

Ancient Seeds vs Hybrid Seeds: Their Differential Impacts on Soil Carbon

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ABSTRACT

Soil organic carbon (SOC) is a principal regulator of soil fertility and one of the largest terrestrial carbon pools. This popular article reviews how 'ancient' seeds (traditional landraces and locally adapted varieties) and modern hybrid seeds influence SOC through differences in root architecture, biomass allocation, phenology and management practices. Evidence indicates that genotype-driven differences particularly root biomass and rhizosphere interactions can alter carbon inputs to soil (Heinemann *et al.*, 2023; Junaidi *et al.*, 2018). However, effects of seed type cannot be divorced from cropping systems, management (tillage, residue return, fertilization) and environment, which which Paustian *et al.* (1997, 2016) and Sanderman *et al.* (2010) identify as the primary controls on SOC. The

article synthesizes empirical studies and outlines research and policy implications for breeding and carbon-smart agriculture.

INTRODUCTION

Soil organic carbon (SOC) underpins soil health, crop productivity and climate mitigation potential. The balance between carbon inputs (plant residues, roots, exudates) and outputs (decomposition, erosion) determines SOC stocks. Classic reviews by Paustian *et al.* (1997) and Sanderman, Farquharson & Baldock (2010) emphasize that Management and land use are dominant controls on SOC, but growing evidence suggests the genetic identity of crops whether they are ancient landraces or modern hybrids also plays a measurable role via root traits and rhizosphere effects. Anthropogenic greenhouse gas (GHG) emissions, particularly carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) are primary drivers of contemporary climate change. Among these gases, CO₂ accounts for approximately 65 per cent of total global emissions (Rodas-Zuluaga *et al.*, 2021; Rogelj *et al.*, 2018). The continued rise in atmospheric CO₂ concentration has led to an increase in global mean temperature, thereby accelerating climate change. Currently, global food demand is projected to rise by 25-70 per cent by 2050, necessitating substantial improvements in agricultural productivity, defined as biomass production per unit time (e.g., per year for annual crops). However, the natural resources underpinning agricultural systems are soil, water and biodiversity are increasingly constrained and degraded under changing climatic conditions. Humanity therefore faces the dual challenge of ensuring food security for an estimated 9-10 billion people by mid-century while simultaneously mitigating climate change (Godfray *et al.*, 2010). To date, relatively few studies have examined the interactions between agronomic productivity

and pedological processes in this context (Smith *et al.*, 2014).

Certain agricultural practices are recognized for their capacity to enhance soil carbon (C) sequestration. These include practices that incorporate substantial biomass inputs, minimize soil disturbance, conserve soil and water, improve soil structure, promote soil fauna diversity, and strengthen nutrient cycling mechanisms. Nevertheless, mitigation-oriented strategies such as agroforestry systems or reductions in synthetic chemical inputs may generate unintended trade-offs. For example, tree crop competition in agroforestry systems can reduce grain yield, while lower chemical inputs may limit nutrient availability (Smith *et al.*, 2014). Thus, achieving simultaneous enhancement of soil carbon storage and high crop productivity may appear paradoxical.

Soil carbon sequestration fundamentally depends on the stabilization of organic matter (OM) through mechanisms such as aggregate formation and organo-mineral associations. Stabilization implies that a substantial fraction of organic inputs escapes mineralization. Conversely, in low-input agricultural systems, sustaining high grain yields requires sufficient mineralization of OM to ensure nutrient release and plant availability. Soil fertility also relies on relatively stable OM fractions that contribute to cation exchange capacity and soil water retention (Arenas-Calle *et al.* 2021). These contrasting processes suggest the potential existence of a trade-off between carbon sequestration and grain yield, particularly in low-input systems.

One potential strategy to reconcile this trade-off is to modify the relative proportions of soil carbon pools with differing turnover rates,

thereby enhancing long-term stabilization while maintaining adequate mineralization for nutrient supply (Enebe *et al.*, 2025). Agricultural practices such as no-tillage and straw incorporation have demonstrated the capacity to increase soil carbon stocks without compromising grain yields.

An additional but comparatively underexplored approach to soil carbon management is the selection of cultivated varieties. Crop genetic diversity encompasses a wide-range of traits influencing both productivity and carbon inputs, particularly root biomass and shoot-to-root ratios. For instance, wheat typically produces 15-20 t ha⁻¹ of total biomass, distributed approximately as 50% grain, 30% roots and 20% straw (Arvalis, 2019). Post-harvest, straw may be either removed or incorporated into the soil, whereas root biomass remains in situ. Across various soil types, 7.5-10 t ha⁻¹ of combined straw and root residues can contribute approximately 1.1-1.5 t ha⁻¹ of stabilized organic matter, corresponding to 450-600 kg C ha⁻¹ (equivalent to 1,650-2,200 kg CO₂ eq ha⁻¹) (Arvalis, 2019). Because root-derived carbon generally exhibits slower mineralization rates than aboveground residues, root systems represent a critical component of soil carbon dynamics. Notably, approximately 50% of soil carbon stocks are located below 0.3 m depth (Balesdent *et al.*, 2018), suggesting that deeper root systems may provide enhanced opportunities for long-term carbon sequestration.

Within wheat germplasm, farmers can select between ancient and modern varieties, hereafter referred to as distinct “breeding types.” Several studies indicate that ancient varieties tend to develop deeper root systems and produce greater root biomass than modern varieties under controlled conditions (Pour-Aboughadareh *et al.*, 2017). Differences in tissue composition and root architectural traits (Beyer *et al.*, 2019; Junaidi *et al.*, 2018)

between breeding types may also influence decomposition dynamics. Specifically, ancient varieties may exhibit greater biochemical recalcitrance or structural characteristics that reduce microbial accessibility, thereby slowing mineralization. Moreover, differences in root exudation profiles (Beyer *et al.*, 2019; Junaidi *et al.*, 2018) may shape rhizosphere microbial communities, potentially affecting carbon stabilization processes.

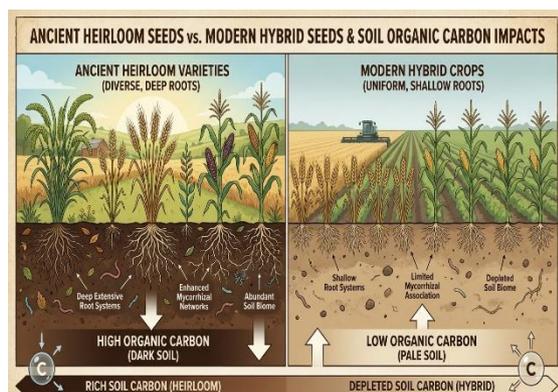
Because the effects of agricultural practices on soil carbon storage and grain yield are highly context-dependent (Shang *et al.*, 2021), evaluating the potential of selecting ancient versus modern wheat varieties requires consideration of environmental variability. Several soil properties are particularly relevant to root-derived carbon mineralization. Soil texture influences water retention and the physical protection of organic matter through adsorption onto mineral surfaces (Baldock, 2007). Soil structure affects organic matter stabilization through aggregation, as well as water movement, pore connectivity and compaction (Balabane & Plante, 2004). Soil pH regulates acid-base equilibrium and microbial activity while soil depth determines the volumetric capacity for carbon storage (Jobbagy & Jackson, 2000).

In this article, we therefore mentioned grain yield and root organic matter mineralization across contrasting pedological contexts under similar climatic conditions. The objective was to assess whether varietal selection specifically the choice between ancient and modern wheat breeding types can serve as a viable strategy to simultaneously optimize grain production and enhance soil organic matter stabilization.

What is mean by 'ancient' and 'hybrid' seeds

For clarity, 'ancient' seeds in this article denotes traditional landraces and locally adapted varieties that have evolved under

farmer selection or natural selection over centuries. 'Hybrid' seeds refer to modern, breed hybrid cultivars selected for yield, uniformity and specific agronomic traits. Landraces often retain high genetic diversity, which can manifest in diverse root architectures and phenologies (Lazaridi, 2024). Hybrids are optimized for aboveground yield and may trade off belowground allocation in some contexts, although this is not a universal rule.



Mechanisms linking seed genetics to soil carbon

Three biological mechanisms explain how seed genetics can influence SOC:

1. Root biomass and architecture

Root inputs (biomass and exudates) are major contributors to SOC. Genotype differences in root biomass and argued that selecting for higher root C input is a promising route to increase SOC. Genotypes differ (Junaidi *et al.*, 2018) substantially in root: shoot ratios and root length, that mediate carbon transfer to soil.

2. Rhizosphere interactions

Landrace genotypes can support distinct microbial communities and mycorrhizal associations, with downstream effects on carbon stabilization (Gleridou *et al.*, 2023). Seed origin can influence rhizosphere composition, which affects decomposition rates and particulate vs. mineral-

associated organic carbon fractions.

3. Phenology and residue quality

Differences in timing of growth, root turnover and straw chemistry 'lignin: N' ratios alter decomposition dynamics and the residence time of carbon in soil. Older varieties may have slower decomposition-prone residues compared with high-yielding hybrids, depending on the crop and environment.

Evidence: what studies show

Direct comparisons of landraces and hybrids with a specific focus on SOC are still sparse, but several empirical lines of evidence are informative

- **Genotype and root-driven carbon input:** Heinemann *et al.* (2023) Compiled global data showing measurable differences in root biomass and potential root-derived carbon inputs across genotypes, suggesting breeding could increase soil C inputs without major management change.
- **Root traits alter soil C dynamics:** Junaidi *et al.* (2018) Wheat genotypes vary in root:shoot ratios and root length; genotypes with larger root systems tended to have traits associated with greater soil C inputs under identical management.
- **Landraces shape rhizosphere communities:** Gleridou *et al.* (2023) Lentil landrace seed origin influences rhizosphere microbiomes, which may modulate decomposition and C stabilization pathways.
- **System-level context matters:** Ren *et al.* (2020) and Paustian *et al.* (1997, 2016) Fertilizer use, tillage, cropping sequence and residue management overwhelmingly control SOC outcomes at landscape scales. Sanderman *et al.* (2010) concluded that technical potential exists; the

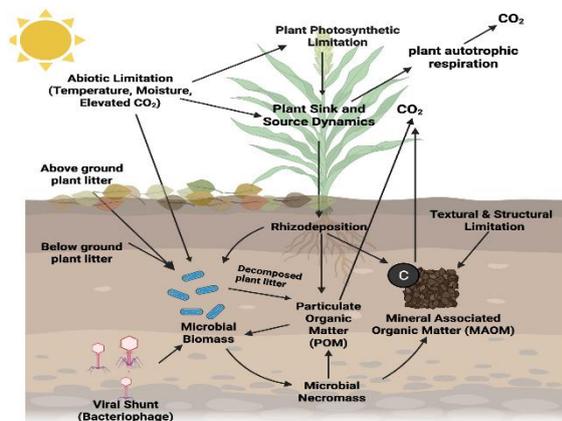
practical SOC gains achievable depend on management and soil mineralogy.

Hybrids - Benefits and Trade-offs for Soil Carbon

Modern hybrids deliver big yield gains (and often economic benefits for farmers), which can increase total aboveground and sometimes belowground biomass returned to soil if residues are retained. Sanderman and colleagues (2010) and subsequent note that yield increases can be compatible with SOC gains, particularly when accompanied by conservation practices. However, breeding emphasis on harvest index and aboveground harvestable biomass can in some cases reduce belowground allocation (i.e., smaller roots relative to shoots), potentially limiting root-derived C inputs (Heinemann *et al.*, 2023). The effect is genotype- and crop-specific: some hybrids maintain or even increase rooting depth and root biomass.

Ancient Seeds - resilience and carbon co-benefits

Landraces often show greater belowground allocation and plasticity under stress, which can translate to higher root-derived C inputs in marginal environments. They also tend to support greater microbial diversity in the rhizosphere (Lazaridi, 2024; Gleridou *et al.*,



2023), potentially enhancing soil aggregation and mineral-associated organic carbon formation. That said, absolute contributions to

SOC depend on the cropping system and how much residue is returned to the soil.

Synthesis - weighing genotype vs. system effects

Two clear messages emerge: 1) Genotype matters mechanistically via root traits and rhizosphere interactions. Reviews and meta-analyses (Heinemann *et al.*, 2023; Mathew, 2022) show realistic room for breeding to enhance root C inputs. 2) Management and land use remain dominant determinants of SOC stocks. Paustian *et al.* (1997, 2016), Sanderman *et al.* (2010) and Ren *et al.* (2020) emphasize that tillage, residue management, crop rotations and fertilization explain large fractions of SOC variability at the field and regional scale. Thus, seed choice alone is unlikely to deliver large SOC gains without complementary conservation practices.

Practical implications for farmers and breeders

For farmers: Choose varieties that fit a systems approach. If your goal includes building SOC, prioritize crops and varieties that foster root biomass, retain residues and fit rotations with cover crops and reduced tillage.

For breeders: Explicitly include root traits and rhizosphere indicators in breeding targets. Heinemann *et al.* (2023) argue Genotype selection can raise root C inputs, but breeders must balance yield goals and farmer adoption.

For policymakers: Incentivize integrated practices are cover cropping, residue retention, reduced tillage alongside support for breeding programs that target belowground carbon.

CONCLUSION

Ancient seeds (landraces) and hybrid seeds influence soil organic carbon through distinct, sometimes overlapping mechanisms.

Landraces can offer valuable root and rhizosphere traits conducive to carbon inputs and resilience, while hybrids provide yield advantages that when managed correctly can also support SOC. The strongest evidence indicates that seed genetics can contribute to SOC outcomes (Heinemann *et al.*, 2023; Junaidi *et al.*, 2018), but management choices remain the decisive factor at scale (Paustian *et al.*, 1997; Sanderman *et al.*, 2010; Ren *et al.*, 2020). A pragmatic path forward is integrated breed for beneficial belowground traits and pair variety choice with carbon-friendly management.

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