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Editorial

Climate change is ravaging small-holder, rain-fed cotton farmers in Africa and Asia, putting the livelihoods of millions at risk. These regions, where cotton is a crucial cash crop, are grappling with more frequent and severe droughts due to shifting climate conditions. Prolonged dry spells and rising temperatures are causing crop failures, pushing farmers into a cycle of poverty and food insecurity.

Regenerative agriculture offers a solution by tackling both climate change and farmers' well-being. Healthy soils — a cornerstone of regenerative practices — can retain more moisture, which makes crops resilient to drought. Techniques such as cover cropping and reduced tillage improve soil structure and enhance moisture retention, reducing the impact of erratic rainfall. Biodiversity, promoted by regenerative methods, creates a buffer against climate risks and provides alternative sources of income. Farmers can cultivate diverse crops alongside cotton, ensuring food security even during crop failures.

Moreover, regenerative agriculture sequesters carbon from the atmosphere, mitigating climate change. These practices can remove substantial amounts of carbon dioxide from the atmosphere, helping combat the global climate crisis. To achieve this, support through training, improved access to seeds and other inputs, improved market connectivity, and financial resources is crucial. NGOs, governments, and international organisations have an important opportunity to empower small-holder farmers and promote sustainable, resilient farming practices that benefit both the farmers and the planet.

The ICAC RECORDER dedicates this issue to the pressing issue of climate change and the potential of regenerative agricultural practices to empower cotton farmers in their battle against it. With three insightful articles, this edition covers the impacts of climate change on cotton production, the principles and practices of regenerative agriculture, and the proposal for the 'ICAC Carbon Neutral Cotton Farm Plan'. In Dr Michael Bange and Dr Katrina Broughton's article, 'Improving Cotton Productivity in a Changing Climate - The Role of Research,' the authors highlight the need for adaptation strategies in response to climate change's impact on cotton production. These articles emphasize a multifaceted, systems-based approach and early implementation of resilience-enhancing strategies.

The second article, 'Regenerative Agriculture: The Climate Connection' by Keshav Kranthi and Sandhya Kranthi, explores the principles of regenerative agriculture, emphasising its role in bolstering carbon sequestration, emissions reduction, soil health enhancement, and sustainable crop production systems.

Lastly, Dr Keshav Kranthi's article introduces the 'ICAC Carbon Neutral Cotton Farm Plan', which proposes its implementation in collaboration with partner organisations from ICAC Member governments. This plan is built around a new sustainable model to inspire broader agricultural and environmental transformation by utilizing cotton's carbon-capturing capabilities to combat climate change, envisioning cotton farms as potential net carbon sinks.

As the world confronts the urgent need to reduce carbon emissions and combat climate change, the 'ICAC Carbon Neutral Cotton Farm Plan' exemplifies the potency of nature and innovation in achieving carbon neutrality. It serves as a testament to the potential of a brighter, carbon-neutral future — and it can begin in a cotton field.

In this endeavour, the ICAC stands as a steadfast partner to our stakeholders from farm to consumer, dedicated to disseminating knowledge and inspiring change that transcends cotton farming to contribute to a sustainable and climate-resilient world.

– Keshav Kranthi

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Improving Cotton Productivity in a Changing Climate - The Role of Research

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Dr Mike Bange is currently the Commercial Research Manager with CSD supporting their investment in growing facing research through the Richard Williams commercial research initiative. Recently he was a senior manager with GRDC leading investment in Agronomy, Soils, Nutrition, and Farming Systems. Before these roles he was a Chief Scientist with CSIRO in Narrabri where for nearly 25 years he led initiatives in cropping systems research, crop physiology and agronomy into managing abiotic stress tolerances, fibre quality, crop nutrition, climate change impacts, and water use efficiency. He has also had a long career leading the development and application of decision support systems for assisting crop management and knowledge dissemination.

Dr. Katrina Broughton is a distinguished Research Scientist at CSIRO Agriculture and Food, Narrabri, boasting a wealth of expertise in crop physiology and growth responses in the face of abiotic stress and climate change. Her remarkable career includes fruitful collaborations with esteemed researchers from CSIRO, the University of Sydney, Western Sydney University, and the United States Department of Agriculture.

Katie's extensive research endeavors have revolved around unraveling the intricate impacts of projected climate change on cotton's growth and physiology. Her work has not only shed light on the challenges posed by a shifting climate but has also focused on identifying innovative management strategies tailored to the evolving needs of cotton cultivation in this dynamic environment.

Abstract

Changes in climate factors such as warmer air temperatures and extreme fluctuations in precipitation because of rising CO2 concentration may directly impact cotton plant growth and productivity. There will be both positive and negative effects, in which increased CO_2 concentrations may increase yield in well-watered crops, and higher temperatures will extend the length of the growing season.

However, warmer temperatures also accelerate the rate of crop development and could potentially shorten the time to maturity, which may impact crop management decisions. Higher temperatures also have the potential to cause significant fruit loss, reduce water use efficiencies, lower yields, and alter fibre quality. This article summarises some of the research needed to address cotton production in this changing climate. Indirect effects of climate change on cotton productivity will likely result from a range of government regulations aimed at climate change mitigation, such as reductions in land and water availability, rising costs of production, and a decline in trade because of competition from other commodities and/or man-made fibres. To maximise these opportunities and meet the challenges, sustainable cotton production will need to adopt practices, in combination, that will:

- Increase and/or maintain high yield and fibre quality;
- Improve a range of production efficiencies (water, nutrition, and energy);
- Seek to improve returns for lint and seed; and/or
- Consider other cropping options as alternatives.

Crop management and plant breeding options include high yielding/high quality stress-tolerant cultivars; optimising water; manipulating crop growth and maturity; varying planting time; optimising soil and health for crop nutrition; and maintaining diligent monitoring practices for weeds, pests, and diseases to enable responsive management.

Introduction

Worldwide, cotton is broadly adapted to growing in temperate, sub-tropical, and tropical environments — but its growth may be challenged by future climate change. Production may be directly affected by changes in crop photosynthesis and water use due to rising CO_2 and changes in regional temperature patterns. This article summarises some of the research needed to address cotton production in a changing climate (adapted from the review by Bange et al. 2016).

Cotton production occurs in a large geographical region and thus is already experiencing a wide range of climatic extremes.

Subsequently, technologies and systems have already been developed to mitigate high temperature and water stress. Photosynthetic acclimation occurs in plants occupying thermally contrasting environments and generally exhibit photosynthetic responses that reflect adaptation to the temperature regimes of their respective habitats. For example, cotton is successfully grown at temperatures in excess of 40°C in India and Pakistan (see Table 1), indicating some adaptation and successful breeding selection. However, yield potential is significantly less in Maricopa and Multan due to the hot temperatures.

Table 1. Comparison of the highest monthly average maximum and minimum temperatures for Narrabri New South Wales (Australia), Maricopa, Arizona (USA), and Multan (Pakistan) during their respective summer production seasons.

Location	Summer Maximum °C	Summer Minimum °C
Multan, Pakistan	42.3 (Jun)	28.7 (Jul)
Maricopa, Arizona, USA	41.6 (Jul)	24.1 (Jul)
Narrabri, NSW, Australia	33.8 (Jan)	21.4 (Jan)

Key approaches to raising and maintaining yields are to develop and refine new technologies (such as precision agriculture, cultivars with both yield and fibre quality improvements, chemicals, etc.), agronomic practices (including sowing time, plant population, crop nutrition, etc.) and management systems (integrated weed and pest management, etc.) that enable cotton to grow healthier or more tolerant to both abiotic (temperature and water stress, waterlogging) and biotic stresses (pests and diseases).

Overall, detailed integrative research over a greater range of environments and stresses are needed to properly assess impacts and adaptation options that translate into realised yield and quality improvements (Sankaranarayanan et al. 2010). Few studies have been conducted in any crop that deal with three-way interactions of changes in combinations of atmospheric CO_2 concentrations ([CO_2]), water, temperature, and atmospheric humidity (Jagadish et al., 2014). Future cotton research programs will need to ensure that knowledge and technologies respond to these impacts and strategies are developed to both exploit and avoid maladaptation to climate change.

Importantly, to address challenges across a cotton system, an emphasis on leveraging opportunities through a 'genetic x environment x management (GxExM) interaction needs to be adopted. There are few studies in cotton that have demonstrated the value of GxExM to improve cotton productivity. Analyses by Liu et al. (2013), using advanced line trials containing varieties grown between 1982 and 2009, demonstrates that yield gains in the Australian cotton industry resulted from improvement in varieties (G; 50% improvement), in crop management (M; 26% improvement), and from the interaction between improved varieties and improved management (GxM; 24% improvement). Th challenge is how to exploit the GxExM interaction in research and deliver the benefits to cotton growers. Hatfield and Walthall (2015) contend that the following ingredients in research approaches to GxExM need consideration to successfully meet future challenges:

- A focus on soil improvement to remove limitations for water and nutrient accessibility.
- The incorporation of multidisciplinary science in research teams.
- Development of robust tools to assess photosynthetic efficiency (at the leaf and canopy level).
- An understanding of why crops are not achieving their potential (at the regional and local level).
- Adoption of innovative technologies as part of the (GxExM) approach (such as precision agriculture).
- Involving the grower in applied research to improve outcomes and uptake.
- Characterising plant and crop responses to stress and developing rapid screening and monitoring systems.
- Utilising crop simulation models to assess potential alternative scenarios for differing germplasm with different management to ascertain opportunities in the GxExM approach, as well as understanding how future climate affect these outcomes.

Building on these points in the following sections, we summarise key research considerations that maybe needed to meet these challenges.

Figure 1: Climate change facilities at the Australian Cotton Research Institute (ACRI), Narrabri, Australia, are used to evaluate the integrated effects of climate change on plant and soil impacts on cotton production.

Genetic Improvement and Cotton Physiology

Cultivar choice is a strong component of realising both target yield and fibre quality levels on a cotton farm. A delicate balance needs to be resolved between yield, fibre quality, price, and other important considerations such as resistance to diseases, insecticides and herbicides. Developing an improved understanding of the physiology and genetics underpinning the responses of cotton genotypes to abiotic stress offers substantial opportunities for regional cotton industries to deal with many elements of predicted climate change.

For cotton breeders, delivering commercially available, high-yielding cultivars to cotton growers remains a necessity to keeping cotton systems economically viable. High selection pressure on yields remains a successful means to capture tolerance to both biotic and abiotic stress. Amongst records of improving yields across cotton regions, there is also evidence that this approach has been successful in generating tolerance for abiotic stress. Specific tolerances for heat (Bibi et al. 2008; Constable et al. 2001; Cottee et al. 2010) and water stress in rain-fed environments (Stiller et al., 2005) have been recorded despite no specific selection pressure on these stresses. Genetic variability of transpiration responses to vapour pressure deficits (VPD) have also been established for cotton (Devi and Reddy 2018; Broughton and Conaty 2022) and it was discovered that genotypes could limit transpiration rate at high VPD and approach wilting point slowly when they're under water stress. This warrants more attention in cotton systems that are water limited.

Opportunities to continue to improve yield remain possible, given indications in the review by Constable and Bange (2015). They identified several opportunities for research to address yield potential and theoretical yields in cotton. In breeding, options for longer season and more indeterminate growth habit are required with relatively slow fruit setting, but with greater final fruit numbers (Hearn 1976). Additionally, this would have the effect of delaying crop maturity, and by extending the season, the amount of radiation absorbed by the canopy could be maximised.

Furthermore, advancements in molecular biology should target improvements in photosynthetic capacity (Sharwood et al. 2016) with the goal of increasing canopy radiation use efficiency (RUE). Not surprisingly, the changes recommended above would lead to greater productivity — but also greater demand for resources such as water, and especially nutrients. Thus, future research efforts should also focus on approaches to maximise resource use efficiency.

It is, however, possible that in future climates, there may be challenges associated with increasing canopy level photosynthesis, especially for cotton production environments considered high input (yields greater than 2000kg/ha; Bange et al. 2016). For example, whether increased growth is brought about by changes in breeding efforts or elevated CO_2, growth and demand for resources are inextricably linked, where enhanced vegetative growth significantly increases transpiration (Fig. 2). When combined with elevated temperature, reductions in water use efficiency, as well as excessive shading caused by a dense canopy, may require more aggressive management of early vegetative growth. Management to restrict early vegetative growth (resulting in season-long reductions in transpiration) may include the use of growth regulators, or cultivars that develop fruit early to act as a sink restricting vegetative growth.

However, this would then partially limit cotton's ability to achieve its potential in environments with longer growing seasons. Additionally, recent research by Conaty and Constable (2020) documented that lint yield improvement over the past few decades of breeding efforts in Australia was associated with increases in harvest index and biomass; however, there was evidence that yield was negatively associated with light interception. To assess these considerations, frameworks that scale from leaf-level to canopy level RUE will be needed to address many of these complex considerations in the future.

Figure 2: Cotton grown inside the climate chambers (reflecting future climate change in Australia) were tall and highly vegetative, leading to large reductions in plant-level water use efficiency.

Of all the projected changes in climate, the ongoing rise in CO_2 is the best documented and forecasted climate variable known to impact plant growth. Because elevated CO_2 can mitigate many of the negative impacts of environmental stresses on plants, one promising course of action would be to breed cotton cultivars that are highly responsive to elevated CO_2 as a course of action that appears to be promising for cotton, in part because of the wide range of responsiveness among current crop cultivars to elevated CO_2 already demonstrated in other crop species including rice, soybean, and wheat.

Recent investigations by Broughton et al. (2017) comparing an older cultivar with a current domesticated cultivar did not show any interaction with elevated CO_2 (640 µmol mol-1) in leaf photosynthesis, therefore highlighting an opportunity for breeding. A related question for future research become, 'Is the often-observed photosynthetic acclimation to elevated CO_2 an indication of a lack of genetic fitness to current and future [CO_2]?'

Considering the ever-increasing need to maintain yields in a variable and changing climate, many cotton genetics programs are trying to develop germplasm with tolerance to various abiotic stresses (Allen and Aleman 2011). Efforts have been put forth using molecular markers to identify and characterise quantitative trait loci (QTL) associated with abiotic stress tolerance in cotton (Saranga et al. 2004). For the most part, these efforts have focused on mining traits and genetic variability within the cotton germplasm pool (*G. hirsutum* and *G. barbadense*) and other closely related Gossypium species. Alternatively, genes associated with targeted biochemical pathways involved in conveying a stress tolerance that come from a completely different source could be introduced into the cotton genome through transgenic technologies (Chakravarthy et al. 2014). Although the use of transgenic technology can provide a more focussed approach to the genetic manipulations, it also comes with its own set of problems, such as whether the inserted foreign DNA might affect native physiological processes.

Nevertheless, many private and public breeding programs are devoting resources to select for tolerance to drought and temperature stress. However, these traits are highly complex, meaning progress will be slow. Most of the initial screening and selecting of lines has occurred in controlled environments, such as glasshouse or growth chambers. Field testing and confirmation of these stress-tolerance traits has not proceeded as quickly. It may still be years before stress-tolerant cultivars are available in the market. In addition, the current costs of bringing these traits to the market through strict regulatory processes make this a more difficult realisation.

Climate change also has the potential to negatively affect cotton fibre quality (Lou et al. 2015) through changes in limited access to water during boll filling (resulting in fibre length reductions) and increases in temperature (resulting in changes in micronaire). To ensure that cotton remains an attractive fibre for use in textile manufacturing and delivers sustainable prices for growers, there remains an imperative to remain focused on quality. Cotton spinners require longer, stronger, finer, more uniform, and cleaner cotton to reduce waste, which will allow more rapid spinning to reduce production costs and allow better fabric and garment manufacturing, thus enhancing cotton's competitiveness with synthetic fibres.

A substantial challenge to cotton breeders seeking to improve yields concurrently with fibre quality is the negative association between the two, which prevents the highest-yielding cultivars from attaining premium fibre quality (Clement et al. 2012). Current research efforts are attempting to break this association by utilising early-generation selection strategies that employ the use of a yarn quality index to integrate the fibre properties of length, strength, and fineness together with yield (Clement et al. 2015). Genetic engineering will also potentially play a role in achieving improvements in quality and generating novel fibre traits (such as elongation and moisture absorption) (Chakravarthy et al. 2014). However, to fully realise the benefits of improving fibre quality, all cotton industries will need to work together to address the challenges and opportunities.

The task for cotton growers and industries is to optimise fibre quality in all steps from strategic farm plans, cultivar choice, crop management, harvesting, and ginning. Constable and Bange (2008) have termed this 'Integrated Fibre Management (IFM)' to emphasise the importance of a balanced approach to managing fibre quality, and to be analogous with approaches such as integrated pest management. New technologies, new instruments, and new decision support and communication programs will facilitate IFM. It is also recognised that there are opportunities to improve the value of cotton as a dual food-and-fibre crop by improving the quality of cotton seed oil by removing toxic gossypol and altering the fatty acid composition.

Ultimately, introgression of these traits quickly and efficiently into commercial breeding material remains a significant challenge for breeders, especially considering the need for constant yield improvements and inclusion of transgenic crop protection traits. Along with traditional approaches to breeding, future breeding efforts will also need to rely on both improved genotyping and phenotyping approaches for trait selection; the role of genetic selection, in addition to employing genetic prediction models and seed genotyping approaches, will be critical to allow this to happen at pace.

To achieve this effectively and efficiently, concurrent investment is needed in both cotton (Andrade-Sanchez et al. 2013) and other crops (Furbank and Tester 2011) to identify the genes related to the traits of interest; develop an understanding of the physiological responses that changes in the genes effect; and find a cost-effective way of phenotyping the plant's/crop response. Ghanem et al. (2015) also suggested that these approaches must obtain evidence that a hypothesised trait will lead to improvement, and that phenotypic screens are multi-tiered so insights about trait expression are gained at various stages of the breeding process.

Soil Management

Microbial processes have a central role in nutrient cycling, and hence is key determinant of nutrient availability and nitrogen use efficiency in arable fields. Microbes are likely to respond rapidly to climate change. Whether changes in microbial processes lead to a net positive or negative impact on nutrient cycling remains debatable and will depend on soil nutritional status, soil types, and climate conditions.

However, understanding mechanisms and the magnitude of the nutrient cycling response to climate change is important to develop an effective adaptation strategy to minimise impacts on farm productivity and profitability. This involves consideration of the complex interactions that occur between microorganisms and other biotic and abiotic factors. The potential to manage and even enhance nutrient cycling in future climates will require significant research (Singh et al. 2010), and includes the following considerations:

- Developing novel approaches to building resilience in farming fields by increasing soil organic matter through residue management, cover crops, and minimum tillage. Organic matter is not only a key nutritional source for both plants and microbes, it also improves water use efficiency by holding water for longer periods in root zones. Future research is needed to determine whether the benefits of these approaches are maintained under future climatic conditions. Research and innovation are also needed to identify the value of other approaches, such as the incorporation of bioinoculants, external organic matter, and biodegradable polymers that have the potential to promote accumulation of soil organic matter in soils.

- Harnessing soil microflora to improve resource-use efficiency. Soil microflora have a central role in determining resource availability and resource use efficiency. Previous studies have reported that biologically rich soils improve both resource and nutrient-use efficiency, and hence farm productivity and profitability. Improved nitrogen use efficiency in biologically rich soils was achieved by continuous release and reduced loss of N and P in the soil profile (Bender and van der Heijden 2015). Further research is needed to identify key microbial populations, which contribute to NUE, and the factors that determined their activities under current and future climatic conditions.
- Increasing the understanding of responses of key functional populations. Functional groups that are directly linked to nitrogen (N mineralising, nitrogen-fixing communities, nitrifiers, denitrifiers) and phosphorus (P mineralising and P solubilising communities) availability and their response to climate change — including extreme weather — is not fully understood. Both the magnitude and direction of their response will be critical to developing nutrient management strategies, as their abundance, diversity, and activity will ultimately determine the fate of applied, as well naturally available, N and P in the farmland. Recent research in Australia has attempted to understand the effects of climate change on soil microbe populations and importantly, link these with plant and soil performance (Table 2).
- Assessing the utility of bioinoculants and biostimulants. It is proposed that addition of bioinoculants and biostimulants could increase the activity of beneficial microbes. One such approach includes the utilisation of mixed microbial inoculants (such as plant-growth-promoting bacteria and mycorrhiza), which is believed to have better agronomic outcomes because it allows multiple mechanisms of resource-use efficiency to work simultaneously (Dodd and Ruiz-Lozano 2012). However, our current understanding of the survival of bioinoculants in field conditions and their interactions with crops is limited. Future research is also needed to identify how these bioinoculants respond to future climatic conditions, and how their interactions with crops will be affected by climate change. The outcomes of such studies will ultimately determine if such an approach can be effectively incorporated into climate adaptation strategies.
- Exploring rhizosphere-microbial interactions. Harnessing rhizosphere-microbial interactions could represent a great opportnity to increase farm productivity under current and future climatic conditions. Previous studies have documented potential approaches to harnessing microbe-rhizosphere interactions for increased farm productivity (Macdonald and Singh 2014) — but how those interactions could be exploited for biotechnological applications is not well defined. Plant roots and microbes communicate via chemical molecules for their energy and nutrient requirements, and modulate each other's activities to achieve mutually beneficial outcomes. A major research effort is needed to identify these signal molecules and harness them to improve the interaction between beneficial microbes and plant roots to improve resource availability and use efficiency. Once identified, these molecules can either be directly used — or their transgenic technologies can be used — to genetically modify plants to manipulate microbial activities in the root zone, which can serve this purpose.

Table 2: Summary of measured outcomes of climate change on plant and soil responses from glasshouse and field studies (Broughton et al. 2019).

	Variable	Elevated CO_2		Warmer temperature	
		Glasshouse	Field	Glasshouse	Field
Plant	Photosynthesis	⇧	⇧	⇧	⇧
	Vegetative growth	⇧	⇧	⇧	⇧
	Seed cotton yield	⇧	⇧	⇧	⇩
	Water use	⇧	⇧	⇧	⇔
	Plant-level water use efficiency	⇧	⇩	⇩	⇩
Soil	Soil pH	⇔	⇔	⇩**	⇔
	Soil nitrate concentrations	⇩	⇩	⇧***	⇔
Microbes	Nitrifier abundance	⇔ AOB ⇧ AOA	⇧ AOB ⇧ AOA	⇔ AOB ⇧ AOA	⇔ AOB ⇧ AOA
	Nitrifier community composition	↻ AOB* -	↻ AOB* ↻ AOA*	↻ AOB* -	⇔ AOB ↻ AOA*
	Potential nitrification rate	⇩	⇧	⇔	⇔
	Microbial abundance	⇩ Fungal-to-Bacterial ratio	-	⇔	-
	Microbial community composition	↻ Bacterial community*	-	↻ Bacterial community*	-
	Microbial activity (respiration)	⇧*	-	⇧*	-

⇧ indicates increase, ⇩ indicates decrease, ⇔ indicates no significant difference and ↻ indicates change
AOA indicates ammonia oxidising archaea, AOB indicates ammonia oxidising bacteria
* Dependent on growth stage of crop
** Dependent on soil type
*** Based on plant N uptake

Cotton System Management

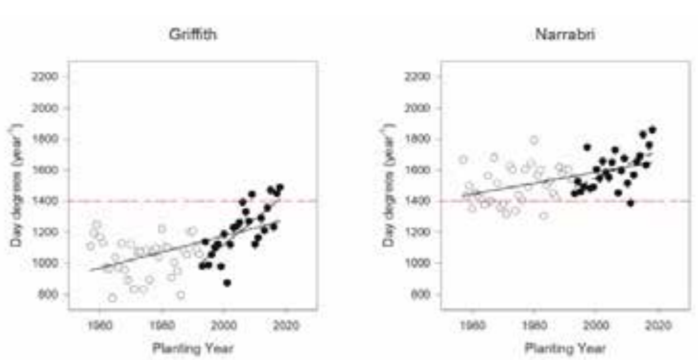
Climate change is a multifaceted and complex challenge for cotton and it will affect the sustainability of farms, ecosystems, the farming community and the cotton sector. Fortunately, many potential adaptation responses that are currently available have immediate production efficiency benefits, making them attractive options regardless of the rate and nature of future climate change. Below are some key considerations around needs pertaining to the management of the cotton system.

Climate Information and Use

Climate change is occurring against a background of naturally high climate variability. For each cotton region, it will be important to distinguish between climate variability and climate change because there is the potential for maladaptation, if not identified clearly. Adaptation in farming practices may respond and change to short-term variations in climate, which is not indicative of overall climate change, thereby leaving an industry vulnerable in the longer term. It will be also important for the provision of information on the likely impacts at the business level (such as downscaling climate change predictions to regional scales) and provide tools and extension networks to enable farmers to access climate data, and subsequently interpret data in relation to their crop records and analyse alternative management options. More accurate forecasting of extreme weather events like heatwaves (which impacts plant growth) and heavy and excessive rainfall (which can impact plant growth and soil erosion) will be vital. Crop simulation models can play an important role in assessing the skill and value of weather forecasts if decisions are changed in response to the forecast (McIntosh et al. 2015).

While much research has focussed on assessing future climatic conditions on cotton production, there remains significant opportunity to better understand climatic changes that have already occurred, to gain insights on how existing and new regions are adapting to change. Recent assessments of climate variables relating to cotton production in Australia show that southern cotton growing regions now have climates like those in the northern regions in the 1970s, during the establishment of the modern Australian cotton industry (Fig. 3). Recognising that regions have experienced specific changes may help to guide current and future agronomic practice across different regions.

Figure 3: The number of day degrees per year (DD) in Griffith (Southern region) and Narrabri (Central region) in Australia. The red dotted line at 1400 DD shows that the number of DD in more recent planting years are like the number of DD that Narrabri experienced in the past. Data is grouped by time periods (black circles= 1957-2018; white circles= 1957-1996; black triangles= 1997-2018). Regression lines are only shown where trends are significant. Griffith is now experiencing similar climate to Narrabri in the 1970's when the modern Australian industry initiated (taken from Broughton et al. 2021).



Policy and Industry Considerations

The impacts of climate change and the approaches to adaptation will need to reflect changing social, political, and economic drivers at scales that move from the field to the farm, across varied agriculture industries, and with national and international influences. As an example, there is a need to invest in field-based research into production, but concurrently we need research that assists in setting government policy. Without these types of considerations, the marginal return on investment into adaptation options can be severely diminished. Key considerations that capture some of these issues from a cotton production perspective include the following:

- An assessment of the likely impacts of climate change on worldwide cotton production. Understanding these impacts is necessary for the cotton supply chain to maintain market share against synthetic textiles. Strengthening information-sharing networks on the impacts and adaptations to change will be vital to assist this process.
- Identifying opportunities for the expansion of cotton production in existing and new agriculture production regions. Region-specific impacts will need to be assessed so cotton growers can improve their capacity to assess likely impacts at the business level.
- Identifying competition and synergies for use of resources (land, water, labour, energy) from other agriculture enterprises. There is a need to address the question of just how much climate change it would take to make it more appropriate to consider using land and water resources for purposes other than cotton or irrigated production.
- Integrating research outcomes that are optimal in delivering sustainable cotton systems, considering triple bottom line concerns (environmental, economic, and social). An example here is the need to develop a practice that is accepted in minimising environmental concerns whilst optimising grower profit. Some recent factors influencing this are: the need for reductions in water accessibility for irrigation to meet environmental river flows; and the need for improved N management (with improved timing, rate, and use of legumes) to minimise greenhouse gas emissions and water contamination. How these are managed can sometimes be in the form of government regulation, or the adaption of industry environmental management systems. In the case of government regulation influencing grower practice, it's worth noting that an investment in a production practice tailored and demonstrated to improve productivity can be simply overridden by government regulation influenced by other social, environmental, and economic concerns outside cotton production.
- Development of multi-peril crop insurance schemes to assist cotton producers in dealing with extreme climate events.
- Coupled with the above points, streamlining the use of technologies for traceability for efficient, transparent, and credible supply chains. The cotton supply chain is complex and remains a challenge for many industries. However, the demands of the consumer will place increasing pressure on the need for research in these areas of production.

To meet these challenges, there will be a greater need to incorporate other concepts of production-use efficiencies into the analysis of modern cotton systems — including fuel or energy use, or carbon emissions per unit of lint produced — in addition to existing production-use efficiencies, such as water and N. There will need to be 'trade-offs' to minimise economic, social, and environmental harm, while maximising new opportunities.

One example that highlights this tension is the ever-increasing need for water use efficiency, which has led to demand for more sophisticated irrigation systems that are ultimately more energy intensive. Importantly, to assist in making valid and fair comparisons within the cotton production system and beyond (such as with other cropping systems or industries), it will be necessary to present these efficiencies on an economic basis (revenue generated/MJ, unit of GHG emitted, kg of N applied etc.).

Ultimately, sustainable, low-environmental-impact cotton systems are required to maintain modern cotton production systems' 'licence to farm'. Research into the development of new technologies and tools that integrate knowledge at many scales — whilst understanding the linkages of on-farm production with the off-farm impacts — will be needed to reliably harness opportunities for ongoing investment.

Crop Management

Considerable changes in climate may necessitate a reassessment of cotton systems to ensure maximum sustainability and economic return with all available tools and resources. Strategies to mitigate the damage incurred when encountering episodes of extreme environmental stress (through tolerance or avoidance) will need to be developed, as will building adaptive capacity and resilience. When formulating these strategies, we must consider all aspects of the production system, from planting through to harvest, and consider all the possible tools available (precision technologies and new genetics, for example).

To help build resilient and productive systems, a knowledge of yield potential — or 'yield gap' in different cotton systems across regions — will be important. This will assist in identifying the major limiting factors in systems and will also provide insights into the approaches needed to overcome these limitations. Importantly, these limitations require reassessment amidst future climate change predictions so changes to the systems are not short-lived or maladaptive in the future. In many cases, the reduction in the yield gap between farm averages and yield potential most likely will be achieved by removing the yield constraints of the poorest fields and systems (Constable and Bange 2015; Hatfield and Walthald 2015). Crop simulation tools will play a key role in assessment of yield gaps.

For rain-fed systems, Hochman et al. (2012) measured farmers' yields and compared them with the regional yields predicted using simulation models of an adapted crop without limitations, but under water-limited conditions. They also assessed yield potential using crop competition results. For irrigated crop comparisons, it will be important that knowledge of the amount of water available for irrigation across farms is considered, because it can vary dramatically, thereby affecting yield and fibre quality.

One of the most significant challenges for cotton management in the future will be diminished access to water due to reductions in the availability of irrigation (surface or groundwater), less rainfall, or increases in evapotranspiration through increased air temperature. Elevated [CO_2] increased water use efficiency (kg lint/mm evapotranspiration) by increasing biomass production rather than by reducing consumptive use (Mauney et al., 1994). Much of the existing research has been undertaken with unlimited water conditions, and limited research has considered the implications of cotton growth and yields in current and future conditions with the same amount of water availability. Integrated climate change studies for cotton grown under varied [CO_2] and temperature regimes for irrigated cotton need to be conducted with different amounts of water availability that result in season-long reductions in transpiration compared to fully irrigated crops. Rain-fed cotton systems will require closer examination of the response to various water deficits and drought-recovery cycles. These effects will also need to be considered in light of other management options suggested in this article relating to water use: the development cotton systems that are earlier maturing; that use less water and allow more crops to be grown in rotation; and improved management options in limited water situations utilising changes in planting time, alternative irrigation systems, row configurations, irrigation scheduling strategies, all with the intent to maximise water use efficiency and maintain fibre quality.

One of the key research challenges will be the development of large-scale CO_2 enrichment facilities. Ziska et al. (2012) summarised engineering challenges in meeting this need and determined that most enclosure systems (various sorts of outdoor growth chambers) may suffer from 'chamber effects' such as light quality and other issues associated with various types of chamber wall materials (c.f. Kim et al. 2004) (Figure 4).

On the other hand, free air CO_2 enrichment (FACE) methods are known to have CO_2 control problems, with large pulses of injected CO_2 over short durations of time resulting in an artificial lowering of plant responses to the apparent target CO_2 set point (Bunce 2014). The solution to these types of engineering challenges may be a combination of methods including large, open-top chamber systems, environmentally controlled glasshouses, and/or the utilisation of naturally occurring CO_2 springs found in some parts of the world (Miglietta et al., 1993).

Figure 4: Canopy Evapotranspiration and Assimilation (CETA) chambers in the field at Narrabri, NSW Australia, that generate warmer and higher CO_2 environments for field- grown cotton.

Although the impacts of elevated CO_2, warmer temperatures, and water deficits on cotton growth and physiology have been studied, gaps remain in our understanding of whether there are interactive relationships between these variables. It is important to understand potential interactions, as it is likely that multiple variables will be altered with future climatic changes.

As mentioned, modelling will play a vital role in quantifying the potential integrated effects of future climate change on the physiology and growth of cotton and translating these impacts into cotton production systems. They will also be important in evaluating the effectiveness of adaptation and mitigation strategies in dealing with climate change risk — potentially even taking advantage of climate change.

While the outcomes of these simulation studies make sense with our current understanding of cotton growth and physiology, it is, however, widely recognised that all crop simulation models still require considerable validation and quantification of the integrated climate change responses for field conditions, in which yield and fibre quality are predicted — not a simple task. This is further complicated by the need to include changes in management and cultivars. In a recent global review of cotton simulation models for cotton systems, Thorp et al. (2014) suggests two needs for cotton simulation modelling to progress:

1. To compare existing cotton simulation models to identify their strengths and weaknesses.
2. Form multidisciplinary teams in the areas of climate science, crop science, computer science, and economics to improve, validate and apply these models.

These approaches could specifically be applied to address both impacts and adaptation options for climate change for many of the concerns listed in this article.

Conclusions

Future climate change will impact cotton production systems; however, there will be opportunities to adapt. This article highlights the risks and opportunities with adaptation and details some consideration for investment in research. Major matters that were identified were:

- Climate change will have both positive and negative effects on cotton. Increased CO_2 may increase yield in well-watered crops, and higher temperatures will extend the length of the growing season (especially in current short season areas). However, higher temperatures also have the potential to cause significant fruit loss, lower yields and alter fibre quality, and reduced water use efficiencies. Extreme weather events such as droughts, heatwaves and flooding also pose significant risks to improvements in cotton productivity.
- Research into integrated effects of climate change (temperature, humidity, CO_2, and water stress) on cotton growth, yield and quality will require further investment. This includes the development of cultivars tolerant to abiotic stress — especially for more frequent hot, water-deficit, and waterlogged situations. Some consideration or allowance will be needed in these studies, both for cotton cultivars and insect pests that have been naturally selected in rising CO_2 environments.
- Although cotton is already well adapted to hot climates, continued breeding by conventional means — and applying biotechnology/molecular tools and traits — will develop cultivars with improved water use efficiency and heat tolerance. Along with this investment in whole-plant and crop physiology, it will be important to develop a robust understanding of the physiological determinants of cotton crop growth and development to determine the value propositions. Undertaking this research with the involvement of agronomic researchers, extension specialists, crop managers and growers is vital achieve the milestones in the field as quickly as possible.
- The potential for declining availability of water resources under climate change will increase competition for these resources between irrigated cotton production, other crops, and environmental uses. These issues emphasise the need for continual improvement in whole-farm and crop-water-use efficiencies, and the need for clear information on water availability.
- There will be a need to improve cotton farm resilience by maintaining and increasing cotton profitability through practices that increase both yields and fibre quality, while improving the efficiency of resource use (especially energy, water, and nutrition).
- Region-specific effects will need to be assessed thoroughly so cotton growers can assess the likely impacts at the business level. Also, as cotton is a global commodity, so it will be vital for cotton industries to understand the global changes affecting cotton markets as part of its overall adaptation strategy.
- Simulation models will play a vital role in assessing impacts and adaptation options for future climate change; however, they will require investment in development and their validation for climate change issues. Once new, forecasted future climate change scenarios are developed, they will also need to be used to update and quantify impacts and to reevaluate adaptation options. Crop bio-physical modelling should be appropriately linked to economic, whole farm/catchment-scale modelling efforts. Similar considerations need to be given to cotton decision-support tools that utilise day-degree functions. It is possible that many systems do not accommodate future predicted extremes associated with climate change (such as heatwaves that slow crop development).
- Implementation of whole-farm designs that build system resilience through diversity in crops, while increasing soil fertility and protection from erosion (through the inclusion of rotation and cover crops) will also need further attention.

We acknowledge that most approaches discussed here are decidedly production focussed, and therefore the list is by no means comprehensive. There is no doubt that other significant efforts to combat the challenges posed by a changing climate come from various perspectives and scales, including policy initiatives, community engagement, and broader environmental strategies.

Ultimately, a multifaceted, systems-based approach that combines all elements mentioned here — as well as others — will provide the best insurance to harness the change that is occurring, and best allow cotton industries to adapt. Given that there will be no single solution for all the challenges raised by climate change and variability, the best adaptation strategy for industry will be to develop more resilient systems. Early implementation of adaptation strategies — particularly relating to enhancing resilience — has the potential to significantly reduce the negative impacts of climate change.

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A ‘Crop Spraying Robot’ in Australia

Regenerative Agriculture
The Climate Connection

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Introduction

Regenerative agriculture practices are designed to restore and enhance soil health, ultimately establishing self-sustaining farming systems. These practices are guided by six key principles:

1. Minimal disruption of biodiversity through reduced use of agro-chemicals,
2. Zero-tillage,
3. Organic mulching and use of farm-derived organic inputs,
4. Diversity in cropping systems,
5. Live cover crops and crop rotation, and
6. Integration with animal husbandry and managed grazing.

The principles collectively work toward rejuvenating soil health by enriching it with organic matter, which supports the growth and proliferation of soil organisms that provide valuable services to crops and the environment. In return, crop plants provide soil life with rhizo-deposits and crop residues as nourishment and shelter, leading to self-sustaining crop production systems that rely less on human intervention. Thus, the overarching goal of regenerative agriculture is to build soil carbon reserves, facilitating a reciprocal and mutually beneficial relationship between plants and soil organisms, thereby fostering climate-resilient and self-sustaining farming systems.

Figure-1. The six key principles of regenerative agriculture, emphasizing biodiversity preservation, zero-tillage, mulching and organic inputs, crop diversity, live cover crops, and integration with animal husbandry for sustainable and eco-friendly farming practices (Illustration: Keshav Kranthi).

Ecosystem Services

A healthy soil produces a healthy crop, a healthy environment, and a healthy society (Howard, 1947). Regenerative agriculture concepts evolved over time, drawing inspiration from indigenous practices, sustainable agriculture pioneers like Sir Albert Howard and J.I. Rodale, and modern proponents like Allan Savory and Joel Salatin. These innovators collectively shaped the principles of soil health, biodiversity, and ecosystem restoration that underpin regenerative agriculture today.

Regenerative agricultural practices offer a multitude of ecosystem services through their positive impact on soil health and biodiversity (Rehberger et al., 2023). These practices promote the enrichment of soil organic matter, fostering the growth of diverse microbial communities that enhance nutrient cycling (Kallenbach et al., 2019; Prescott et al., 2021; Khangura et al., 2023).

Additionally, regenerative approaches - such as the incorporation of live cover crops and minimal disruption of biodiversity - provide habitat and forage for beneficial insects and pollinators, thereby contributing to enhanced pest control and pollination services (Bommarco et al., 2013; Dainese et al., 2019; Schmid and Schöb, 2023). Furthermore, the reduction in chemical inputs associated with regenerative agriculture reduces the potential for environmental pollution and water contamination, positively impacting water quality and aquatic ecosystems (McLennon et al., 2021).

Overall, these practices create a virtuous cycle in which healthier soils, increased biodiversity, and reduced environmental impacts collectively contribute to the provision of vital ecosystem services in agricultural landscapes.

Figure-2. Regenerative agriculture benefits ecosystems by improving soil health, biodiversity, and pest control through practices like organic matter enrichment and habitat creation for beneficial insects. (Illustration: Keshav Kranthi).

ECOSYSTEM SERVICES

Figure-3. CO_2, released by natural and human activities including fossil fuel combustion, contributes to the greenhouse effect, causing global warming and significant ecological and societal impacts. (Illustration: Keshav Kranthi)

CLIMATE CHANGE

Climate Change

Regenerative agricultural practices have garnered significant attention due to their potential to effectively mitigate the impacts of climate change. These practices offer a multifaceted approach to combat climate change, primarily by reducing greenhouse gas (GHG) emissions and enhancing the sequestration of carbon dioxide (CO_2) through innovative land management techniques.

CO_2, a crucial component of the Earth's carbon cycle, is released into the atmosphere through a variety of natural and anthropogenic processes. These occur primarily through respiration by microorganisms, plants, and animals, as well as degradation of organic matter. Additionally, CO_2 emissions result from biological activities in oceans, changes in land use patterns, forest fires, and the combustion of fossil fuels like coal, oil, and natural gas, predominantly used in industrial processes and transportation.

These emissions, coupled with those of other greenhouse gases such as methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs), contribute to the formation of a thermal insulating layer in the atmosphere, commonly referred to as the greenhouse effect (Smith et al., 2008).

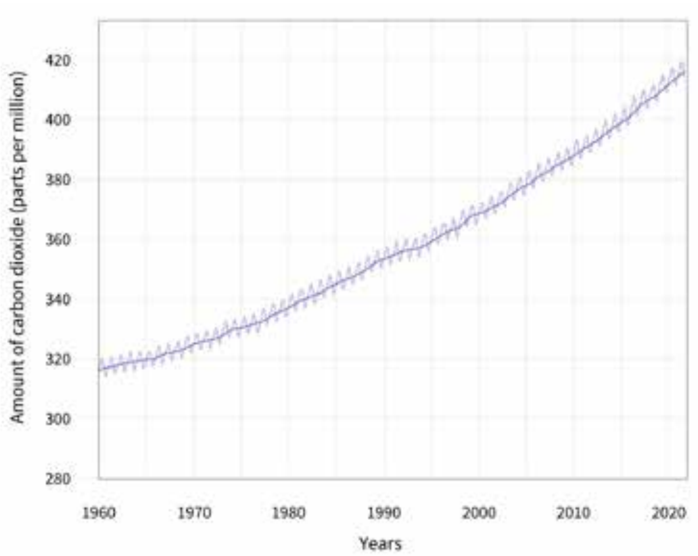
This phenomenon traps heat and ultimately leads to global warming, which in turn drives climate change with far-reaching ecological and societal consequences.

Scientific research underscores the opportunity of regenerative agricultural practices to address climate change. By adopting practices such as cover cropping, crop rotation, reduced tillage, and improved agroforestry, agricultural systems can sequester substantial amounts of atmospheric CO_2 in the soil (Lal, 2004). This sequestration not only aids in mitigating the concentration of CO_2 in the atmosphere, it also enhances soil fertility and resilience (Paustian et al., 2016). Studies have shown that these practices can potentially contribute to the sequestration of significant amounts of carbon in the soil, thereby acting as a carbon sink and mitigating the impacts of CO_2 emissions (Minasny et al., 2017). The adoption of regenerative agricultural practices presents a promising pathway to counteract the challenges posed by climate change by reducing GHG emissions and enhancing the storage of carbon in soils, contributing to a more sustainable and resilient future globally.

The Carbon Crisis

The critical state of our planet due to increasing greenhouse gas (GHG) emissions has raised significant concerns (Le Quéré et al., 2018). Before the pre-industrialisation era approximately a century ago, the Earth's atmosphere naturally harboured around 600 gigatons (Gt) — equivalent to one billion metric tons — of carbon (Stocker et al., 2013). This carbon existed in the form of 280 parts per million (ppm) of CO_2. However, the subsequent century has witnessed a remarkable transformation catalysed by anthropogenic activities.

Figure-4. Amount of CO_2 in the atmosphere. It too just 60 years from 1960 to 2020 for CO_2 to increase by 100 ppm.



Human actions, spanning industrialisation, deforestation, and chemical-intensive agriculture, have ushered in a new era sometimes referred to as the 'Anthropocene Era'. A staggering 300 additional Gt of carbon, translating to approximately 140 ppm of CO_2, have been introduced into the atmosphere due to these activities (Ciais et al., 2013).

Figure-5. Global warming refers to the long-term increase in Earth's average surface temperature due to the accumulation of greenhouse gases, primarily carbon dioxide, in the atmosphere, resulting in climate change and its associated impacts. (Illustration: Keshav Kranthi).

CLIMATE CHANGE

Since the Industrial Revolution, the conversion of natural ecosystems into agricultural land has led to a decline in soil organic carbon (SOC) levels, releasing about 100 gigatons (Gt) of carbon from the soil into the atmosphere (Lal 2009).

In recent years, data have shown an alarming addition of four Gt of carbon to the atmosphere annually (Le Quéré et al., 2018). The ramifications are substantial: This surplus carbon inventory fuels global warming and disrupts established rainfall patterns, culminating in erratic precipitation events that detrimentally impact agricultural yields. Among those disproportionately affected are rainfed farmers, especially rainfed cotton farmers. This is exacerbated by rising temperatures that depress cotton yields and are further compounded by the turbulence and unpredictability of precipitation patterns (Lobell et al., 2014).

The trajectory of our environmental crisis is escalating at a frightening pace. This relentless accrual of carbon exacerbates the challenges faced by ecosystems and societies alike. Scientific investigations project that even if measures are undertaken immediately, the process of removing the excess carbon from the atmosphere could span centuries.

Mitigation Measures

Mitigating the pressing issue of escalating greenhouse gas (GHG) emissions necessitates a multifaceted approach, incorporating both innovative strategies and well-established scientific principles.

Two main approaches have emerged to address this challenge:

Enhanced Carbon Sequestration: One essential strategy involves enhancing carbon sequestration mechanisms, which means capturing excess CO_2 from the atmosphere and storing it long-term, primarily in terrestrial ecosystems and oceans. The goal is to transform atmospheric CO_2 into fixed carbon and securely store it in these reservoirs. Importantly, carbon sequestration goes beyond mere containment; it focusses on creating conditions that make the stored carbon resistant to reverting into CO_2.

This process relies on complex biogeochemical interactions within the biosphere, particularly soil carbon sequestration, which plays a critical role in stabilising carbon (Lal, 2004; Minasny et al., 2017).

GHG Emission Reduction: The second approach centres on curtailing the emission of GHGs into the atmosphere. This encompasses an array of actions aimed at decreasing the volume of GHGs released, spanning diverse sectors such as energy, transportation, agriculture, and industry. Transitioning to renewable energy sources, enhancing energy efficiency, optimising transportation systems, and adopting sustainable agricultural practices all contribute to reducing the influx of GHGs into the atmosphere.

This strategy is founded on a comprehensive understanding of the intricate interplay between human activities, emissions, and their far-reaching consequences (Edenhofer et al., 2014; Rogelj et al., 2018).

Combining regenerative agriculture with reforestation is a powerful way to address carbon emissions (Lal, 2015; Jat et al., 2022). These approaches have a dual impact: increasing carbon storage and reducing greenhouse gas emissions. Regenerative agriculture techniques such as cover cropping, reduced tillage, and crop rotations enhance the relationship between plants and soil microbes, boosting carbon storage in the soil. Meanwhile, reforestation increases vegetation, helping absorb more CO_2 from the air and storing it in plants and soil. Using both methods together offers a comprehensive response to the challenge of reducing greenhouse gases, paving the way for a more sustainable and resilient future (Philippot et al., 2013).

Carbon Sequestration by Plants

It is well understood that plants, both on land and in the oceans, play a vital role in the quest to save our planet. They capture CO_2 from the atmosphere, use sunlight and water to create food for all life on Earth, and provide us with oxygen to breathe (Field et al., 1998). In oceans and coastal areas, phytoplankton, mangroves, seagrass, and salt marshes act as carbon sinks, taking in atmospheric CO_2.

Figure-6. In recent years, the atmosphere has been gaining 4 gigatons (Gt) of carbon annually, with approximately 9 Gt coming from human activities, while soils sequester 3 Gt and oceans absorb 2 Gt. Three gigatons (3 Gt) are sequestered in the soil, a result of plant life capturing 123 Gt of CO_2 and emitting 120 Gt into the atmosphere, while oceans sequester 2 Gt due to capturing 92 Gt of CO_2 and emitting 90 Gt back into the atmosphere. Image created by the authors based on the data available on: https://pressbooks.umn.edu/environmentalbiology/chapter/chapter-7-climate-change/

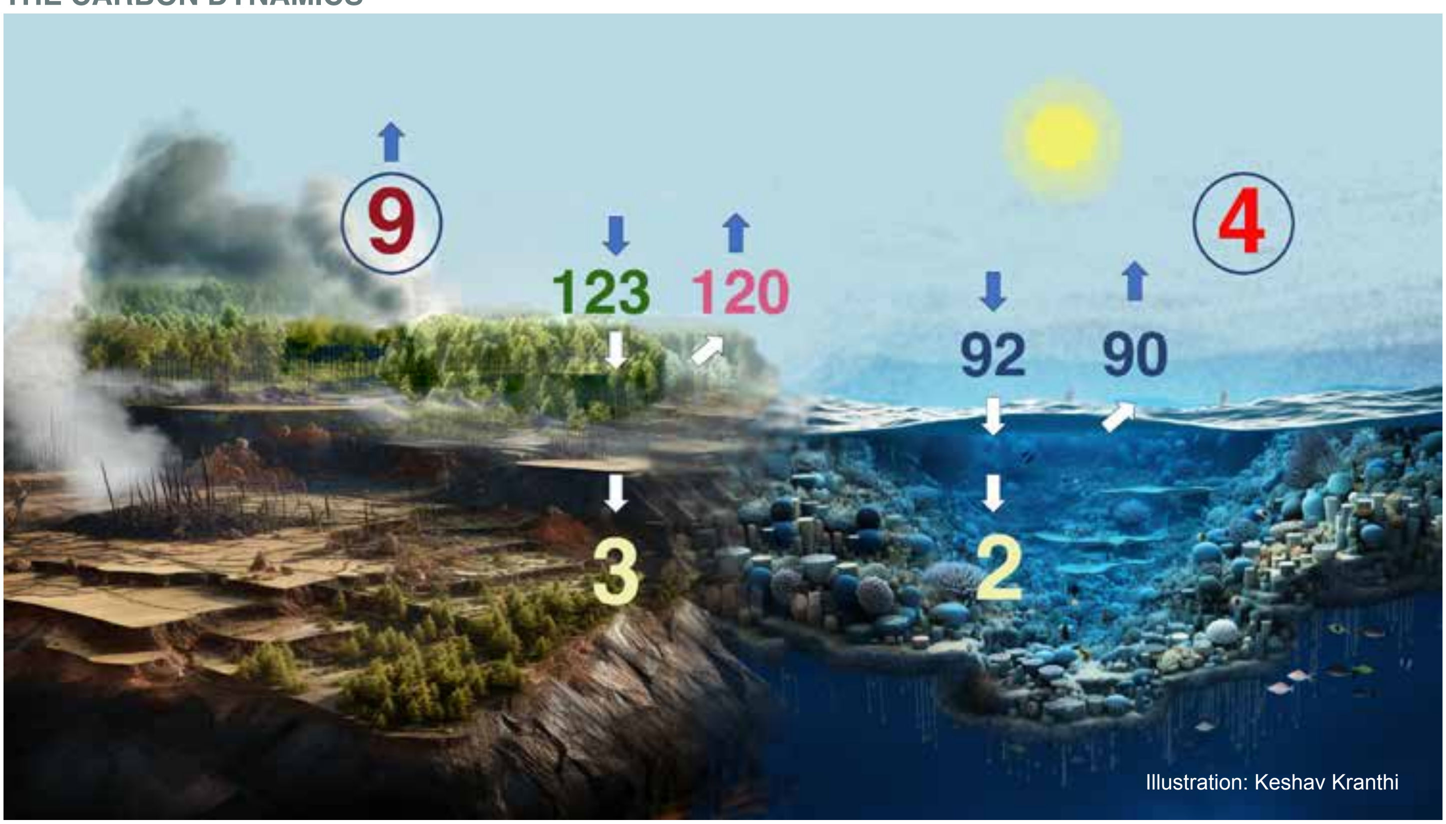
Plants then convert this CO_2 into energy, which supports life on Earth. While most of the carbon captured by plants is returned to the atmosphere through respiratory cycles and organic degradation, a small portion of the carbon is sequestered in the soil.

The sequestered carbon is stored in various recalcitrant forms, such as humus, glomalins, suberins, and fossil fuels like coal, oil, natural gas, methane hydrate, and limestone found in soil and oceans (IPCC, 2019). Oceans, in particular, hold substantial quantities of sequestered carbon in the form of calcium carbonates and coccolithophores, which have been stable for thousands of years without converting to CO_2 (Schlesinger, 2017).

The carbon cycle shows how living things interact with Earth's systems. As mentioned earlier, there are about 900 Gt of carbon in the atmosphere in the form of CO_2 Plants on earth and oceans together absorb around 210 Gt of carbon annually. Unfortunately, approximately 204 Gt of carbon is released back into the atmosphere through processes like plant respiration, microbial and animal activity, and the decay of organic matter. This means that not all the CO_2 absorbed by plants returns to the atmosphere in the carbon cycle. About 5 Gt of carbon is effectively stored in the soil and oceans, where it can remain for hundreds or even thousands of years (Fig. 6)

Geological reservoirs also store carbon in different forms, including fossil fuels such as oil, gas, and coal. Earth and the oceans collectively contain 928 Gt of carbon stored as coal, oil, and gas (IPCC, 2021). We currently burn nine Gt of fossil fuels every year. If we subtract the five Gt of sequestered carbon, the

THE CARBON DYNAMICS



net carbon emissions into the atmosphere stand at four Gt per year. Our significant challenge lies in increasing our capacity to capture more than five Gt of carbon and reducing our emissions to less than nine Gt of carbon each year.

Figure-7. Plants on land and in oceans, including phytoplankton, mangroves, seagrass, and salt marshes, serve as crucial carbon sinks, capturing CO_2 and supporting life on Earth. (Image: Keshav Kranthi).

Figure-8. Plants use photosynthesis to capture CO_2 and release organic compounds into the soil (Rhizo-deposition), fostering a diverse ecosystem of microorganisms. These soil organisms reciprocate by providing various benefits to plants, including protection, nutrient solubilization, and enhanced growth. (Illustration: Keshav Kranthi)

SYMBIOSIS BETWEEN PLANTS AND MICROORGANISMS

Rhizo-deposition & Carbon Sequestration

At the core of Earth's narrative is a remarkable collaboration between plants and soil microbes. Plants release liquid carbon to sustain soil microorganisms, creating a dynamic ecosystem below the surface.

This phenomenon, known as root exudation or rhizo-deposition, has been observed since 1894 (Krasilnikov, 1958). It's a natural and dynamic process that occurs in the rhizosphere, where plant roots release various organic compounds into the soil, including sugars, amino acids, organic acids, enzymes, and complex molecules (Shamoot et al., 1968).

As plants grow, the composition of these exudates changes. In the early stages, they release alcohol and sugars, while in later stages, amino acids and phenolic compounds become more prevalent (Chaparro et al., 2014). This change attracts different microorganisms during early growth and selects specific ones later (Bais et al., 2006; Berg and Smalla, 2009; Chaparro et al., 2014).

The type and quantity of exudates can vary based on factors such as plant species, plant health, soil type, nutrient availability, and environmental conditions. These exudates serve as essential nutrients for the diverse soil organisms.

In the soil, a thriving world of life exists, including fungi, algae, bacteria, earthworms, termites, ants, nematodes, and dung beetles, with 90% of them being bacteria and fungi. These tiny organisms rely on carbon for their energy, growth, reproduction, and cell structures. Surprisingly, most of this carbon comes from plants. Roots generously share a significant portion (about 20%-40%) of the carbohydrates they produce with soil microorganisms.

This interaction creates a bustling ecosystem in the rhizosphere, where microorganisms — including bacteria, fungi, nematodes, and others — feed on the liquid carbon (Bulgarelli et al., 2013). Fuelled by this organic sustenance, these microorganisms evolve beyond mere beneficiaries; they become caretakers of a mutually beneficial relationship, nurturing the very life that sustains them.

Under the ground, plants and the microorganisms in the soil work together in a special way; they share a strong partnership that benefits the environment.

When plants release liquid carbon from their roots into the soil, it signifies an evolutionary milestone where plants and microorganisms have developed a mutually beneficial symbiotic process, creating a harmonious balance in nature (Bulgarelli et al., 2013).

Figure-9 The soil teems with diverse life, with the majority being bacteria and fungi that depend on plant-derived carbon for energy and growth, as plant roots share a substantial portion of their carbohydrates with these soil microorganisms, fostering a vibrant ecosystem in the rhizosphere. Illustration: Keshav Kranthi.

HEALTHY SOILS HAVE A RICH MICROBIAL DIVERSITY

Plants that are healthy and strong produce a lot of liquid carbon that they give to the soil around their roots (Bulgarelli et al., 2013). This helps the soil microorganisms to survive and proliferate. The soil microorganisms in turn make sure that more carbon is stored in the soil. In simple terms, when plants are healthy, they absorb more CO_2 and release more rhizo-deposition. This encourages the growth of microorganisms, which, in turn, sequester more carbon in the soil in the form of soil aggregates. Soil microorganisms use the liquid-carbon as food and use it to create soil aggregates, which are like their homes. Soil aggregates contain stable carbon compounds called humus and glomalins, which are resistant to decomposition by other organisms and can stay in the soil for several decades — as long as they are not destroyed by tillage operations. So, the more microorganisms there are in the soil, the more carbon gets stored in these soil aggregates, and it remains in the soil for many years. In simple words, when plants are healthy, they support the growth of more microorganisms, which enhances carbon sequestration in the soil.

In addition to soil microorganisms that consume rhizo-deposits, soils also contain other microorganisms known as saprophytes. The saprophytes don't rely on plant root food; instead, they break down dead things, turning them into carbon-rich compounds that makes the soil even better (Orwin et al., 2010). In soils with lots of organic matter and diverse microbes, carbon from living and dead things moves quickly, leading to more carbon getting stored in the soil. It's like soil organisms teaming up to store carbon, which helps fight climate change (Sinsabaugh, 2010).

Soil Microorganisms and Plant Health

The presence and activity of soil microorganisms are critical for maintaining soil health. Soil microorganisms play a crucial role by extracting nutrients from soil minerals and trace elements, which makes the soil more favourable for plants to grow (Behr et al., 2023). This partnership not only facilitates nutrition for plants, but also keeps them safe from pests, diseases, and droughts, making sure the environment stays strong.

A diverse and balanced microbial community can improve soil fertility, structure, disease resistance, and carbon sequestration, ultimately supporting healthy and productive ecosystems (Smith & Read, 2010).

Soils with low organic matter content have low microbial activity. A lack of beneficial soil microorganisms or an overabundance of harmful ones can disrupt nutrient cycling, disease suppression, and organic matter decomposition, negatively affecting soil health.

The predisposition theory, first proposed by HM Ward (Ward, 1901) and later supported by many scientists, suggests that nutrient imbalances can lead to plant stress. Stressed plants tend to produce free amino acids, which can attract insect pests and diseases. On the other hand, plants that receive the right nutrients from the soil are healthy and less stressed (Marschner, 2011). They can produce chemicals that help them resist insects and diseases. Therefore, it's well-established that healthy soils result in healthy plants that are less likely to be attacked by pests and diseases.

Figure-10 Healthy soils, rich in organic matter and balanced microbial activity, support thriving crops and human well-being, while poor soil health disrupts nutrient cycling, disease resistance, and overall agricultural productivity, often referred to as "agricologeny." Illustrations: Keshav Kranthi.

HEALTHY PLANTS AGRICOLOGENY

Sir Albert Howard, considered the father of organic farming, discussed this in his book 'The Soil and Health'. He pointed out that many pests and diseases are a result of human interventions in agriculture, which he called 'agricologenic' (Howard, 1947). Contrary to the common belief that organic farms suffer more from insect and disease damage, there is scientific evidence to show that properly established natural farms have fewer insect and disease problems, like what one would find in a forest ecosystem.

Arbuscular Mycorrhiza and Plant Health

Figure-11. Arbuscular mycorrhiza benefits crops through improved nutrient uptake, drought tolerance, disease resistance, enhanced growth, and sustainable agriculture practices. Illustration: Keshav Kranthi.

Soil fungi play a crucial role in fostering plant health. One key player in this team is arbuscular mycorrhizae, a fungus that partners with plants to help them get more phosphorus from the soil. But these fungi do more than that. They send out tiny threads into the soil, like an underground network, and this helps plants to communicate and protect themselves.

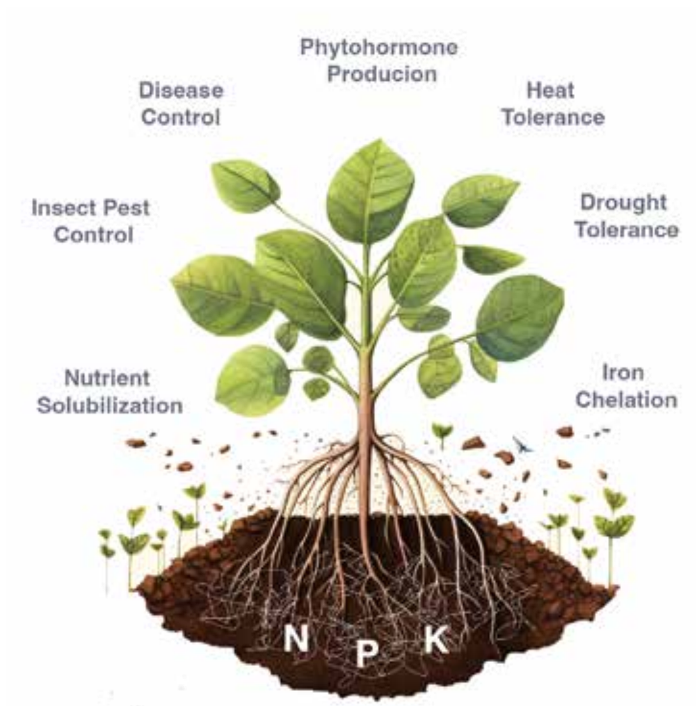
Arbuscular mycorrhiza has been reported to send signals to nearby plants when they are attacked or sense impending attacks by pests or diseases. This works like a warning system for the plants to help them gear up for defence.

Many species of bacteria and fungi also help plants by getting nutrients like potassium from the soil, which makes plants better at resisting insects and diseases (Niu et al., 2011). Mycorrhizae also give plants a boost to their immune system, making them even tougher in the face of challenges.

Arbuscular mycorrhiza benefits crops by enhancing nutrient uptake, increasing drought tolerance, improving disease resistance, boosting nutrient use efficiency, promoting growth, ensuring stress tolerance, enhancing soil structure, supporting ecosystem health, fostering sustainable agriculture, and enhancing crop quality (Fall et al., 2022)

Endophytes and Plant Immunity

Figure-12. Endophytes safeguard plants from pathogens, combat insect pests, enhance soil mineral solubility, shield against abiotic stress, bolster immunity, and stimulate plant growth through phytohormone production. Illustration: Keshav Kranthi.



Microorganisms called endophytes colonise and live inside plants. Endophytes don't harm the plants; in fact, they help plants defend themselves. When insects feed on these plants, the endophytes infect the insects and debilitate them. Endophytes defend plants from pathogens, induce diseases in insect pests, solubilize minerals for plant uptake, shield against abiotic stresses, enhance plant immunity, and stimulate growth via phytohormone production (Akram et al., 2022). It is also possible to inoculate endophytes to plants, using methods like treating seeds, enriching the soil, or spraying the leaves (Vidal & Jaber, 2015). The symbiotic co-evolution of plants with endophytes represents a delicate balance, showing how everything in nature is interconnected (Suryanarayanan, 2023).

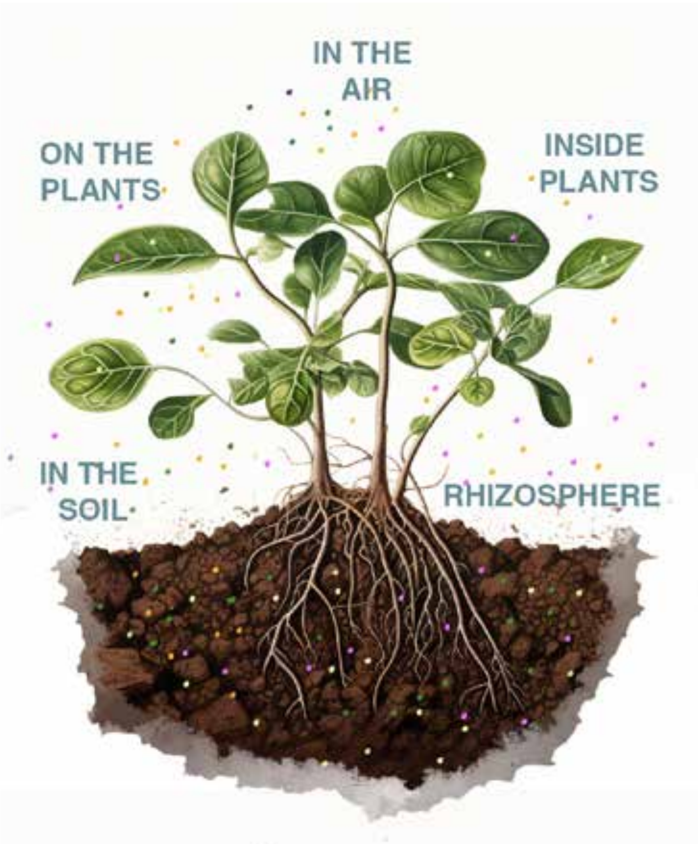
Microbiomes in the Ecosystem

Microorganisms are found in the air, on leaves, within plants, and in the soil.

Microbes inhabit five distinct zones in and around plants:

1. The root zone known as the rhizosphere,
2. The soil between the root zones,
3. The air,
4. The phyllo sphere on the leaves and stems, and
5. Inside the plants as endophytes.

Figure-13. Microorganisms inhabit various zones in and around plants, including the root zone (rhizosphere), soil between roots, air, phyllo-sphere on leaves and stems, and inside plants as endophytes. Illustration: Keshav Kranthi.



This microbial diversity, spanning from the air to the soil, helps shield plants from various stressors, including pests, diseases, drought, and heat (Bulgarelli et al., 2013). Different plants are associated with different groups of microbes. Therefore, it is crucial to cultivate a diverse range of crops. This diversity enriches the soil with a wide array of microbes, promoting crop health and effective carbon sequestration (Larkin, 2015). Having diverse cover crops and a variety of intercrops in the ecosystem help to recruit and maintain a rich diversity of soil microorganisms. In a natural agro-chemical-free environment, these microbiomes exhibit a heightened capacity to assist plants in fending off challenges (Staley & Konopka, 1985). Pesticide applications, however, disrupt these delicate links, leaving plants bereft of their microbial allies.

Humus, Glomalins and Suberins

Carbon sequestration, in the form of recalcitrant carbon as soil aggregates, offers not only a solution to combat global warming but also substantial benefits for soil and plant health (Six et al., 2004). Soil microbes play a crucial role in creating stable carbon-rich structures known as soil aggregates, composed of humus and glomalins, which can endure for centuries without decomposition. Additionally, plants contribute to soil stability by producing a long-lasting carbon compound called suberin in their roots, akin to carbon polyester. Suberin's durability ensures its persistence in the soil for thousands of years. These resilient carbon compounds, such as humus and glomalins, are pivotal for the formation of soil aggregates, which function as moisture-absorbing sponges during heavy rains and provide vital water to plant roots during dry spells.

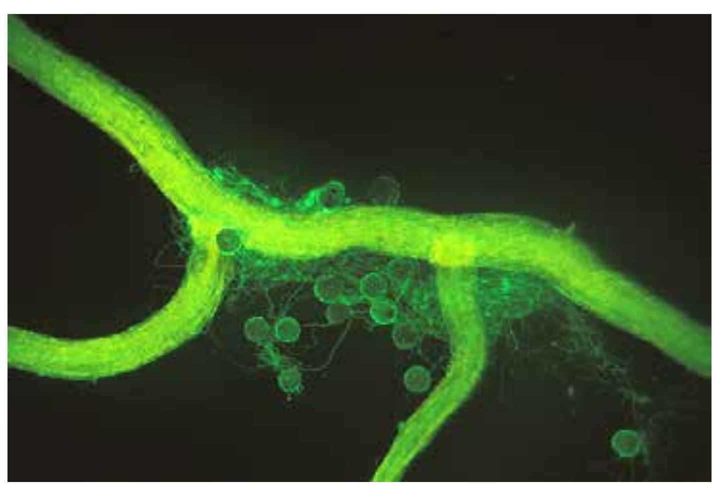
Figure-14. Glomalin, extracted from undisturbed Nebraska soil and then freeze-dried. Image Number K9969-2: Photo by Keith Weller. https://agresearchmag.ars.usda.gov/2002/sep/soil

Soils abundant in organic matter tend to harbour ample soil aggregates, serving as reservoirs for excess water, thus safeguarding plants from issues like waterlogging and drought.

The presence of robust soil aggregates in the soil not only reduces erosion but also enhances nutrient and water availability and elevates crop quality and yield, ultimately bolstering agricultural productivity.

The most effective way to achieve this is by promoting diversity and population growth among plants and soil microorganisms.

Figure-15. A close-up image of an arbuscular mycorrhizal fungus thriving on the root of a corn plant. The spherical structures are spores, while the slender, thread-like structures are hyphae. The outer coating consists of glomalin, detected using a green dye affixed to an antibody targeting glomalin. Photograph ID: K9968-1: Photo by Sara Wright. https://agresearchmag.ars.usda.gov/2002/sep/soil



Anthropogenic Impacts

Healthy soils play a crucial role in maintaining a healthy crop (Six et al., 2000). Unfortunately, certain human activities — like using technologies such as tillage, synthetic fertilisers, and harmful pesticides — can harm both the soil and the environment.

Tillage destroys soil structure and soil aggregates. Plant roots play a crucial role in securing the topsoil, forming a protective cover that acts as a barrier between the soil and the air. This protective barrier aids in minimising carbon emissions by soil microbes (Rumpel et al., 2002). Unfortunately, practices like tillage can expose soil carbon to air oxidation, causing damage. Tillage disrupts soil structure by breaking down soil aggregates, fungal hyphae, glomalins, and pore spaces (Rillig & Mummey, 2006). It also exposes many soil organisms and microorganisms to drying out and predators.

Figure-16. Tillage harms soil structure, disrupts protective root cover, and exposes soil carbon to air oxidation, causing damage to soil health by breaking down aggregates, fungal hyphae, glomalins, and pore spaces, while also affecting soil organisms. Illustration: Keshav Kranthi.

Fertiliser application can harm soil health in several ways. Nitrogenous fertilisers, for example, can lead to soil acidity due to elevated ammonium ion levels, which can disrupt soil biology. Additionally, when fertilisers are applied to the soil surface, plant roots tend to spread more in the topsoil, reducing the need for root depth and limiting their access to soil microorganisms in deeper layers. This can cause plant roots to stop depending on microbes for nutrients, thereby disrupting the exchange of 'liquid carbon' that nourishes these microorganisms, thus damaging their relationship. Furthermore, crops with shallow roots become more susceptible to drought.

Pesticides also have a detrimental impact on soil life because they kill including microbes (Pagano et al., 2023). Several insecticides, herbicides, and fungicides kill soil microorganisms (Karpouzas et al., 2022). Studies (Boerner et al., 1990) showed that fungicides used in seed treatment can harm endophytes, which are fungi that live inside plants and protect them from pests and diseases. These actions underscore the need for sustainable and environmentally friendly agricultural practices to preserve soil health.

Figure-17. Pesticides, including insecticides, herbicides, and fungicides, harm soil life by killing microorganisms, with fungicides in seed treatment even affecting endophytes that protect plants from pests and diseases. Illustration: Keshav Kranthi.

Regenerative Agriculture

These complexities of plant and soil biology and chemistry point to possible opportunities to rethink some agricultural practices. Can regenerative agriculture and organic farming play a role in combating climate change? How do these practices relate to the intricate relationship of plants, soil, and microbes?

Regenerative agriculture is based on the tenets of natural farming and incorporates the principles of conservation agriculture. Regenerative agricultural practices include minimal disruption of biodiversity, zero-tillage, organic mulching, live cover crops, diversity in cropping systems, and animal husbandry have been reported to reduce carbon emissions and to sequester higher levels of carbon in the soil. Research (Tadiello et al., 2022) suggests that by implementing zero-tillage practices on cotton farms, it would be possible to sequester 480 kg of carbon per hectare. Zero tillage reduces net emissions by 643 kg per hectare (Abdalla et al., 2016). Without question, if all farms around the world were to adopt zero-tillage, it would have a remarkably positive effect on the environment.

One of the key practices in regenerative agriculture focusses on enhancing soil organic carbon through the recycling of crop residues and organic matter derived from the farm. Although recycling crop waste and residual biomass can lead to decomposition and CO_2 emissions into the atmosphere, the transformation of crop waste into a stable carbon form known as biochar enables the conversion of carbon from biomass into a long-term sequestered form. Crop biomass such as cotton stalks can be converted into stable biochar through a process called anaerobic pyrolysis. Biochar has the potential to sequester at least one tonne of carbon per hectare from cotton crop residues obtained from a hectare (Kranthi, 2021). When regenerative agriculture is used in combination with biochar, it is conceivable that we could increase the carbon storage capacity by about two tonnes per hectare (Lehmann & Joseph, 2015; Novak et al., 2012). Therefore, by integrating regenerative agriculture practices with technologies such as biochar, cotton farms have the potential to become significant carbon sinks, contributing positively to the fight against climate change (Lal, 2004; Baltrėnaitė-Gedienė et al., 2023).

Principles of Regenerative Agriculture

Regenerative agriculture is guided by six fundamental principles, supported by various practices:

1. **Avoid or Minimize Agrochemicals:** Minimise the use synthetic fertilizers and pesticides that disrupt natural ecosystems' delicate balance. Regenerative agriculture avoids synthetic fertilizers and pesticides because they can harm ecosystems. These chemicals, meant to boost productivity, can disturb the delicate balance of life in the soil and surrounding areas (Pretty, 2008; Reganold and Wachter, 2016).

AVOID HARMFULCHEMICALS

AVOID OR MINIMIZE TILLAGE

2. **Zero Tillage:** Avoid aggressive soil tilling methods that harm soil ecosystems and networks. Zero tillage protects the soil's complex web of life from being destroyed. Tilling damages the soil network. Regenerative agriculture avoids tilling and creates a healthy environment where organisms, soil structure, and the underground life can thrive (Derpsch et al., 2010; Lal, 2015)

3. **Organic Mulch:** Keep the soil consistently covered to reduce the conversion of organic carbon into CO_2 and minimise moisture evaporation. Organic mulching covers and protects the soil to prevent the loss of organic carbon as carbon dioxide. It also helps keep moisture in the soil, which is essential for life (Blanco-Canqui et al., 2015; Liu et al., 2023).

ORGANIC MULCH or LIVE COVER

MAINTAIN COVER CROPS

4. **Cover Crops:** Keep the soil covered with living plants all year round. This ensures that plant roots constantly release liquid carbon, which feeds a variety of soil organisms and protects against soil erosion. Cover crops act like a living blanket for the soil, teaming up to nurture a vibrant soil community. Their roots supply food for soil organisms and fortify the topsoil, making it resilient and less prone to harm (Sainju et al., 2009; Zhou et al., 2017).

5. **Crop Diversity:** Cultivate a wide variety of crops with differing root lengths and ecological characteristics. This fosters a thriving network of soil organisms underground and ecological balance above the ground. Different types of crops working together — which occurs when you mix and rotate them — create a balanced environment for ecosystems to thrive. They help both the soil life below and the vibrant community above the ground (Bender et al., 2016; Lei et al., 2023; Baetz and Martinoia, 2014)

6. **Animal Husbandry:** Integrate animal farming into agricultural systems to provide valuable manure that enriches both plant and soil life. In regenerative agriculture, animals play a crucial role by providing manure and positive cues to soil microorganisms that benefits both plants and soil, creating a cycle that supports all life (Bloch et al., 2015; Gregorini et al., 2021)

MAINTAIN CROP DIVERSITY

INTEGRATE ANIMAL HUSBANDRY

In addition to these principles, practices such as incorporating green manure, cultivating legume crops, composting, applying biochar, and implementing cell grazing also play a vital role in improving soil ecology, increasing nutrient levels, enhancing soil organic matter, and overall soil health. Furthermore, they contribute to the improvement of air and water quality.

Epilogue

Regenerative agriculture helps fight climate change by lowering greenhouse gas emissions and capturing CO_2 from the atmosphere, storing it in the soil for the long term to reduce the impact of global warming.

The main goal of the six practices of regenerative agriculture is to rebuild the mutually beneficial relationship between crops and soil microorganisms (West, 2023; Badgley et al., 2023). This creates a self-sustaining crop production system that requires fewer human interventions. These and other issues create the opportunity to promote regenerative agriculture as a sustainable farming system with a significant role in providing ecosystem services. This benefits farmers, preserves biodiversity, revitalizes soil health, reduces greenhouse gases, and enhances climate resilience on farms (Seufert et al., 2012; Lal, 2004; Reganold and Wachter, 2016).

Embracing regenerative agriculture signifies a dedication to restoring ecosystems and healing the Earth. It entails the reduction of greenhouse gas emissions and the permanent storage of excess carbon from the atmosphere in the soil, ultimately leading to sustainable increases in crop yields that can also support higher farm incomes and poverty reduction.

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The 'ICAC Carbon Neutral Cotton Farm Plan' Turning Cotton Farms into Carbon Sinks

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Introduction

The world is facing a critical challenge in the form of climate change, driven primarily by the excessive accumulation of greenhouse gases, particularly carbon dioxide (CO_2), in the atmosphere (IPCC, 2021). The biosphere has already experienced an approximate 1.1°C temperature increase since the onset of industrialisation — and unless there are substantial reductions in greenhouse gas emissions, it is expected to warm an additional two to five degrees by the year 2100 (IPCC, 2021).

Addressing this challenge requires innovative and sustainable approaches in various sectors, including agriculture. Cotton, one of the most widely cultivated crops globally, is now emerging as an unexpected hero in the fight against climate change. This article explores the groundbreaking 'ICAC Carbon Neutral Cotton Farm' plan, which not only highlights the remarkable carbon-capturing abilities of cotton plants, but also presents a sustainable solution for transforming cotton farms into carbon sinks.

Figure-1. The 'ICAC Carbon Neutral Cotton Farm Plan' focuses on five main carbon-sequestration strategies, including carbon sequestration within cotton fabrics, biochar compost, cover crops, minimum/zero tillage practices, and reducing emissions from cotton farming. Illustration: Keshav Kranthi.

The 'ICAC Carbon Neutral Cotton Farm' plan

The ICAC is launching the 'ICAC Carbon Neutral Cotton Farm Plan' in collaboration with partner organisations from its Member governments; several research institutions and non-profit organisations in India and Africa also have expressed interest in implementing the programme.

The plan encompasses five primary regenerative, carbon-sequestration pools (Figure-1):

1. Carbon sequestration within cotton fabrics.
2. Carbon sequestration via biochar compost.
3. Carbon sequestration using cover crops.
4. Carbon sequestration in association with minimum/zero tillage practices.
5. Reduction of emissions from cotton farming.

The following passages elaborate the carbon dynamics of the five pools:

Plant Based Carbon Capture

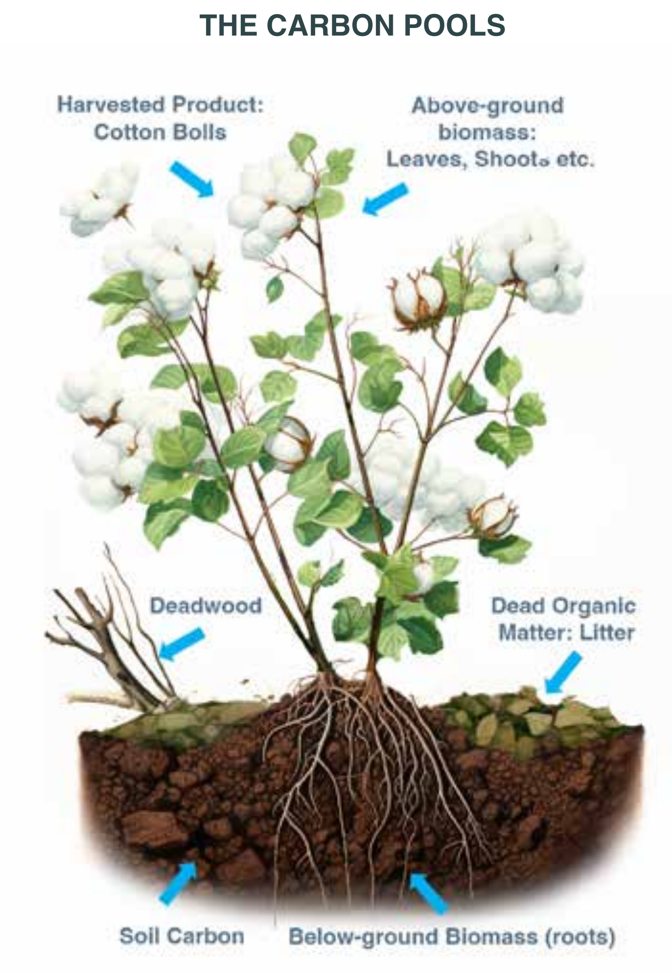
During their growth, plants perform the vital process of photosynthesis, capturing carbon dioxide (CO_2) from the atmosphere and utilising sunlight and water to produce carbohydrates and oxygen. This mechanism is fundamental to carbon cycling in ecosystems. Plants play a vital role in mitigating climate change by absorbing CO_2 through photosynthesis and storing carbon in their biomass (Kwiatkowski, et al., 2023).

According to the IPCC guidelines for Land Use, Land-use Change and Forestry (Ogle et al, 2019), land, plants, and products have the capacity to capture CO_2 from the atmosphere and store carbon in four distinct biogenic carbon pools (Figure-2):

1. The above-ground and below-ground biomass carbon pool.
2. The dead organic matter (DOM) carbon pool comprising litter and deadwood.
3. The soil carbon pool.
4. The harvested wood product pool (adapted to cellulose fibres: Xie, 2021).

However, it's essential to recognise that carbon removal from these biogenic reservoirs typically is temporary, lasting less than a century. This temporariness stems from its reversible nature because carbon can be re-released into the atmosphere as carbon dioxide due to natural decay, wildfires, changes in land management practices, or the disposal of manufactured products.

Figure-2. Land, plants, and products can capture and store carbon in four biogenic carbon pools: above-ground and below-ground biomass, dead organic matter (DOM), soil, and harvested products. Illustration: Keshav Kranthi.



While most carbon stored in annual crop biomass is transient and can rapidly return to the atmosphere, carbon within items crafted from plant products has a significantly longer shelf life, ranging from 5 to 100 years, with an average of approximately 20 years (Xie, 2021; Ogle et al., 2019). These manufactured products — such as clothing made from natural fibres, wooden furniture, or particle boards created from crop residues — retain carbon until they are eventually discarded, decomposed, or incinerated, which is often many years later.

Long-Term Carbon Storage in Fibres & Stalks

According to reports (Cotton Incorporated, 2017), it is suggested that cotton crops have the potential to capture more CO_2 than the total greenhouse gases (CO_2-equivalent) emitted throughout the entire cotton production process. To illustrate, cotton farms generate cotton stalks, which have a weight more than four times that of the cotton fibres they produce. The worldwide production of cotton fibres stands at approximately 26.0 million tonnes, whereas the estimated global production of cotton stalks is around 100 million tonnes (Kranthi, 2021). Notably, both cotton stalks and cotton cellulose fibres contain a significant carbon content of 44.0%.

Figure-3 Cotton crops have the potential to capture a significant amount of CO_2 and store it as carbon in cotton stalks and cotton cellulose fibres. Illustration: Keshav Kranthi.

Carbon Sequestration in Cotton Fabrics

Cotton, a widely grown natural fibre crop, possesses a unique ability to capture and store carbon. Unlike many other crops, cotton plants capture CO_2 for photosynthesis and fix carbon in the form of cellulose fibres during the process of biogenic sequestration. Cotton fibres are renowned for their high purity, comprising 96%-98% cellulose $(C_6H_{10}O_5)_n$. This exceptional purity means that cotton can sequester a significant amount of carbon in its fibres, making it a potential game-changer in the quest for carbon neutrality.

Calculations reveal that a staggering 11.4 million tonnes of carbon are captured in cotton fibres each year. While cotton fibres are transformed into textiles and clothing, the carbon they contain remains stable, representing 41.8 million tonnes (11.3 X 3.67 = 41.8) of CO_2 captured and stored annually in a relatively stable form, persisting in fabrics for several years.

These carbon stores remain intact while cotton clothes are in use but are eventually released when the clothes are discarded and degraded to CO_2 by soil microbes (USDA, 2020).

Though estimates of the life of cotton fabrics vary according to the type of fabric, place and nature of its use, the value of cotton's product-in-use half-life was assumed to be about 10 years, and the material lifetime was estimated to be 20 years (Xie, 2021).

The life estimates of biogenic carbon sequestration in cotton fibres for carbon footprint assessment could thus be assumed to be at least an average of 10 years.

Figure-4. Carbon dioxide (CO_2) captured and stored in cotton fabrics remains relatively stable and can persist for about 10 years, making it important for carbon footprint assessments. Illustration: Keshav Kranthi.

Cover Crops

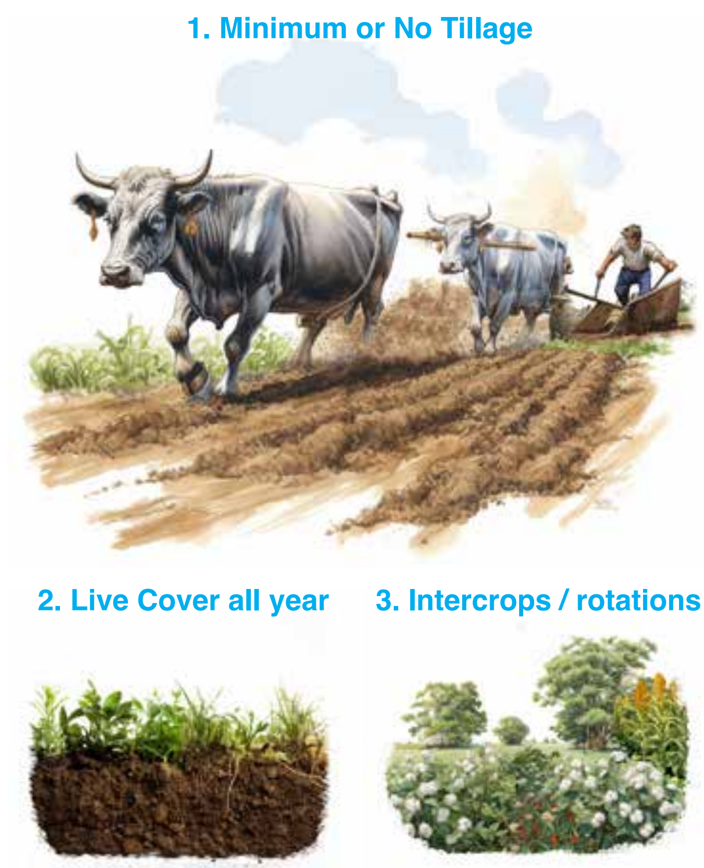
Figure-5 Cover crops have the potential to accumulate significant quantities of carbon each year in the topsoil. Illustration: Keshav Kranthi.

Cover Crops: Carbon Capture Powerhouse: The cultivation of cover crops in agricultural systems offers a promising strategy for carbon sequestration in soils, with a meta-analysis revealing that cover crop treatments significantly increased soil organic carbon (SOC) stocks compared to reference croplands. Several cover crops such as sweet clover, rye grass, and hairy vetch are used in cotton production systems.

A meta-analysis study derived from 139 plots at 37 different sites (Poeplau and Don, 2015) found a linear correlation between the time cover crops were introduced into crop rotations and SOC stock changes, with an annual accumulation rate of 320 kg carbon per hectare per year in a mean soil depth of 22 cm over up to 54 years of observation. The 320 kg of carbon equates to the capture and fixation of 1,174.4 kg of CO_2 from the atmosphere per hectare of soil area. On a global scale, cover crops have the potential to sequester 10.24 million tonnes of carbon, which is equivalent to 37.58 million tonnes (10.24 X 3.67 = 37.58) of CO_2 captured from the atmosphere and stored in the soil annually.

Conservation Agriculture and Carbon Sequestration

Figure-6 Conservation agriculture encompasses three main principles: minimum tillage or zero-tillage, continuous maintenance of live soil organic cover throughout the year, and the implementation of intercropping and crop rotations with a diverse range of crops. Illustrations: Keshav Kranthi.



Conservation Agriculture and Carbon Sequestration: Quantitative estimates from a review (Causarano et al, 2005) of 20 studies from cotton production systems in the United States indicate that the implementation of no-tillage compared to conventional tillage can lead to an average increase of 481 kg of soil organic carbon per hectare per year.

Data from the studies suggested that no-tillage with a cover crop can sequester 672 kg of carbon per hectare per year, whereas no-tillage without a cover crop sequesters 336 kg of carbon per hectare per year.

Similar results were obtained with a meta-analysis (Tadiello et al, 2022) conducted from 47 global studies in various climates, aiming to explore the factors contributing to variations in SOC responses to conservation agriculture (CA). Their analysis revealed that within the specified climatic region, CA had an overall 12% greater impact on SOC accumulation in the ploughed layer (0–0.3m) compared to conventional agricultural practices. On average, this outcome equates to a carbon increase of 480 kg carbon per hectare per year.

Research (Smith et al, 2007) indicates that no-tillage practices can lead to the sequestration of a minimum of 250 kg of carbon per hectare annually, corresponding to the capture and fixation of 917.5 kg of CO_2 from the atmosphere into the soil. On a global scale, no-tillage has the potential to capture 29.36 million tonnes of CO_2 from the atmosphere and fix it in the soil, equivalent to 8.0 million tonnes of carbon.

Biochar: A Long-Term Carbon Solution

Cotton stalks, often considered agricultural waste, possess substantial potential for combatting climate change. Through conversion into biochar, the carbon derived from these stalks can be integrated into the soil for long-term sequestration.

Figure-7. The carbon stored in biochar derived from cotton stalks represents a significant amount of CO_2 that is captured from the atmosphere and securely sequestered in the soil annually. Illustrations: Keshav Kranthi.

On average, a cotton farm yields a minimum of 3.0 tonnes of dry weight in cotton stalks (Kranthi, 2021), with carbon comprising about half of this dry weight. By returning biochar produced from cotton stalks to the field, it's possible to retain approximately 50% of this carbon, resulting in 750 kg of carbon per hectare per year available for potential carbon sequestration (Kranthi, 2021; Chen et al, 2023).

Globally, an estimated 44 million tonnes of carbon are contained within the 100 million tonnes of cotton stalks produced each year. Assuming a 50% efficiency in retaining carbon during the biochar production process, it is feasible to generate biochar containing at least 22 million tonnes of carbon each year, contributing to permanent soil storage and the effective removal of carbon from the atmosphere (Lehmann, 2007).

It is noteworthy that each unit of carbon sequestered corresponds to 3.67 units of CO_2. Consequently, the 750 kg of carbon in biochar represents 2,752.5 kg of CO_2. On a global scale, the 22 million tonnes of carbon stored in biochar produced from cotton stalks translates to an impressive 80.74 million tonnes (22 X 3.67 = 80.74) of CO_2 captured from the atmosphere and securely sequestered in the soil each year.

Mitigating Carbon Emissions

Figure-8. Cotton production has been associated with greenhouse gas emissions, with emissions levels varying among different countries. Illustrations: Keshav Kranthi.

Mitigating Carbon Emissions in Cotton Farming: Cotton production has been linked to greenhouse gas emissions, with varying emission levels reported across different countries. For instance, in Pakistan, approximately 2.37 tonnes of CO_2-equivalent greenhouse gases (GHG) are estimated to be emitted for every tonne of cotton fibre produced (Imran et al, 2020). In Australia, this figure stands at 1.60 tonnes of CO_2-equivalent GHG (Hedayati et al, 2019), while Iran emits 1.47 tonnes (Sami and Reyhani, 2018). In a group of countries including China, India, Pakistan, Tajikistan, and Turkey (BCI), the emission rate is 2.93 tonnes of CO_2-equivalent GHG per tonne of cotton fibre (BCI, 2021), and the USA emits 1.70 tonnes (USDA, 2019).

Considering a conservative estimate of 3.0 tonnes of CO_2-equivalent GHG emissions for every tonne of cotton fibre produced (based on global data), the cumulative global emissions from cotton farms amount to a significant 78 million tonnes (26 X 3 = 78) of CO_2 each year.

Biological Sequestration

Figure-9. Biological sequestration enriches carbon reserves in ecosystems and land-derived products, temporarily reducing atmospheric CO_2 and mitigating radiative forcing when carbon remains isolated. Illustration: Keshav Kranthi.

Biological sequestration has the potential to enhance carbon reserves in non-atmospheric reservoirs, including terrestrial ecosystems and products derived from land resources.

When this sequestered carbon remains removed from the atmosphere for a specific period, it contributes to a temporary reduction in atmospheric CO_2 concentration and helps mitigate certain radiative forcing effects.

While the carbon storage and associated benefits may be temporary in nature (Brandão et al, 2013), they still hold promise as a tool to address climate change by mitigating its adverse impacts.

Although temporary carbon removal cannot fully offset GHGs with lasting climate consequences due to the differing timeframes of their effects on global warming, they do play a significant role in postponing emissions, thus reducing the overall heat-trapping effect (Minx et al, 2018; Levasseur et al, 2012; Dornburg et al, 2008; Noble and Scholes, 2001).

Cotton Farms as Net Carbon Sinks

Figure-10 Cotton farms have the potential not only to offset their emissions but also to make a substantial contribution to the global carbon balance by sequestering significant quantities of CO_2 for every ton of cotton fiber produced. Illustration: Keshav Kranthi.

Carbon stored in cotton fibres exhibits a longer lifespan compared to most agricultural commodities, which aids in retaining carbon in a stored form for several years, thus mitigating GHGs and their radiative impact. Furthermore, the potential of transforming cotton stalks into biochar is noteworthy. If cotton stalks are systematically converted into biochar and integrated into the soil, in conjunction with the carbon sequestration potential of cotton fibres, cotton farms could potentially function as net carbon sinks. For instance, even if we only consider the conversion of cotton stalks into biochar, the annual carbon sequestration capacity of 80.74 million tonnes surpasses the 78 million tonnes of CO_2 emitted during cotton production. This implies that cotton farms could not only offset their emissions but actually make a significant contribution to the global carbon balance, resulting in a net sequestration of 2.74 tonnes of CO_2 for every tonne of cotton fibre produced.

Facilitating Collaborations

1. The proposed collaboration framework for the programme includes the following steps:
2. Public sector or private organisations from ICAC Member governments are encouraged to express their interest in volunteering to participate in the programme.
3. The ICAC will assess the credentials of these agencies and, upon approval, establish non-financial memorandums of understanding to collaborate on the development of

'ICAC-(implementing partner's name) Carbon Neutral Cotton Farms' within a 3-4 year timeframe.

4. The ICAC will organise on-farm training programmes with lectures and hands-on training classes, and offer technical guidance on regenerative agriculture, carbon sequestration strategies, and methods for measuring carbon footprints to the collaborating partners under mutually agreed terms.

5. Collaborating partners are expected to identify villages with cotton farmers willing to participate in the programme and work toward the establishment of 'Carbon Neutral Cotton Farms'.

6. The ICAC will closely cooperate with collaborating partners to create a roadmap that supports the implementation of enhanced carbon sequestration strategies and assessment methods, ultimately working toward the goal of achieving 'Carbon Neutral Cotton Farms'.

Conclusions

The 'ICAC Carbon Neutral Cotton farm' plan offers an innovative and sustainable solution to address climate change through the remarkable carbon-capturing abilities of cotton plants.

By harnessing the carbon stored in cotton fibres and converting cotton stalks into biochar, cotton farms can potentially become net carbon sinks, sequestering more carbon than they emit during cotton production.

This initiative not only has the potential to make the cotton industry more sustainable, but also to significantly contribute to the overall global effort to combat climate change. As the world seeks urgent solutions to reduce carbon emissions, the 'ICAC Carbon Neutral Cotton Farm' plan showcases the power of nature and innovation in achieving carbon neutrality. It's a model that can inspire change across the agricultural landscape and beyond, demonstrating that the path to a carbon-neutral future may be closer than we think — and it could start with a field of cotton.

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