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CULTIVATING SUSTAINABILITY: BREEDING PERENNIAL GRAINS FOR A SUSTAINABLE AGRICULTURAL FUTURE

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Presently, perennial grain crops are not grown at large scale, mainly due to their early stages of domestication and current low yields. Perennial grains are a type of grain crop that differs from traditional annual grains, such as wheat, rice and corn in their growth and reproduction patterns as well as production capacity. Although still in the early stages of development, researchers and agriculturalists are working to breed and establish perennial versions of major grain crops to unlock their potential benefits.

Need for Perennials

While annual grains complete their life cycle within one growing season, perennial grains can live for multiple years, regrowing each year without the need for replanting. They continue to produce grains season after season, making them a promising option for sustainable agriculture and food security. Currently, discussions on breeding strategies for perennial grains have focused on distributing photosynthetic resources between seeds and vegetative structures. Nevertheless, as perennials are cultivated in more diverse agro-ecosystems, they will demand a wide range of traits that differ significantly from those typically addressed by annual crop breeders. While it might be feasible to expand food production to feed the projected 10 billion population by 2050, relying on agricultural methods that deplete soil and exhaust non-renewable resources could jeopardize the earth's ability to sustain sufficient food production in the 22nd century.

Key Characteristics of Perennial Grain Crop

Deep Root Systems: Perennial grains invest more energy in developing deep root systems, enabling them to access water and nutrients deeper in the soil profile. This adaptation makes them more drought-resistant and less reliant on irrigation.

Reduced Soil Erosion and weed suppression: The continuous growth and coverage of perennial grains help stabilize the soil, reducing erosion and nutrient runoff. This can contribute to soil health and conservation.

Enhanced Biodiversity: Perennial grain systems promote greater biodiversity compared to monoculture annual crops. The perennial growth habit provides a habitat for diverse plant and animal species.

Crop Resilience: Perennial grains have the potential to be more resilient to climate variability and extreme weather events compared to annual crops. Their deep root systems allow them to access water and nutrients from deeper soil layers, making them more tolerant of drought and better equipped to withstand fluctuations in rainfall patterns.

Soil Health and Nutrient Cycling: The extensive root systems of perennial grains increase organic matter in the soil, which improves soil fertility, nutrient cycling and carbon sequestration. This can contribute to sustainable agriculture and help mitigate climate change by reducing greenhouse gas emissions.

Reduced Chemical Inputs: With their deeper roots and persistent growth, perennial grains generally require fewer fertilizers and pesticides compared to annual crops.

Enhance pollinators: Perennial plants have the ability to produce more habitat for pollinators and extend the food resources for all beneficial insects.

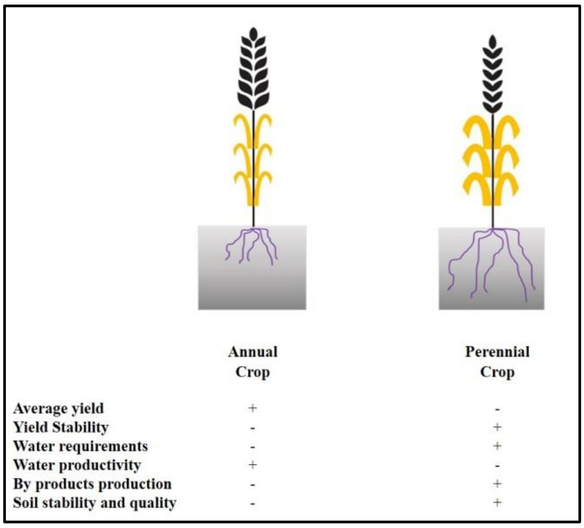

Fig. 1. Comparative diagram of perennial and annual crop characteristics and requirements

Breeding Determinants for Perennial Grains

1. Grain yield (seed size, seed weight, floret fertility, head weight)
2. Growing season
3. Plant architecture (Plant height, moderate tillering, erect leaves)
4. High regrowth ability, minimal shattering and low seed dormancy
5. Heading time, resistance to biotic and abiotic stress, food quality and nutrient use efficiency.

Major Approaches and Progress in Introducing Perennialism into Annual Grain Crops

- **Wide Hybridization:** Fortunately, the introduction of perennial characteristics into annual grain crops has seen significant achievements through wide hybridization. By crossbreeding perennial species with closely related annual crops, we can able to incorporate domestication genes much more rapidly compared to the methods used by our ancestors. Successful attempts have been made to combine the desirable traits of perennials with the high-yielding capabilities of annuals, with rice being the most advanced example. Perennial rice for instance, was created by hybridizing annual rice (*Oryza sativa* ssp. indica) with the rhizomatous perennial relative, *O. longistaminata* (Sacks *et al.*, 2003). Through backcrossing with annual rice and subsequent breeding, we now have perennial rice cultivars that offer grain yields comparable to annual rice while persisting for eight harvests. Nevertheless, challenges remain, such as ensuring the stability of the perennial trait, maintaining fertility among progeny and preserving perennialism while developing high-yielding lines. Similar efforts are being made for perennial grain sorghum, which involves hybridizing annual grain sorghum (*S. bicolor*) with perennial *S. halepense*. While hybrid progeny might struggle in cold temperate climates, it is feasible to produce high-yielding perennial varieties in warmer conditions. Other perennial grains, like rye (Daly *et al.*, 2022) and perennial wheat, are also under development through wide hybridization, with ongoing work to enhance perennial survival and genetic stability. Additionally, the breeding of perennials necessitates extended phenotyping over multiple seasons to assess yield stability and long-term climate resilience, which stands in sharp contrast to annual crops.
- **Domestication of Existing Grain Crops:** Another approach to achieving perennial grain crops is through the accelerated domestication of existing, low-yielding

perennial grain species (Osterberg *et al.,* 2017). This strategy mirrors the historical domestication process of annuals, where major domestication genes were repeatedly selected and breeding improvements were made over several years. These "domestication genes" play a crucial role in enhancing primary and harvestable grain yield for farmers, as well as regulating plant structure, dormancy and spike morphology, which includes traits like threshability, harvestability and lodging resistance. Plant breeding has been utilized to increase the productive capacity of perennial species, coupled with agronomic practice optimization. For example, wheatgrass (*T. intermedium*), traditionally used for forage purposes, is now undergoing de novo domestication to serve as a perennial grain crop. Nevertheless, this process comes with challenges, such as achieving chromosomal stability and perenniality while preserving the domestication traits. The direct domestication of wild perennial species offers the advantage of retaining perenniality but requires considerable time to enhance traits like shattering resistance, threshing ability, seed size, grain yield and other domestication-related characteristics.

- **Induced Random Mutagenesis**

To unlock the potential of perennial grains, it is essential to introduce beneficial alleles for these traits, be they naturally occurring, induced or edited (DeHaan *et al.*, 2020). Based on reverse genetic techniques, such beneficial genetic variants (induced mutant) can be identified using the recently developed method FIND-IT (fast identification of nucleotide variants by digital PCR) (Knudsen *et al.*, 2021).

In 2009, The Land Institute developed Kernza perennial grain, the first commercially available and economically viable perennial grain crop. It is a domesticated version of wild intermediate wheatgrass (*Thinopyrum intermedium*) and can be used as a substitute for annual wheat.

In perennial systems, intra and interspecific diversity must be deployed in space, through polycultures, for effective pest regulation and to increase stand structural complexity and floristic diversity which are associated with significant environmental benefits. Incorporation of perennial grains into polycultures may be additionally through increasing soil carbon sequestration (Sprunger *et al.*, 2020). Therefore, a future research could be aiming on the identification of leguminous perennial species for intercropping with perennial grains to gain maximal environmental benefit, and, potentially, greater economic return through delivering two harvestable crops for human consumption as well as animal feed and other industrial purpose (Schlautman *et al.*, 2018).

Conclusion

Perennial grains can revolutionize agriculture with sustainable and eco-friendly alternatives to annual crops. Early-stage development shows promise in improving soil health, conserving resources and increasing agricultural resilience. Continued research, breeding and market efforts are vital for widespread adoption, creating more sustainable food systems. However, significant R&D investment and time are needed to achieve sufficient yield potential for mainstream use beyond niche health food markets. High seed yields are crucial for successful adoption and while challenges like nutrient supply and pest management can be overcome, achieving high-yielding perennial grains remains the primary focus.

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