Climate Change and Plant Breeding

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Plant breeding is, by definition, the art and science of changing the traits of plants through genetic improvements to produce desired characteristics for the benefit of humanity. Thus, plant breeding strives to use diverse genetic material to change the genetic composition of desirable plants/crops and select and multiply those with the highest attributes, structure, and nutrient composition for the most suitable uses related to human requirements. Crop yield has been a major target of plant breeding, although resistance and quality have also been important. Climate change calls for breeding efforts to improve characters in agricultural crops that can contribute to mitigating greenhouse gas (GHG) emissions. The assessment of plant characters has shown that an increased nutrient use efficiency is a major character that has a larger impact in decreasing the GHG emissions in wheat production.

carbon sequestration | crop production | greenhouse gas emissions

1. Impact of Climate Change on Agricultural Crops and Implications for Plant Breeding

Climate change is one of the major global concerns, evident from observations of increasing atmospheric CO_2 concentration and temperature, thereby resulting in melting glaciers and rising sea levels across the world [1]. Climate change is currently impacting a range of environmental factors that directly and indirectly influence crop adaptability and productivity. As a result, food production, food quality, and food security are severely influenced, not least in developing and vulnerable countries [2][3]. The increased frequencies and severity of abiotic and biotic stresses from climate change contribute to a change in the chemical and physical properties of the soil, plant nutrient uptake efficiency, soil microbial activity, and other biotic factors such as the activity of insects and pests [4][5].

Water deficiency in plants is known to induce changes in the physiological, morphological, biochemical, and molecular characteristics of plants. In wheat, drought stress affects the flag-leaf area, root and plant biomass, days to anthesis, and tillers per plant, which directly affect overall crop yield [4]. Similarly, high temperatures and drought stress during production negatively influence the yield, therefore changing the choice of areas suitable for rice production [6]. The current extremely rapid change in climate requires an upscaling of time-effective plant breeding, including the use of a wide array of genetic resources in combination with modern phenotyping and genotyping methodologies [7][8].

2. Opportunities of Using Plant Breeding of Agricultural Crops as a Tool to Mitigate Climate Change

Plant breeding has been identified not only as a sustainable method to address plant adaptability to a changing climate but also as a tool for its mitigation [9]. Efforts have been made to understand complex stress-adaptive mechanisms, stress uncertainty, and genotype-environment interactions in breeding for crops adaptable to the future climate [10]. Consequently, there is also a pressing need to accelerate the genetic gain of the major crops by taking into account gene x gene and genotype-environmental interactions. A comprehensive understanding of the above-mentioned factors can significantly enhance the adaptation of wheat cultivars and help in defining the goals for future wheat breeding strategies [11]. Currently, characters mitigating climate change are less studied, and breeding as a tool has been less utilized. Two crop characteristics that have an impact on climate change mitigation are (i) the ability of the crop to fix carbon dioxide and thereby contribute to the formation of soil organic carbon (SOC) [12] and (ii) the nutrient use efficiency (NUE) of the crop so that a high content of biomass is obtained with low input [13]. Modern plant breeding provides substantial opportunities for the introduction of these characters through speed breeding, bioinformatics, and big data phenomics/genomics-led approaches, together with the availability of relevant germplasm [14][15].

Both approaches above have their own systematic limitations. Modern agriculture has striven towards a lower total plant biomass production (at higher yields of harvestable product), thus the amount of plant residues potentially contributing to the SOC build-up has historically decreased, and with it, the amount of carbon potentially stabilized in the soil [16]. Currently, a return to an increase in the total plant biomass is not an aim for plant breeding, although coming requirements might lead to a shift. For NUE, a major limitation is how to make enough nutrients available in the soil with low additions of fertilizer [17].

3. Opportunities to Use Plant Breeding as a Tool for Carbon Sequestration by Agricultural Crops

Plant breeding efforts to increase carbon sequestration by agronomic crops have been limited until now. Carbon sequestration by crops will directly contribute to an increased SOC in the soil and thereby, a decrease in CO_2 in the atmosphere [12]. Generally, SOC present in the soil is the result of two mechanisms: (i) the accumulation of organic matter through the humification of plant residues and (ii) organic compounds released from, e.g., roots during crop growth [18]. The potential to store carbon in the soil is tremendous, as most soils have the ability to store higher amounts than they do today [19]. However, differences in the degree of stabilization of carbon in the soil have been noted for above- and belowground biomass, where root biomass contributed three times more carbon to the pools than shoot [20]. Also, a higher stabilization degree was found for clay-rich soils (>40% clay), especially for the aboveground biomass and with increasing soil clay content [21].

Currently, crops such as cereals are known to contribute about 20–30% of the assimilated carbon to soil organic matter [18]. Based on the above, plant breeding activities to increase SOC are then related either to an increase in root and straw (for cereals) biomass to result in the addition of plant residues after harvesting or to exploring genetic differences in the release of organic compounds during plant growth. Until now, breeding activities for such characters have been basically lacking.

4. Opportunities to Breed for Nutrient Use Efficiency in Agricultural Crops

Increased NUE has not been considered a major breeding goal for agricultural crops, although some research and breeding activities have been carried out [22][23]. However, studies have also shown that the standardized selection of traits with a primary focus on yield has contributed to the loss of genes responsible for other characters such as efficient nutrient acquisition and adaptation to soil-related biotic and abiotic stresses [24]. Furthermore, old wheat cultivars, i.e., those developed before 1950, were shown to have superior mycorrhizal symbiosis, resulting in higher yields at low P availability and in acidic soils compared to modern varieties grown in similar conditions [25][26][27]. Previous studies have shown large genetic variation in phosphorus use efficiency (PUE) in wheat genotypes, which is largely related to their root architecture [28]. A recent meta-analysis has shown that mycorrhizal symbiosis can benefit the growth and yield of agriculturally significant crops by increasing phosphorus acquisition in plants [29]. However, to improve PUE in wheat, future breeding programs should include efficient screening/phenotyping for high PUE in different genotypes, identification of QTLs and genes responsible for specific root architecture for mycorrhizal symbiotic interactions, and marker-assisted selection of those specific traits [30].

The work on NUE has until now mainly focused on increasing yield and production per area [13], while reducing climate change effects has not been a major breeding target. NUE is known as a complex trait that is the result of a range of physiological characteristics [22]. Thus, the focus on breeding needs to be on a combination of effects from N regimes, genotypes, and several developmental stage traits of the plants [13]. Some of the more important characters are related to the uptake, transport, and transfer of N in the plant. The fast development of new methods allowing the determination and high-throughput screening of quantitative trait loci (QTLs) and major and minor genes involved in complex traits opens an avenue for breeding on NUE and other similar characters [22]. The fact that NUE is also related to yield would make this an important breeding objective for the future, also connecting it to climate change mitigation.

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