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Special Issue: Climate smart innovations as gamechangers for cotton production

The ICAC Recorder

Editorial

Climate change stands as the paramount challenge of our time, one that affects not only our current generation but also the well-being of generations to come. As we advance in our daily lives, our relentless exploitation of natural resources to meet our needs and enhance our comfort poses an ever-growing threat to the future of our planet and, in turn, to our own survival. Fascinatingly, recent findings indicate that regenerative agriculture holds promise not only in advancing the sustainability of our agricultural practices but also in combatting climate change. In this edition of the ICAC RECORDER, we delve into these transformative perspectives and explore the potential of regenerative agriculture as a vital solution to the climate crisis.

In 1958, Charles David Keeling recorded the first historical measurement, indicating that atmospheric CO_2 levels stood at 317 ppm at Mauna Loa in Hawaii. Over the ensuing decades, the concentration of CO_2 has steadily increased, reaching 420 ppm by December 2023. This alarming rise of over 103 ppm has occurred in just 62 years, contributing significantly to the global carbon load. To put this into perspective, each ppm of CO_2 equates to a mass of 7.821 billion metric tons, containing approximately 2.13 billion tonnes of carbon. Consequently, during this 62-year period, humanity has introduced a staggering 219 billion tonnes (corresponding to 103 ppm of CO_2) of carbon into the atmosphere.

On average, atmospheric CO_2 is currently increasing by at least 2 ppm annually, translating to the addition of more than 4 billion tonnes of carbon into the atmosphere each year. Given the ongoing growth of the global population, greenhouse gas (GHG) emissions are poised to continue their upward trajectory, indicating a potentially worsening situation. While reducing emissions is undeniably crucial, it constitutes only one facet of the solution. The more substantial challenge lies in capturing the excess 219 billion tonnes of carbon and permanently sequestering it back into the Earth's soils.

If any entity can accomplish this task, it is the plant kingdom. With approximately 1.5 billion hectares of arable land worldwide, there exists a significant potential to capture over 4.0 billion tonnes of carbon annually through biomass production, a portion of which can be effectively sequestered into the soil. The degree of success in achieving this permanent sequestration will largely depend on the development and implementation of climate-smart innovations that accelerate sequestration processes. Additionally, it will hinge on the collective determination of humanity to take action and persist until targeted sequestration goals are met.

Interestingly, even a relatively small fraction of global arable land can make a substantial difference. Currently, cotton cultivation occupies less than 2.3% of this available land. However, if all cotton farmers were to transition to regenerative agricultural practices and adopt carbon sequestration techniques such as converting cotton stalks into biochar, the cotton crop could emerge as a climate-positive contributor. By sequestering more greenhouse gases than it emits, cotton cultivation has the potential to play a pivotal role in mitigating climate change and promoting sustainable land use practices.

A Technical Seminar titled 'Climate-Smart Innovations: Transforming Cotton Production' took place as part of the ICAC Plenary meeting in Mumbai from December 2nd to December 5th, 2023. This seminar convened experts and thought leaders from around the world to explore climate-smart innovations poised to revolutionize cotton production. The seven distinguished experts delivered remarkable presentations, offering valuable insights into the various challenges and solutions within the realm of cotton production.

These experts collectively emphasized that in a world increasingly focused on mitigating greenhouse gas emissions, the cotton farming sector is faced with a unique set of challenges and opportunities. Recent research findings indicate that the adoption of climate-smart technologies not only contributes to emission reduction but also plays a pivotal role in enhancing carbon sequestration, improving soil health, and ultimately increasing crop productivity.

Carbon sequestration is a critical component of climate-smart agriculture (CSA). One particularly notable finding is that no-till cotton acreage can store more atmospheric carbon than it emits during production, establishing it as a net carbon sink. These innovations not only benefit the environment, biodiversity, and soil health but also enhance the profitability

of cotton farming. Climate change factors, including global warming, disrupted precipitation, and elevated CO_2 levels, significantly impact cotton yields. Rainfed cotton cultivation, reliant on monsoon rains, faces challenges due to delayed onset, dry spells, and rainfall deficits, all of which can result in significant yield losses. Climate-smart agriculture helps mitigate many of these climate-induced stress factors. Climate-smart cotton production technologies directly impact soil health, biodiversity, and yield. Climate-smart plant breeding is another avenue for addressing the challenges faced by cotton growers. Drought tolerance, a long-standing goal, presents complexity due to its quantitative nature. Traits associated with tolerance, such as stomatal conductance, transpiration, and photosynthesis, play pivotal roles in addressing this challenge. Integrating data from root system analysis and plant growth parameters is essential for identifying genotypes with advantageous traits for stable biomass accumulation under water deficit conditions.

The world is facing unique challenges in cotton production, including factors like soil nutrients, pests, diseases, heat stress, aridity, and ozone. The IPCC has reported that temperature increases can have both positive and negative effects on cotton yields. Resilient cropping systems, regional assessments, and science policy engagement are essential for addressing the impact of climate change on cotton production and soil health. In sub-Saharan Africa, rainfed cotton farming is vital for livelihoods. Soil organic carbon plays a crucial role in maximizing soil health and crop production. Climate-smart practices for rainfed cotton farming encompass improving water retention, reducing soil compaction, enhancing water infiltration, increasing nutrient availability, and improving crop yield stability. Regenerative agriculture principles and practices, such as cover cropping and conservation tillage, promote soil health, carbon sequestration, and climate change mitigation while addressing challenges faced by smallholder farmers.

Regenerative agriculture, zero budget natural farming (ZBNF), and organic cotton farming are promising climate change mitigation strategies. Reducing chemical fertilizer usage, implementing cover crops, practicing conservation agriculture, and converting cotton stalks into biochar are key steps in reducing greenhouse gas emissions and enhancing soil health. Organic farming and ZBNF, with their reduced reliance on chemical fertilizers, can play pivotal roles in the global fight against climate change.

Emerging technologies now quantify soil carbon, translating it into measurable carbon credits to provide incentives for farmers effectively sequestering carbon on their farms. Digitizing carbon farming empowers smallholder farmers and promotes climate change mitigation. Practices like no-till, organic fertilizer application, intercropping, and optimized fertilizer usage can enhance carbon sequestration rates. Capacity building and knowledge transfer programs are essential for widespread adoption.

We are delighted to present the December 2023 special issue of the ICAC RECORDER, devoted to capturing the insightful presentations and discussions from the Technical Seminar on 'Climate smart innovations as gamechangers for cotton production'. This edition of the RECORDER features seven articles authored by the experts who delivered lead presentations at the Technical Seminar, along with an additional invited article by Dr. Marcelo Paytas, a renowned cotton scientist who, regrettably, couldn't attend the seminar.

The Technical Seminar underscored the urgent need to embrace climate-smart innovations in cotton production. These innovations not only mitigate climate change but also enhance soil health and boost yields. It is imperative that governments, organizations, and farmers work collaboratively to implement these practices, ensuring a sustainable and resilient future for cotton farming while contributing to global climate change mitigation efforts.

Against the backdrop of global efforts to combat climate change and reduce greenhouse gas emissions, the articles in this issue shed light on the transformative potential of these innovations. From regenerative agriculture practices that enhance soil health and carbon sequestration to climate-resilient technologies, our contributors have shared their expertise and insights on how cotton farming can not only adapt to a changing climate but also become a part of the solution to mitigate its effects. I earnestly hope this special issue serves as a valuable resource for cotton stakeholders and inspires continued progress in sustainable and climate-smart cotton production.

– Keshav Kranthi

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Climate-Smart Plant Breeding of Cotton: Enhancing Resilience in the Face of Climate Change

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He worked for 13 years in Brazil with Embrapa's Cotton Research Center (Campina Grande, 2005-2010; Goiânia, 2010-2018), and currently works in cooperation with cotton improvement programs in Africa (Cameroon, Benin, and Côte d'Ivoire). His areas of expertise include cotton breeding and molecular genetics, and he presently is working mainly in pre-breeding and breeding. He currently serves as CIRAD's Cotton Supply Chain Correspondent.publications to credit.

Introduction

Cotton production faces significant challenges due to the impacts of climate change, particularly in rainfed areas. Our research focuses on the urgent need to address three major climate-related challenges: disrupted rainfall patterns affecting water availability, rising temperatures, and increased atmospheric CO_2 concentrations.

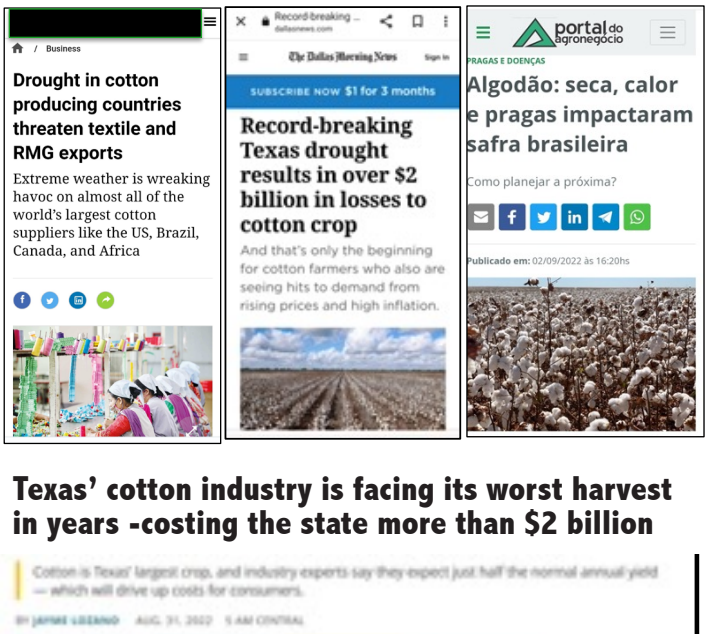


Figure-1. Climate change threatens cotton crop across the world.

Water Availability and Climate Change

Cotton cultivation relies heavily on sufficient water availability during critical stages of its growth, making it vulnerable to the erratic distribution and irregular rainfall patterns associated with climate change (Monfreda et al., 2008). Disrupted monsoons can severely impact water availability for crops, jeopardizing cotton production. Furthermore, the rise in global temperatures and climate variations lead to increased evapotranspiration, which in turn, places higher demands on water resources for agriculture (Hatfield & Prueger, 2015).

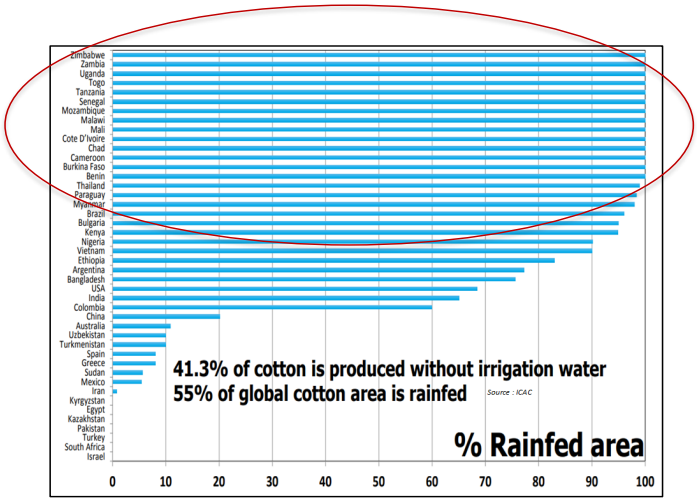


Figure-2. More than 55% of the global cotton area is dependent on rainwater. More than 95% of the area in Africa is rain dependent. Source: ICAC Databook 2021.

Elevated temperatures and changing climate conditions have far-reaching effects on cotton plants (Dhankher and Foyer, 2018; Thompson et al., 1996). High temperatures, prolonged periods of above-optimal temperatures, and warmer night temperatures can result in several detrimental outcomes. These include pollen sterility, poor formation of squares, flowers, and bolls, as well as fruit shedding (Echer et al., 2014). Such effects can significantly reduce cotton yields and quality.

The increase in atmospheric CO_2 concentrations, another hallmark of climate change, can affect cotton in both positive and negative ways. While elevated CO_2 levels may stimulate photosynthesis, potentially increasing crop productivity (Osborne et al., 2014), the benefits are often constrained by the accompanying rise in temperatures (Suzuki et al., 2014). Thus, the overall impact of increased CO_2 on cotton yields remains a complex interplay of various factors.

Impact of Water Deficit:

Water deficit during critical growth stages has been well-documented as a significant threat to cotton production (Ul-Allah et al., 2021). Early-stage water deficits can lead to poor seedling emergence, hinder root development, and result in an insufficient plant stand, often necessitating re-sowing (Reddy et al., 2020). However, there is evidence (McMichael and Quisenberry, 1991; Ball et al., 1994; Pace et al., 1999) to show that water stressed cotton seedlings produced longer roots accompanied with a reduced root diameter.

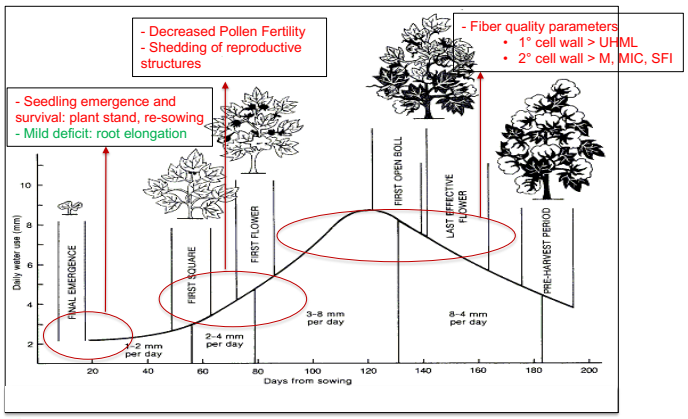


Figure-3. Effects of water deficit on cotton development are well documented.

However, a mild water stress at early stages can also increase root length. Water deficits during the squaring stage can reduce pollen fertility and lead to the shedding of reproductive structures (Oosterhuis and Snider., 2011). Subsequent water deficits during flowering and green boll development stages can cause severe yield losses (Bange et al., 2016).

Even slight changes in temperature can have a profound impact on cotton fiber quality (Reddy et al., 2017). A one-degree Celsius change can significantly affect fiber length, while a two-degree Celsius change can negatively impact micronaire and fiber strength (Lokhande and Reddy, 2014). These temperature-induced variations in fiber properties can have implications for the textile industry's final product quality.

Breeding for Drought Tolerance

Addressing these climate-related challenges through plant breeding is a daunting task, given the complex nature of "drought tolerance" and the quantitative traits associated with it (Furlow et al., 2011; Mollaee et al., 2019). Drought tolerance is a multifaceted trait influenced by various genetic factors, making it challenging to characterize and breed for (Magwanga et al., 2020). Moreover, such traits generally suffer from low heritability, adding to the complexity of breeding efforts (Boopathi, et al., 2015).

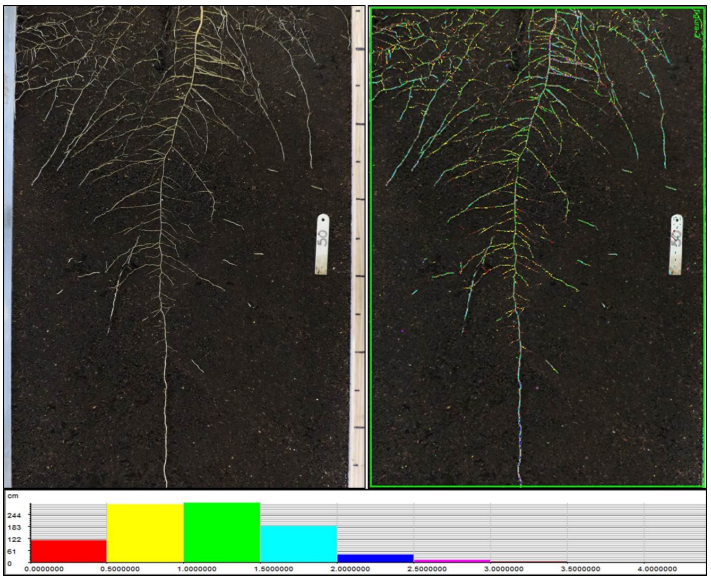
Figure-4. Climate-Smart Plant Breeding of Cotton – Generate phenotypic data for roots system architecture (RSA) and aerial parts

Figure-4a. Climate-Smart Plant Breeding of Cotton – CAWaS. Panel of 269 genotypes: main cotton breeding pools; modern and obsolete varieties, advanced breeding lines.

Efforts to breed for drought tolerance have been ongoing for several years, and researchers are exploring various morphological, physiological and biochemical traits associated with tolerance. These traits include stomatal conductance, transpiration, canopy temperature, osmotic adjustment, water-use

efficiency (WUE), specific leaf area (SLA), fluorescence, and photosynthetic rate (Aboukheir al., 2011).

Despite the challenges, there is a ray of hope in the high level of genetic variability observed for traits associated with drought tolerance in cultivated cotton and related species. This genetic diversity provides an opportunity for plant breeders to develop cotton varieties that can withstand water deficits and climate-related stresses (Banga and Kang, 2014).



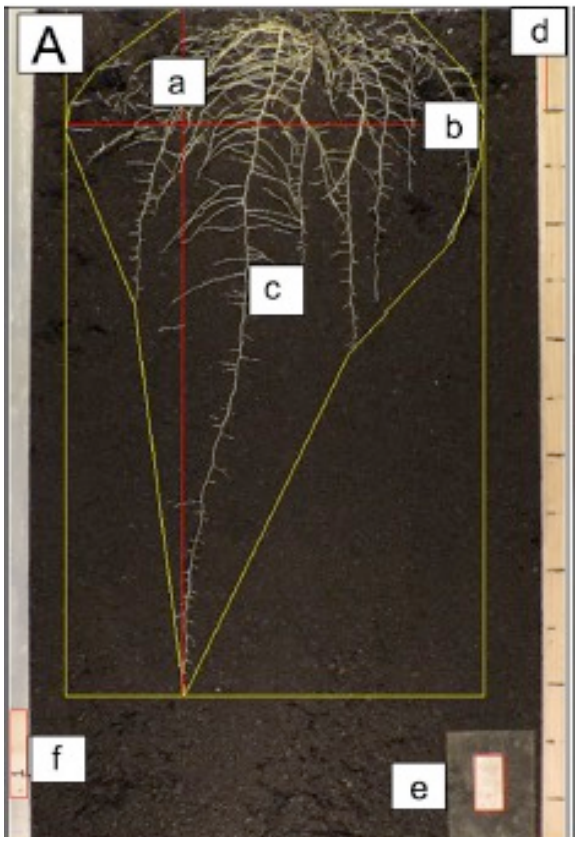


Figure-5. Pheno-Roots an inexpensive non-ivasive phenotyping system to assess the variability of root architecture.

The Role of Phenotyping in Cotton Breeding

One of the pivotal approaches to address these challenges is the use of advanced phenotyping techniques (Pandey et al., 2017). Our research emphasizes the importance of accurately characterizing root system architecture (RSA) and aerial parts to enhance cotton adaptation to water stress (Martins et al., 2019). The Cotton Adaptation to Water Stress (CaWaS) project primarily focuses on root phenotyping to determine the genetic and morphological characteristics related to drought stress response during the vegetative phase of plant development.

An innovative system known as 'PhenoRoots' has been developed for this purpose (Martins et al., 2019). The 'PhenoRoots' system is cost-effective and non-invasive, enabling real-time visual assessment of variability in root growth and architecture. This system provides valuable insights into parameters such as total root length, average root diameter, maximum root depth, root area explored at different soil depths, root surface area, root volume, and root density (Martins et al., 2019).

Research shows that there is a high degree of variability in root traits among cotton genotypes, and this variability typically follows a normal distribution (Klueva et al., 2000). Additionally, there is low to moderate heritability (ranging from 13% to 44%) for key traits associated with drought tolerance (Martin et al., 2019).

Table-1. Determining root traits through PhenoRoots.

Trait	Abbreviation	Unit	Means of determination
Total root length	trl	cm	WinRHIZO
Average diameter of roots	adr	mm	WinRHIZO
Maximum root depth	mrd	cm	Measuring tape
Total area explored by roots	ea	cm^2	ImageJ toolset
Area explored by roots 0-40cm profile	ea_0_40	cm^2	ImageJ toolset
Area explored by roots 40-75cm profile	ea_40_75	cm^2	Calculation
Maximum width reached by roots	mrw	cm	ImageJ toolset
Projected area	pa	cm^2	WinRHIZO
Root surface area	rsa	cm^2	WinRHIZO
Root volume	rv	cm^3	WinRHIZO
Ratio maximum root depth to maximum root width	mrd_mrw	-	-
Density of roots (ratio trl:ea)	trl_ea	cm/cm^2	-

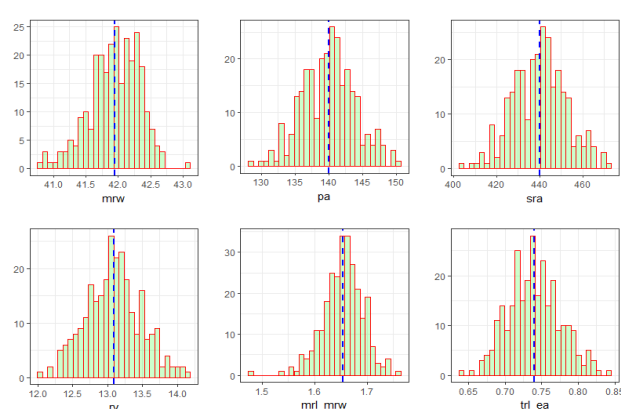


Figure-6. Root traits and parameters. High levels of variability for all roots traits – Normal distribution.

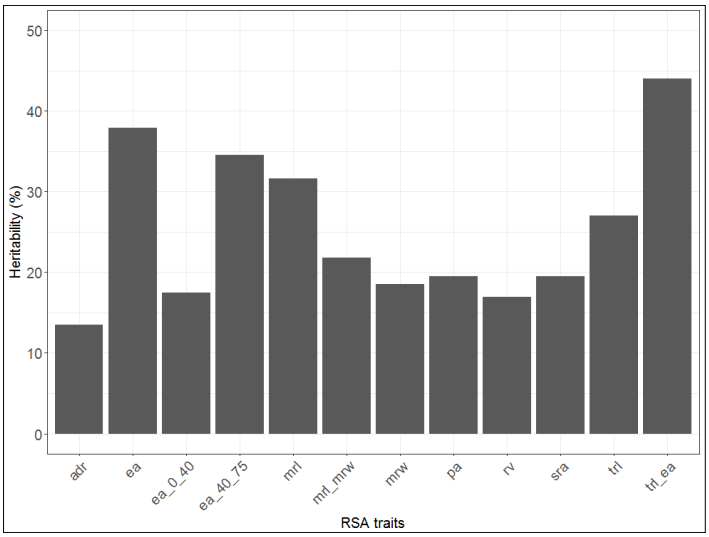


Figure-7. Root traits and parameters. Low to moderate heritability (13-44%): trl_ea = 44% ; ea, ea_40_75, trl > 30%

PhenoArch for Comprehensive Phenotyping

In addition to root phenotyping, comprehensive phenotyping is crucial for understanding cotton's response to water stress. The PhenoArch High-Throughput Phenotyping Platform (HTPP), utilized in our research, characterizes various plant growth parameters and physiological indices under contrasting water regimes (Martins et al., 2022). These parameters include relative reduction, biomass, leaf area, plant height, transpiration, WUE, SLA, carbon isotope discrimination, osmotic adjustment, and leaf water content.

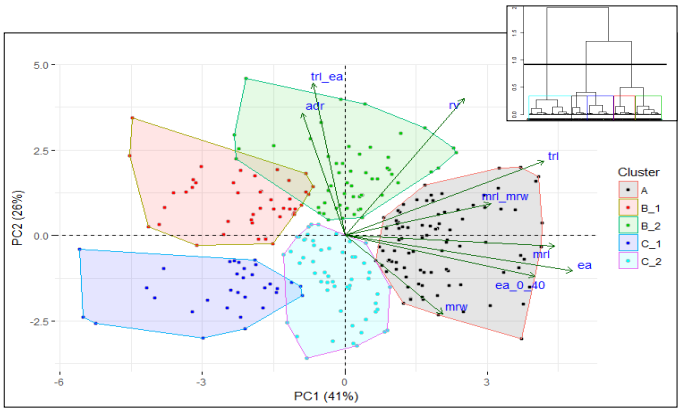


Figure-8. Root traits and parameters. Hierarchical Clustering on Principle Components: 5 groups.

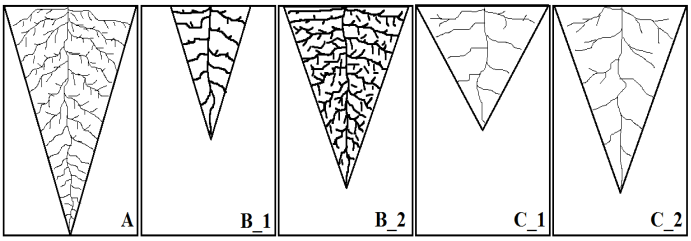


Figure-9. Root traits and parameters. >5 root system architecture morphotypes.

Endpoint measurements reveal high levels of variability for all parameters, with most exhibiting a normal distribution (Bruno et al., 2017). Under conditions of water limitation, values for most parameters decrease significantly, except for water-use efficiency (WUE), which shows a notable increase (Martins et al., 2022).

Figure-10. Traits and Parameters: PhenoArch HTPP (LEPSE, Montpellier, France)

Figure-11. Characterization of plant growth parameters and relevant physiological parameters/indices under contrasting water regimes: 80% Field Capacity vs. 30% Field Capacity.

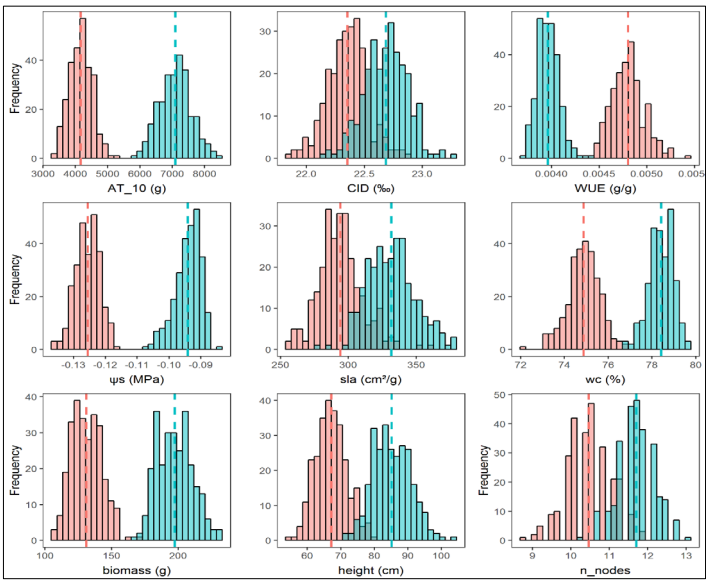


Figure-12. Traits and Parameters: PhenoArch HTPP, Endpoint measurements. High levels of variability for all parameters – Normal distribution.- Decreased values under water limitation – except for WUE

Table-2. Traits and Parameters: PhenoArch HTPP, Endpoint measurements. Effects of Genotype and of Scenario for all parameters. No GxS interaction in most cases.

Charactere[1]	Scenario (S)				Genotype (G)				G x S			
	MS	F	p-value		D	LRT	p-value		D	LRT	p-value	
oa	-	-	-	-	-670,04	13,04	0,0003	***	-	-	-	-
AT_10	1597364421	3977	0,0000	***	26420	25,64	0,0000	***	26398	3,74	0,0531	ns
biomass	1454282	3583	0,0000	***	15798	34,40	0,0000	***	15767	3,41	0,0650	ns
CID	38	176,51	0,0000	***	2815	31,871	0,0000	***	2785	1,965	1,0000	ns
height	96951	3178	0,0000	***	11510	116,29	0,0000	***	11402	7,87	0,0050	**
n_nodes	462	1207	0,0000	***	4182	120,37	0,0000	***	4186	4,27	0,0387	*
ψs	0,329	2768,4	0,0000	***	-9461,4	32,54	0,0000	***	-9491	2,98	0,0843	ns
sla	556353	505	0,0000	***	16632	70,42	0,0000	***	16562	1,00	0,9060	ns
wc	4495	1261	0,0000	***	7535	19,58	0,0000	***	7516	0,71	0,3996	ns
WUE	0,0002	2337	0,0000	***	-20251	35,08	0,0000	***	-20247	3,26	0,0709	ns

Genotype and Scenario Effects

Our research also delves into genotype and scenario effects on cotton's response to water stress. This exploration reveals distinct responses among genotypes, differentiating between optimistic and pessimistic genotypes. Notably, the dynamics of biomass accumulation demonstrate significant variations among individual genotypes. These findings raise critical questions about the relevance of endpoint values, the importance of trait dynamics, and the potential role of phenotypic plasticity in cotton breeding (Martins et al., 2022).

Integration for Resilient Cropping Systems

As climate change continues to exert pressure on cotton production, it becomes imperative to integrate climate-resilient cotton varieties into more sustainable cropping systems. This integration should consider various aspects, including life cycle duration, competition with other crops (such as row cropping), adapted architectural traits (e.g., increased plant density), improved harvest index, and enhanced water use efficiency (WUE), evapotranspiration use efficiency (EUW), and nutrient use efficiency (NUE).

By incorporating climate-resilient cotton varieties into sustainable cropping systems, we can enhance cotton's adaptability to changing environmental conditions and ensure more stable yields. This approach represents a transition from merely focusing on Climate-Smart Plant Breeding of Cotton to a broader perspective of Breeding Cotton for Resilient Cropping Systems.

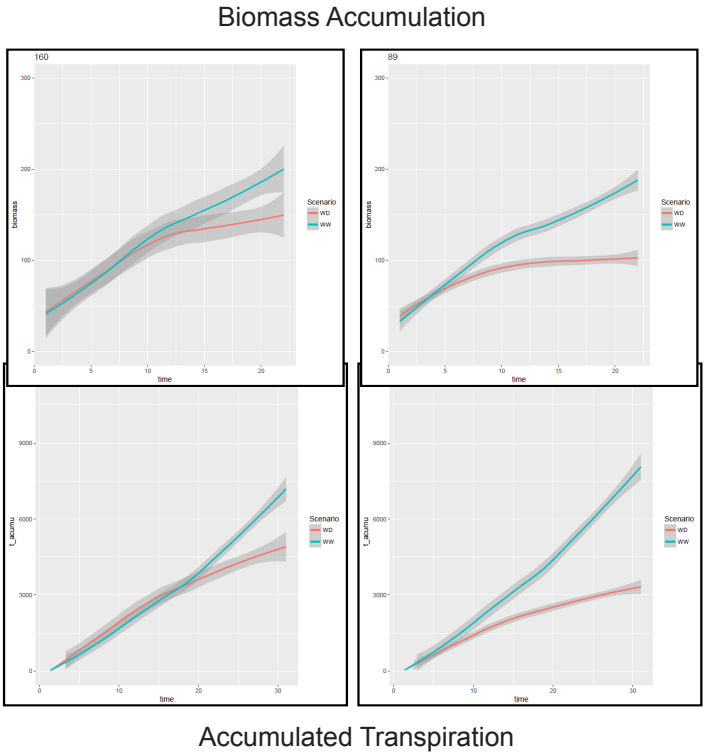


Figure-13. Traits and Parameters: PhenoArch HTPP (LEPSE, Montpellier, France). Dynamics of Biomass Accumulation show clear differences between individual genotypes. Two contrasting behaviors: optimistic vs. pessimistic genotypes.

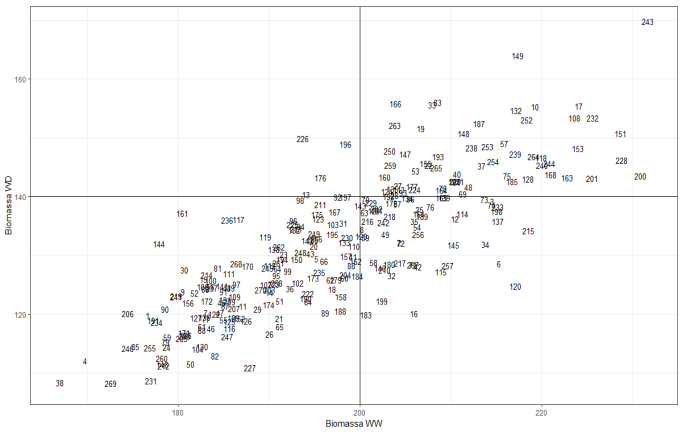


Figure-14. Traits and Parameters: PhenoArch HTPP (LEPSE, Montpellier, France). No correlations between root traits and aboveground characters measured on PhenoArch.

Conclusion

Our research underscores the urgency of developing climate-resilient cotton varieties to mitigate the adverse impacts of climate change on cotton production.

Utilizing innovative phenotyping techniques such as the 'PhenoRoots' system and integrating cotton into sustainable cropping systems offers promising pathways toward a more secure cotton supply chain in the face of evolving climatic challenges.

As cotton growers face increasingly unpredictable weather patterns and rising temperatures, the quest for climate-smart cotton varieties remains paramount for ensuring global cotton sustainability.

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