AgriScope
Monthly e-Magazine on Agriculture and Interdisciplinary Sciences
Visit at us: www.agriscope.in
Email at us: agri4scope@gmail.com
ISSN: 3139-6488

Can We Breed Crops to Store More Carbon?

Abhirami Biju, Govindaraj Kamalam Dinesh
College of Agriculture, Iroisemba, Central Agricultural University, Imphal, Manipur, India
Correspondence: gkdineshiari@gmail.com

Article ID: 21001

Abstract

Crop breeding has traditionally prioritised yield, quality, stress tolerance and resistance to biotic and abiotic stresses. Increasing evidence suggests that genetic improvement could also contribute to climate mitigation by modifying traits that regulate plant carbon acquisition, allocation and transfer to soil. This article examines whether crops can be bred to enhance carbon inputs to agricultural soils while maintaining productivity and resilience. Particular attention is given to root biomass, root architecture, rooting depth, rhizodeposition, carbon allocation and plant–microbe interactions as potential breeding targets. Recent evidence indicates substantial genetic variation in root traits and suggests that genotype selection can increase root-derived carbon inputs without necessarily reducing yield. Advances in quantitative genetics, genome-wide association studies, genomic selection and high-throughput root phenotyping provide opportunities to integrate these traits into crop improvement programmes. However, greater biomass or root carbon input does not automatically result in persistent soil organic carbon (SOC) sequestration because the fate of plant-derived carbon is regulated by decomposition, microbial transformation, soil properties, aggregation and environmental conditions. Therefore, carbon-oriented breeding requires multi-environment field evaluation that links genotype, root traits, carbon inputs and changes in soil carbon stocks over time. The emerging concept of "high-carbon crops" provides a framework for integrating productivity, climate resilience, resource-use efficiency and carbon-related traits within breeding objectives. Carbon-smart crops could complement agronomic practices such as residue retention, diversified rotations and cover cropping, but their climate benefits must be demonstrated through appropriate measurement, reporting and verification. Breeding crops for greater and more persistent soil-carbon inputs is therefore a promising research direction, but remains an emerging frontier rather than an established pathway for agricultural carbon sequestration.

Introduction

Crop improvement has traditionally focused on increasing yield, improving grain quality, enhancing resistance to pests and diseases, and developing varieties capable of performing under drought, heat, salinity and other environmental stresses. However, climate change is creating a

new challenge for plant breeders: can crops be developed not only to produce more food but also to contribute to atmospheric carbon dioxide (CO_2) removal and soil carbon storage?

Plants naturally capture atmospheric CO_2 through photosynthesis and convert it into organic carbon. Overtime this carbon is distributed in plant parts such as leaves, stem, grains and roots. A portion of the carbon returned to agricultural soils through roots, root exudates and crop residues may contribute to soil organic carbon (SOC). However, not all carbon captured by a crop becomes long-term soil carbon. Some is rapidly decomposed and returned to the atmosphere.

This distinction has opened an emerging research area at the intersection of genetics, plant breeding and soil science. If genetic variation among crop varieties affects biomass production, root growth, carbon allocation and rhizosphere interactions, then it may be possible for breeders to select genotypes with traits that enhance carbon inputs to soil without compromising crop productivity.

Recent studies indicate that genetic improvement has already affected carbon inputs for some major crops and that root traits are an important but underexploited avenue for future breeding (Poffenbarger et al., 2023). The question, therefore, is not simply whether crops can capture more carbon, but whether breeders can develop **carbon-smart crops that combine productivity with greater and more persistent carbon inputs to soil**.

From Carbon Fixation to Carbon Sequestration

The basic pathway through which crops interact with the carbon cycle can be represented as in the **Fig.1**

AgriScope
Monthly e-Magazine on Agriculture and Interdisciplinary Sciences
Visit at us: www.agriscope.in
Email at us: agri4scope@gmail.com
ISSN: 3139-6488

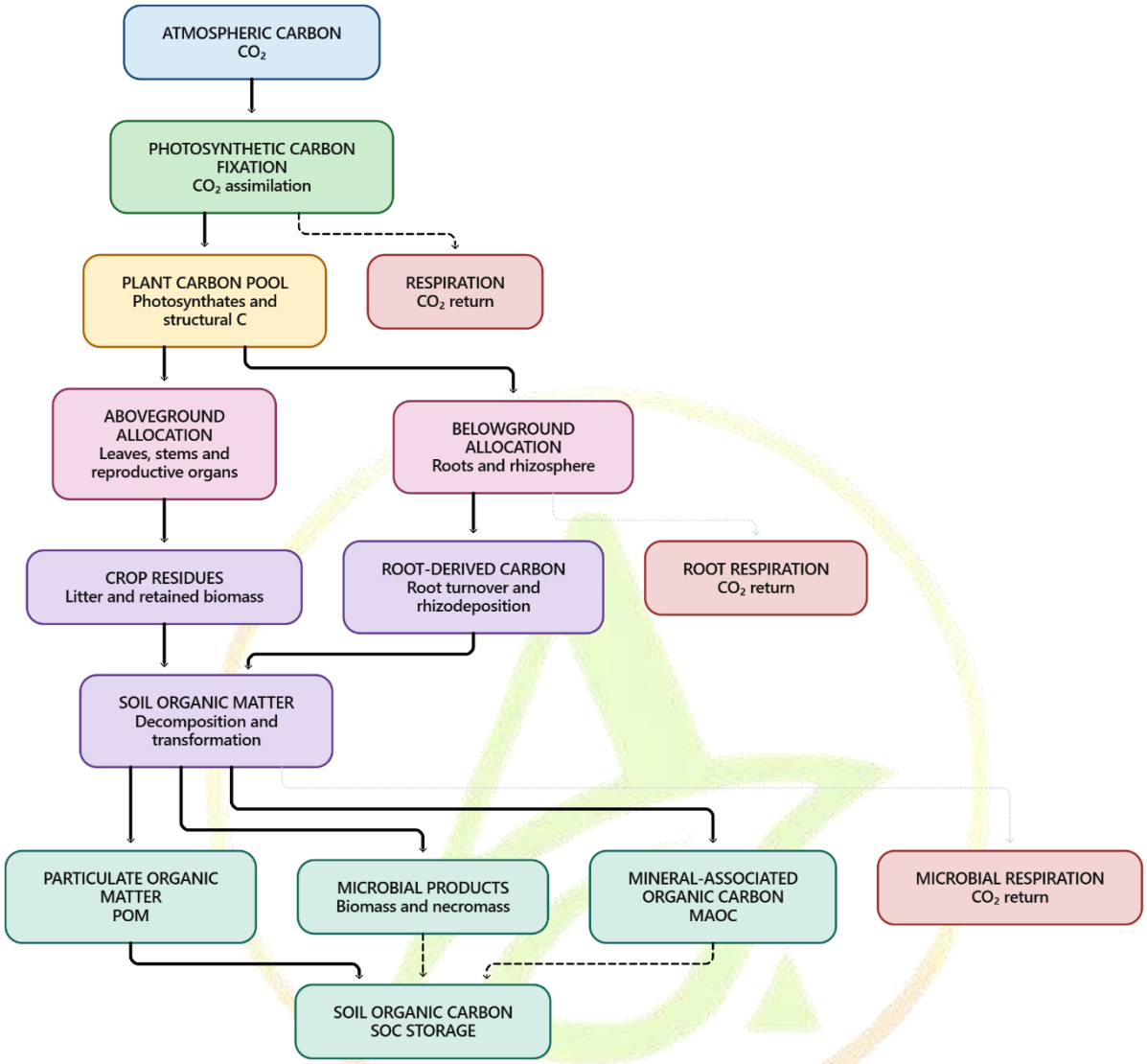


Figure 1. Conceptual pathway of plant-derived carbon from atmospheric CO_2 fixation to soil organic carbon storage

Photosynthesis is the primary process through which atmospheric CO_2 enters plant biomass. During crop growth, carbon is allocated to different plant organs according to genotype, developmental stage and environmental conditions. At harvest, a substantial proportion of aboveground carbon may leave the field as grain, whereas roots, root-derived compounds and retained residues remain important pathways for carbon return to soil.

It is important to distinguish carbon fixation, carbon storage and carbon sequestration. Carbon fixation refers to the incorporation of atmospheric CO_2 into organic compounds through photosynthesis. Carbon storage refers to carbon retained within a biological or soil pool at a particular point in time. Carbon sequestration is any net increase of carbon inside reservoir over time. As a result, a higher biomass crop does not necessarily mean higher long-term carbon

sequestration. The persistence of plant-derived carbon depends on decomposition, microbial transformation, soil aggregation, mineral interactions and environmental conditions. For plant breeders, this means that increasing biomass alone may be an insufficient objective. The more relevant question is how a genotype captures, allocates and transfers carbon into soil pools.

Where Genetics Enters the Carbon Equation

Genetic variation occurs in many traits that influence crop carbon acquisition and allocation. Crop genotypes can differ in photosynthetic characteristics, biomass production, phenology, root-to-shoot ratio, root architecture, nutrient-use efficiency and water-use efficiency. Root traits are particularly interesting because they have traditionally received less attention in breeding than aboveground traits. Root systems are important for water and nutrient uptake, soil exploration, plant anchorage and interactions with soil microbes. Thus, genetic variability in root provides an opportunity to incorporate belowground traits in crop improvement programmes (Mathew and Shimelis, 2022).

A particularly relevant review by Heinemann et al. (2023) brought together data from 13 international field studies involving winter wheat, spring wheat, silage maize, winter rapeseed and sunflower. Across the studies, systematic genotype selection increased mean root biomass by 22%. The authors estimated that median root-carbon inputs could potentially be increased by 6.7% in spring wheat, 6.8% in winter rapeseed, 12.2% in silage maize, 21.6% in winter wheat and 26.4% in sunflower without reducing yield. These findings do not demonstrate that all high-root-biomass varieties will increase long-term SOC. However, they provide an important breeding message: there is exploitable genetic variation in root biomass, and root traits can potentially be selected alongside yield (Heinemann et al., 2023).

Why Roots Could Be the Hidden Carbon Opportunity

The most interesting opportunity for carbon-oriented breeding may lie belowground. Roots transfer carbon into soil through several pathways, including root biomass, root turnover and rhizodeposition. Root-derived compounds can subsequently be transformed by microorganisms and incorporated into different soil organic matter pools. Root depth may also be important. Carbon deposited deeper in the soil profile can encounter different physical, chemical and biological environments from those near the surface. Consequently, breeding for deeper or differently distributed root systems has been proposed as one possible pathway for increasing the efficiency of soil carbon storage.

A 2024 study by Cotrufo et al. investigated whether encouraging deeper rooting in maize could sequester additional soil carbon. They conducted a two-year field experiment with isotopically labelled maize roots and exudates, they tracked the formation of new SOC to a depth of 90 cm. The result showed that root decomposition and root exudates contributed differently to soil organic matter formation. Through modelling, they estimated that shifting root inputs deeper or increasing root allocation could yield SOC gains on the order of 0.05-0.15 Mg C ha^{-1} yr^{-1} under the scenarios considered. Importantly, they concluded that the per-hectare impact for maize is relatively modest compared with some management-based strategies, although the extensive global maize area means modest effects could become meaningful at scale (Cotrufo et al., 2024).

This represents an important scientific lesson. **Deep roots may contribute to carbon sequestration, but the magnitude of the effect must be quantified rather than assumed.**

Can Modern Breeding Technologies Find Carbon-Smart Genotypes?

Traditional breeding depends on phenotypic selection within genetically varied populations. Modern plant breeding adds tools for detecting and choosing complex characteristics.

Quantitative trait locus (QTL) analysis and genome-wide association studies (GWAS) can identify genomic regions associated with root architecture and other physiological traits. Marker-assisted selection can assist the transfer of favourable alleles, while genomic selection can potentially predict breeding values using genome-wide molecular information.

However, genomic technologies are only useful when the phenotype is measurable. Root traits remain difficult to quantify at the scale required for breeding programmes. Root excavation, soil coring, imaging, hydroponic systems, rhizotrons, digital phenotyping and other approaches are therefore increasingly important.

Mathew and Shimelis (2022) emphasized that combining root phenotyping with genomic tools is essential for developing crop varieties with desirable root systems. They also emphasized that root traits have historically been underused because of difficulties in measurement and incomplete understanding of their genetic control.

For carbon-oriented breeding, this suggests a future pipeline in the **Fig. 2.**

AgriScope
Monthly e-Magazine on Agriculture and Interdisciplinary Sciences
Visit at us: www.agriscope.in
Email at us: agri4scope@gmail.com
ISSN: 3139-6488

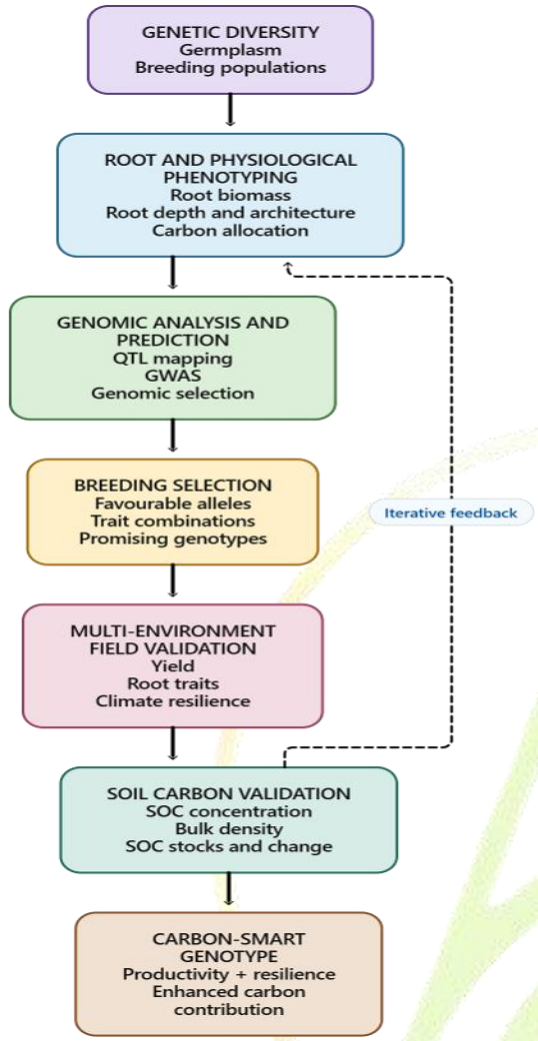


Figure 2. Conceptual framework for integrating genetic improvement with carbon-related crop traits and soil carbon assessment

Such an approach would allow carbon-related traits to be evaluated together with yield, disease resistance and climate resilience rather than as isolated breeding objectives.

The Plant-Microbe Connection

Carbon entering soil does not remain biologically unchanged. Roots interact continuously with bacteria, fungi and other soil organisms. Microbial activity influences the stabilization and transformation of plant derived organic matter, with root exudates serving as carbon substrates for microorganisms. Therefore, genotype can affect soil carbon indirectly through changes in root traits and plant-microbe interactions. This constitutes an important research frontier:

Genotype × Root traits × Microbiome × Soil × Environment

Plant breeders have traditionally selected plants based mainly on plant performance. but, future breeding may increasingly take into account how plant traits affect the rhizosphere and soil

biological processes. The scientific challenge is that plant-microbe interactions are strongly influenced by soil type, climate, management and microbial community composition. Therefore, selecting a genotype for a particular microbial association does not necessarily guarantee the same outcome across different environments. The microbiome should consequently be viewed as an important component of the carbon system, but not yet as a simple breeding target with predictable outcomes.

More Biomass Does Not Necessarily Mean More Carbon Sequestration

One of the biggest misconceptions in carbon-oriented agriculture is that increasing plant biomass automatically increases long-term carbon sequestration. The relationship is considerably more complex. A genotype with greater shoot biomass may return more residue to soil, but that residue may decompose rapidly. Similarly, greater root biomass may increase carbon inputs but does not guarantee that the carbon will remain in soil for long periods.

There may also be trade-offs between root growth and reproductive allocation. Carbon invested in roots is carbon that is not simultaneously available for other plant functions. Breeding must therefore seek an appropriate balance between grain production, root development, stress adaptation and carbon allocation. Poffenbarger et al. (2023) found that historical breeding has already changed aboveground residue carbon inputs in crops like maize and soybean, while the effects on root-to-shoot ratios have tended to be smaller or less consistent. They identified root depth, suberin content, rhizodeposition and mycorrhizal association as potential targets for improving the stabilization of crop-derived carbon. This leads to a crucial principle: The goal should not be to breed the crop with the largest biomass, but to breed the crop with the most favourable combination of productivity, resilience, carbon allocation and carbon retention.

How Would We Know Whether a Crop Stores More Carbon?

A carbon-smart genotype cannot be evaluated only by measuring plant height, biomass or root mass. Field experiments need to assess both plant traits and changes in soil carbon. Relevant measurements may include aboveground biomass, root biomass, root distribution, crop residues, soil organic carbon concentration, soil bulk density and soil carbon stocks. The depth of soil sampling is also important. Carbon changes occurring in surface soil may differ from those occurring at depth. Repeated measurements are therefore necessary to determine whether an apparent increase represents persistent accumulation or simply a temporary change in carbon pools. This creates an important distinction between carbon-input traits and actual soil-carbon outcomes.

A genotype may have more roots and produce greater carbon inputs, but the ultimate effect on SOC depends on what happens to those inputs after they enter the soil. Consequently, long-term and multi-environment field trials will be essential before carbon-related traits can become reliable breeding objectives.

From Carbon-Smart Crops to Carbon Credits

Another distinction is necessary between carbon-sequestration potential and carbon credits. A crop variety with deeper roots or greater root biomass does not automatically generate a carbon credit. Carbon-credit systems require quantification of additional carbon removal or avoided emissions under a defined methodology, including appropriate baseline determination, measurement, reporting, verification and treatment of uncertainty. Plant breeding can potentially create biological capacity for greater carbon storage, but this capacity must be demonstrated under actual management conditions before it can be considered a measurable climate benefit. This distinction will become increasingly important as agricultural carbon markets expand. A scientifically credible carbon strategy must therefore connect genetics with field measurements and robust measurement, reporting and verification (MRV).

Towards "High-Carbon" Crops

The idea of breeding specifically for carbon-related characteristics is now moving from a conceptual possibility towards a defined research agenda. A recent perspective proposed the concept of "high-carbon crops": cultivars designed to combine high productivity with enhanced soil-carbon inputs and stabilization. The proposed framework includes aboveground characteristics such as photosynthetic efficiency and carbon partitioning together with belowground traits such as root size, root architecture, exudation and biochemical composition. The concept is important because it does not propose replacing yield breeding with carbon breeding. Instead, it proposes integrating the two objectives. Future breeding programmes could therefore consider a broader selection index:

Yield + Climate resilience + Resource-use efficiency + Root traits + Carbon contribution

Such an approach would also allow carbon-oriented varieties to be combined with improved agronomic management, including residue retention, cover crops, diversified rotations and appropriate nutrient management. The strongest carbon benefit is therefore unlikely to come from genetics alone. It is more likely to emerge from the interaction of genotype, soil, climate and management.

Conclusion

Can we breed crops to store more carbon?

The evidence suggests that we can potentially breed crops with traits that increase carbon inputs to soil, but breeding for durable soil-carbon sequestration remains an emerging scientific frontier. Genetic variation in root biomass, root architecture, carbon allocation and other physiological traits provides opportunities for developing crops with greater belowground carbon inputs. Modern genomic tools and high-throughput phenotyping may further improve the ability of breeders to identify and select these characteristics.

However, greater root biomass or plant biomass should not automatically be interpreted as greater long-term carbon sequestration. The fate of plant-derived carbon depends on decomposition, microbial transformation, soil properties, environmental conditions and agricultural management.

The future objective should therefore be the development of carbon-smart crops: crops capable of maintaining high productivity while efficiently capturing atmospheric carbon, allocating an appropriate proportion belowground and contributing to persistent soil-carbon pools. The next generation of crop improvement may consequently be evaluated by a broader question than "How much grain can this genotype produce?"

It may also need to ask:

"How efficiently can this crop produce food while contributing to a healthier and more carbon-rich soil?"

References

Cotrufo, M. F., Haddix, M. L., Mullen, J. L., Zhang, Y. and McKay, J. K. 2024. Deepening root inputs: Potential soil carbon accrual from breeding for deeper rooted maize. *Global Change Biology* 30: e17591. https://doi.org/10.1111/gcb.17591.

Heinemann, H., Hirte, J., Seidel, F. and Don, A. 2023. Increasing root biomass derived carbon input to agricultural soils by genotype selection - a review. *Plant and Soil* 490: 19-30. https://doi.org/10.1007/s11104-023-06068-6.

Mathew, I. and Shimelis, H. 2022. Genetic analyses of root traits: Implications for environmental adaptation and new variety development: A review. *Plant Breeding* 141(6): 695-718. https://doi.org/10.1111/pbr.13049.

Poffenbarger, H., Castellano, M., Egli, D., Jaconi, A. and Moore, V. 2023. Contributions of plant breeding to soil carbon storage: Retrospect and prospects. *Crop Science* 63: 990-1018. https://doi.org/10.1002/csc2.20920.

Srivastava, R. K. and Yetgin, A. 2024. An overall review on influence of root architecture on soil carbon sequestration potential. *Theoretical and Experimental Plant Physiology* 36: 165-178. https://doi.org/10.1007/s40626-024-00323-6

Breeding for high-carbon crops to achieve dual purposes of food security and carbon neutrality. 2026. *Crop and Environment* 5(2): 100115. https://doi.org/10.1016/j.crope.2025.100115.