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Integrating Agronomic Practices with Genetic Improvement for Climate Resilient Crops

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ABSTRACT

Due to climate change, the abiotic and biotic stress is increasing at the expense of world food security. The review recommends a comprehensive strategy of creating climate-resistant crops, such as incorporating the use of innovative genetic enhancement with the enhancement of agronomic processes. We investigate synergistic approaches, such as conservation agriculture, precision farming, and integrated nutrient management, and accelerated breeding, genome editing, and microbiome engineering. It has been proved that the alignment of the genetic gains and environmental management results in the better systemic resilience, higher yields, and sustainability. We conclude that one of the key elements in implementing this dual strategy will be the harnessing of digital agriculture and artificially Intelligence to enable agrifood systems to adjust to a fast-changing climate.

Keywords: Climate-resilient crops, Genetic improvement, Sustainable agriculture, Genome editing, Integrated crop management

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Introduction

Climate change is increasing extremes in weather conditions and changing temperatures and precipitation patterns that are serious threats to crop productivity and global food security Every degree C increment in temperature may decrease the yields of the major cereals wheat maize rice and degrading nutritional value of crops and random rainfall patterns add to the abiotic stresses and lead to starvation among hundreds of millions of people [1].Traditional crop improvement methods were based on intensive production with agronomic systems and relied on chemical inputs at the expense of environmental stability, resulting in soil erosion and increased green house gas emissions [2]. To effectively achieve future food production in the face of climate uncertainty, there is need to implement an integrated strategy that can improve the soil resiliency through the agronomic methods with genetic improvement of food crops In addition, genetic improvement of genetically modified crops through conventional breeding is a slow process that takes several years to develop genetically modified plant varieties and efforts to genetically modify crops often leads to linkage drag [3].

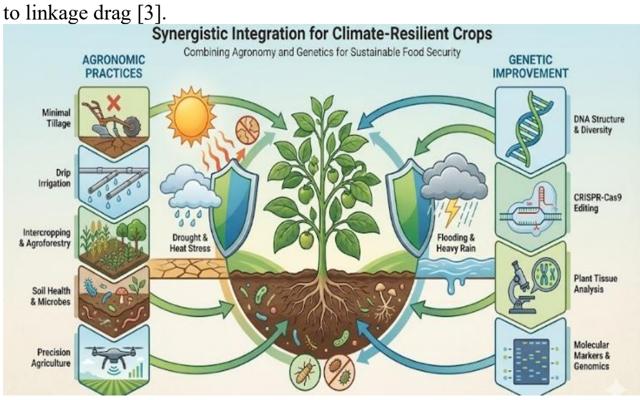

Figure 1: Synergistic integration of agronomic practices and genetic improvement.

2. Climate-resilient Agronomic Practices.

Agronomic interventions alter the agricultural environment to hedge crops to climatic stresses. Important practices are soil conservation precision resource use crop diversification agroforestry better nutrient and pest management and regenerative soil health interventions [4].

2.1. Less tillage and conservation agriculture.

The conservation agricultural philosophy upholds minimal disturbance of the soil permanent soil cover and diversified plantings and rotations. Minimal soil disturbance multiple studies have demonstrated that diversified plantings including legumes and cover crops can increase yields by and suppress erosion and fossil fuel consumption hence improving soil water holding capacity and helping crops endure drought [5].

2.2. Accurate farming and computer-aided technology.

Precision agriculture involves the use of geospatial technologies sensors and variable rate equipment to apply inputs in a precise way Remote sensing and GIS mapping enable site specific control of irrigation, fertilizer use and pest control to optimize resource use and minimize environmental impacts. Digital tools can be used to adjust practices in real-time, such as weather forecasting, yield monitoring, and combines genetic data with precision agriculture to tailor management to crop genotypes [6].

2.3. Diversification and agro-forestry of crops.

Farming systems based on crop rotation intercropping and agroforestry diversify, transferring risk and improving resilience and rotating crops and agroforestry to combine legumes and trees improve biodiversity and fix carbon through biological fixation and improve stress tolerance by reducing land use by a similar amount [7]. Second order meta analysis indicates that cropping systems which have undergone diversification scale up yield by almost a quarter and decrease land requirements by an equivalent proportion. Farming systems based on crop rotation intercropping and agroforestry diversify, transferring risk and enhancing resilience [8].

2.4. INM Integrated nutrient management.

Organic amendments to inorganic fertilizer such as compost and mineral fertilizer used in conjunction with biofertilizers and site-specific application can also combine to optimize nutrient availability Climate change [9]. Destabilizes nutrient cycling and adds to nutrient losses through leaching and volatilization and denitrification. INM can also reduce the emissions of nitrous oxide by combining organic and inorganic fertilizers and biofertilizers with precise placement and timing of nutrient application at the correct rate and place to meet crop nutrient needs Legume based rotations and precision nit [2].

2.5. Pest Integrated pest management IPM.

The IPM uses cultural biological and chemical methods to control pests and reduce the use of pesticides practices include crop rotation sanitation habitat manipulation biological control predators and entomopathogens pheromone traps and judicious pesticide application [10]. IPM lowers the potential risk of pest outbreaks and is a critical part of climate smart agriculture [11].

3. Genetic Enhancement Procedures.

3.1. Traditional breeding and marker aided breeding.

Genetic diversity has been used long in the breeding of plants to design stress tolerant cultivars traditional hybridization and selection. The use of genetic diversity and selection is longstanding and fundamental to breeding, but it is slow and low genetic drag linkage disequilibrium and long generation times Marker assisted selection MAS and quantitative trait locus QTL mapping allow breeders to monitor genomic regions linked to stress tolerance and speed up the process of breeding Periodically. Genome wide association studies GWAS can identify alleles related to complex traits such as drought tolerance heat tolerance and nutrient efficiency [12].

3.2. Omics and genomic selection

Multi omics is a strategy that combines genomics, transcriptomics, proteomics, metabolomics and epigenomics techniques to explain the mechanisms that underlie plant responses to stress. High throughput sequencing and functional genomics determine the crucial genes proteins and metabolic pathways that explain genetic gain per unit time. All of these techniques are specifically useful in elucidating complex traits that are influenced by a large number of loci [13].

3.3. Breeding fast and double haploidy.

Speed breeding reduces generation times with manipulation of photoperiod temperature and light levels that allow up to 6 generations per year in certain species. When paired with MAS gene editing and high throughput phenotyping speed breeding is one of the most promising paths to climate resistant variety. Many species require greater manipulation of photoperiod and light intensities. This reduced breeding period is achieved by combining speed breeding with high throughput phenotyping advanced technologies can enable rapid homozygous lines to be obtained [14].

3.4. Genome editing and gene drives.

CRISPR-Cas systems and other genome editors eg TALENs base editors prime editors enable the precise editing of genes underlying stress tolerance Genome editing has become a standard of next generation breeding, with the opportunity to be utilized in multiplex editing multiple loci in complex traits, and has raised ethical and regulatory challenges. Genome editing has great potential, but with ethical and regulatory issues Multiple loci at once [15].

3.5. Microbiome of plants and grafting.

Plant related microbiomes assist in nutrient acquisition stress tolerance and disease resistance. The integration of microbiome engineering in breeding programs has the ability to enhance the resilience inoculation with advantageous microbes or develop synthetic communities would potentially expand resilience strategies [16].

3.6. Digital breeding and artificial intelligence.

Under changing climatic conditions, to discover complex networks of traits and predict breeding outcomes, AI and machine learning is applied to large datasets of genomics phenomics and environmental monitoring, and complementary agronomic and genetic data is used to give holistic decisions in digital breeding platforms [17].

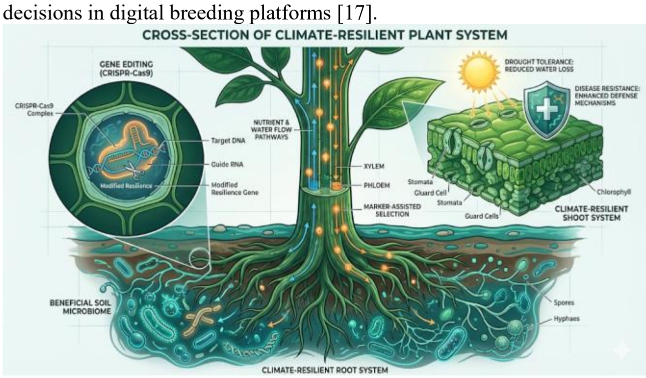

Figure 2: Engineering plant resilience at the genetic and microbiome level.

4. The combination of Agronomic Practices and Genetic Improvement.

4.1. Rationale for integration

Agronomic techniques and genetic advances are perceived to be distinct pillars but together they can be used to achieve synergistic effects. Agronomic techniques create favorable microenvironments and genetics dictate the natural stress tolerance of plants Combinations of them can be used to bring about beneficial effects. Agronomic techniques and pest resistant varieties can be used in IPM systems reducing the use of pesticides Agronomic strategies create favorable microenvironments and genetic advances determine the natural stress tolerance of plants Combinations between the two can produce synergistic benefits [2].

4.2. Wholesome systems and case studies.

Triple goal agrifood framework: A meta-analysis of over k field comparisons found important interventions that yield greater productivity and also improve soil health and reduce emissions of greenhouse gases Integrating legumes and cover crops reduced emissions of nitrous oxide by and increased soil organic carbon. These findings demonstrate that agronomic innovation combinations can be used to achieve climate resilience and mitigation[18].

Integrated NUE management: integrating agronomic break-even of agronomic practices can maximize the use of nitrogen application by combining agronomic agricultural rotations with genetic improvements in toil type application rate, timing, and frequency with agronomic crop genetics and soils and using precision tools to adjust the application to crop demand [19].

Speed breeding with digital agronomy: Modeling speed breeding and CRISPR-Cas edited breeding lines into highly phenotyped and artificial intelligence can yield climate-resilient cultivars with faster breeding cycles.This integrated pipeline can be used to boost adaptation and shorten the gap between the discovery of a gene and its application in the field of agriculture [20].

Plant microbiome and agronomy: The use of inoculants or synthetic communities to enhance the use of plant associated microbes improves nutrient utilisation and stress-resistance. When coupled with organic supplements and lesser tillage desirable microbes will grow even better enhancing soil health. The choice of genotypes that capture advantageous microbiomes may become a new breeding goal [21].

4.3. Problems and socio-economic factors.

Although its adoption has proven to be beneficial, integration has a number of obstacles. Adoption of conservation agriculture and precision technologies needs investment in equipment and training which can be prohibitive to smallholders. Breeding advanced cultivars needs infrastructure to genomics and phenotyping GMOs can hinder adoption. The success of integrated approaches must depend on customizing practices to local soils and climates and socio-economic statuses [22].

5. Future Directions

5.1. Multi omics and digital AI.

The intersection of AI multi omics high throughput phenotyping and precision agronomy. AI driven predictive models will be exploited by future climate resilience strategies to identify optimal combinations of genes and their environmental management combinations that enable breeders to make decisions based on the various environments and management systems. Future developments in algorithms will require investments in open data platforms and computational capacity [23].

5.2. Microbiome engineering and soil well-being.

This will be made possible by future developments in metagenomics and synthetic biology that will facilitate the engineering of microbial consortia to increase stress tolerance to nutrient cycling and disease resistance. Breeding programs can be used to include the capacity of genotypes to attract useful microbiomes in combination with regenerative agronomy microbiome engineering would enhance soil health and resilience [24].

5.3. Policies and participative strategies.

Those scaling strategies need to be supported by policies subsidizing conservation agriculture and incentives on using precise equipment to cover cropping and agroforestry and have clear rules on genome editing. Participatory breeding and farmer scientist partnerships will help to adopt these strategies especially in resource limited regions.

6. Conclusion

Climate change requires a new paradigm in crop improvement Not treating agronomy and genetics as independent disciplines and integrating resilient agronomic practices with state of the art genetic improvement provides a holistic way forward to climate resilient crops Conservation agriculture precision resource management crop diversification integrated nutrient and pest management and regenerative practices build environmental buffers and Policies capacity building and participation research will be the key to scaffolding these innovations and ensuring food systems survive the changing climate Evidence Meta analyses and case studies Both have shown integrated systems can increase yields enhance soil health improve nutrient use efficiency.

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