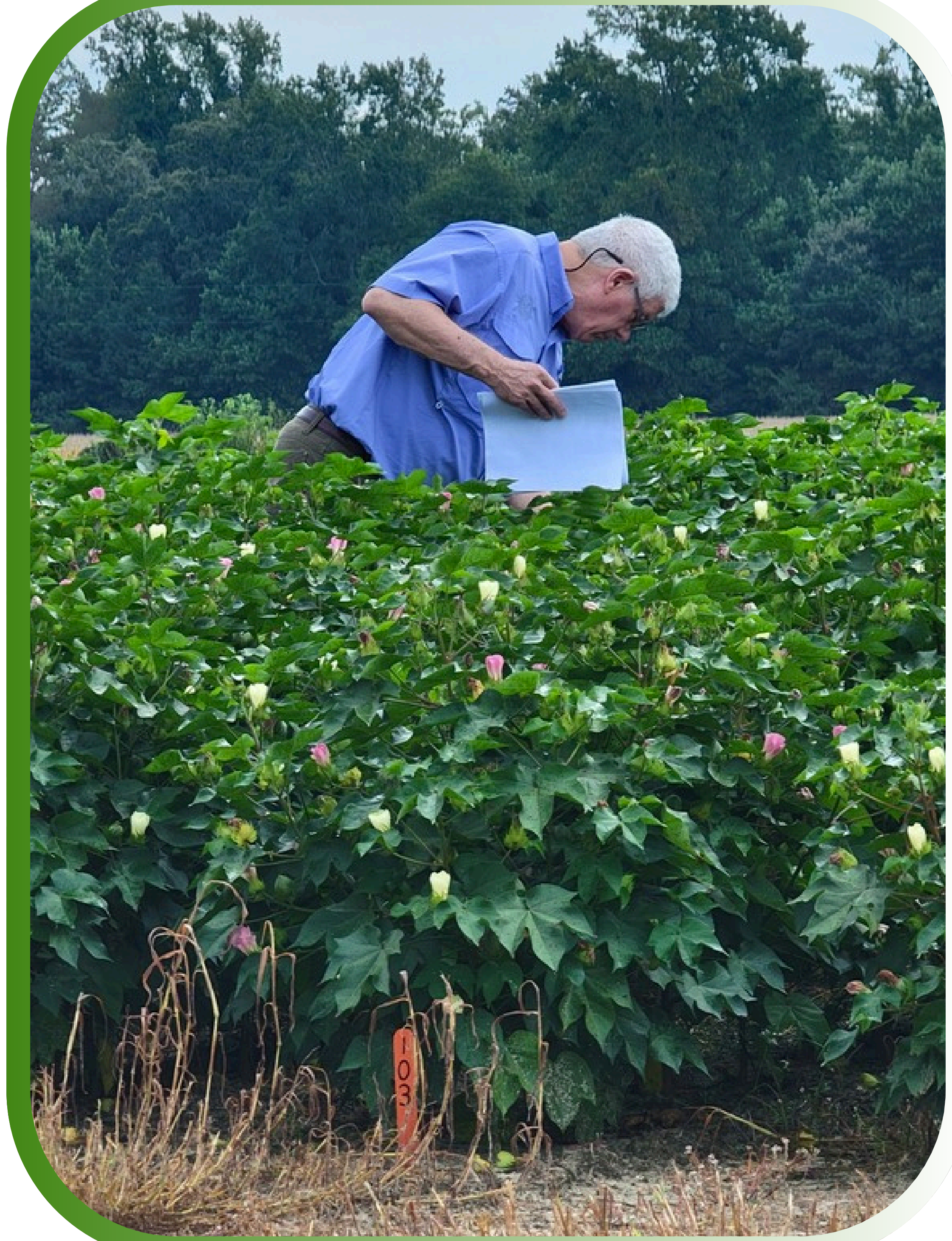
improve nutrient uptake in Regenerative Agriculture fields through mycorrhizal fungi that move phosphate-phosphorus to the roots and bacteria that assimilate nutrients and avoid loss to leaching.[125] Augmenting natural microorganisms with applied microbial consortia is an area of intense commercial research and could help regenerate degraded soils and improve nutrient efficiency.[126] Although corn, with its high fertilizer requirements, has been the commercial focus of free living N fixing bacteria (diazotrophs) to supplement synthetic fertilizer[127,128,129] these products are being tested in cotton.[130] Free living N fixing bacteria derive the substantial amounts of energy required to convert nitrogen gas into plant available ammonia, thus these products may require high soil organic matter or supplemental organic matter.

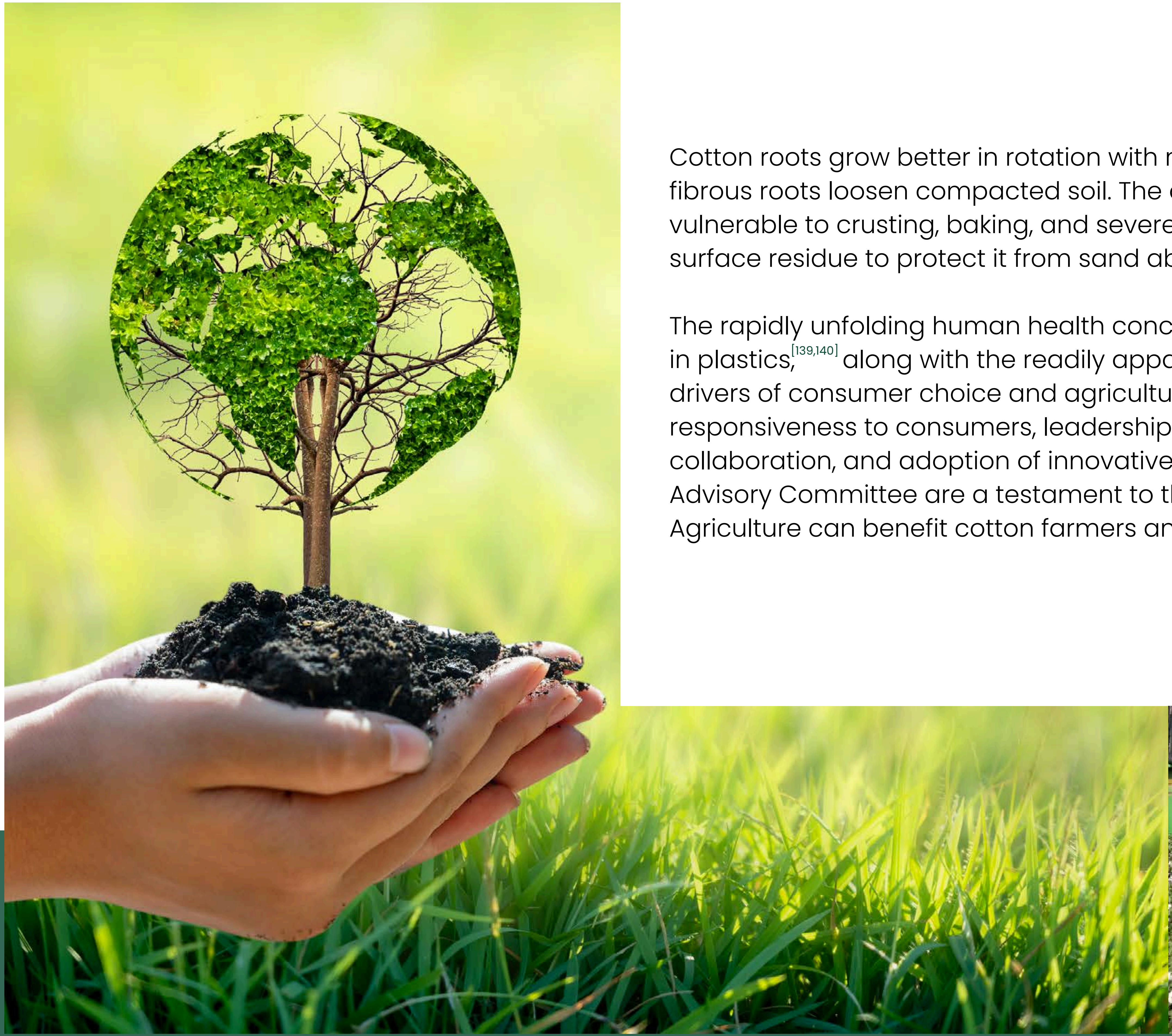
Agriculture benefits from the vast human health knowledge and tools that transfer to soil/plant health. Many of the themes in Regenerative Agriculture have direct parallels in healthy living: avoiding both broad-spectrum antibiotics and soil sterilants, consuming a diverse diet and crop rotations, not binge eating and not sod busting, personalized medicine and precision application, maintaining stable body and soil/plant temperature.[131,132]
As consumers of both medical and plant sciences we should all be excited about the future of medicine and farming.

Cotton's Regenerative Agriculture Path

Cotton's path towards Regenerative Agriculture will be as diverse as the world's agriculture and farming communities. Some regions are just starting to align with Regenerative Agriculture objectives and need resources and financial support. Other regions are highly advanced in Regenerative Agriculture adoption and rapidly assimilating new technologies. Climate change will accelerate the adoption of Regenerative Agriculture. Since farmers and scientists are alarmed to experience the devastating heat waves, floods, and droughts of the last five years. Regenerative Agriculture offers resiliency against climate change by tempering extreme heat and better capturing storm water. Cotton consumers will also drive Regenerative Agriculture objectives from the comfort of cotton garments in hot weather and the desire to move away from fossil fuel fabrics. The cotton plant is ideally suited for regenerative farming. Its relative tolerance of infertile soils and depleted soil nitrogen at harvest means that fertilizer inputs and nitrous oxide (N_2O) emissions from cotton are minimal.[133,134,135]

Cotton deep root system absorbs water and nitrate lost from other crops. Over two dozen common crops can be rotated after cotton since it does not produce allelopathic chemicals. Cotton's indeterminate shoot and root growth allow it to adapt to a wide range of moisture availability and timings. The cotton plant also benefits from regenerative farming. Tillage compacts soil, first by loosening it then applying downforce on the loose soil at moldboard plow bottoms, disc plow edges, and equipment tires. Elongation of the cotton tap root is hampered by this soil compaction.[136]





Cotton roots grow better in rotation with no-till grains (corn, sorghum, wheat, barley, oats) where fibrous roots loosen compacted soil. The cotton plant's awkward upside-down emergence makes it vulnerable to crusting, baking, and severe heat. After emergence, its tender stem and leaves need surface residue to protect it from sand abrasion.

The rapidly unfolding human health concerns about microplastics/microfibers,[137,138] and toxic chemicals in plastics,[139,140] along with the readily apparent impacts of climate change on farming will be strong drivers of consumer choice and agricultural innovation. Cotton already has a long history of responsiveness to consumers, leadership in sustainability, technical expertise in each country, global collaboration, and adoption of innovative farming practices. The activities of the International Cotton Advisory Committee are a testament to this history. The global movement towards Regenerative Agriculture can benefit cotton farmers and consumers. It should be embraced

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