

Roots: The Hidden Foundation of Crop Productivity

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ABSTRACT

Roots are the hidden foundation of crop productivity, yet they have traditionally received less attention than the visible shoot. Root system architecture including rooting depth, growth angle, length, branching, diameter, root hairs and distribution, determines how effectively crops acquire water and nutrients, anchor themselves, interact with soil microorganisms and respond to drought, salinity, compaction and other stresses. The central role of roots in crop growth and climate-resilient agriculture. It explains how root traits influence drought avoidance, nutrient-use efficiency, rhizosphere activity, soil structure and crop establishment, with examples from rice, chickpea, maize and cereal crops. The article also discusses agronomic practices that support root development, including good establishment, reduced compaction, appropriate irrigation, balanced nutrition, residue management and suitable variety selection. Advances in root phenotyping and root-ideotype breeding are making it increasingly possible to select crops according to their below-ground performance. The central message is that productive agriculture requires a shift from managing only the visible canopy to managing the complete crop-soil system. Better roots

do not automatically guarantee higher yield, but crops cannot achieve their potential without root systems capable of efficiently supplying water and nutrients under changing environmental conditions.

INTRODUCTION:

When we look at a wheat, chickpea, maize or mustard field, our attention naturally goes towards the part of the plant that is visible above the soil. We observe the green leaves, plant height, branching, flowering and finally the grains or seeds. Farmers generally judge crop development by what they can see. Researchers have also traditionally devoted considerable attention to shoot traits because they are easier to measure. But beneath the same field lies another world that remains largely invisible. Roots may not be seen during routine crop observation, yet they determine how effectively a plant explores the soil for water and nutrients, anchors itself, interacts with microorganisms and responds to drought and other stresses. In simple terms, the visible crop is only half of the plant story; the other half is underground.

Modern agronomy is increasingly recognising that root characteristics are not merely secondary features. Root depth, angle, length, branching, diameter, root hairs and distribution through the soil can strongly influence crop resource acquisition and adaptation to environmental stress. Recent research has therefore placed root system architecture at the centre of discussions on sustainable crop production and climate resilience (Zhang *et al.*, 2025). This shift in thinking is important because agriculture is being asked to produce more food while facing declining water availability, soil degradation, rising temperatures and increasing pressure to use fertilizers and other inputs more efficiently. Many of these challenges ultimately begin in

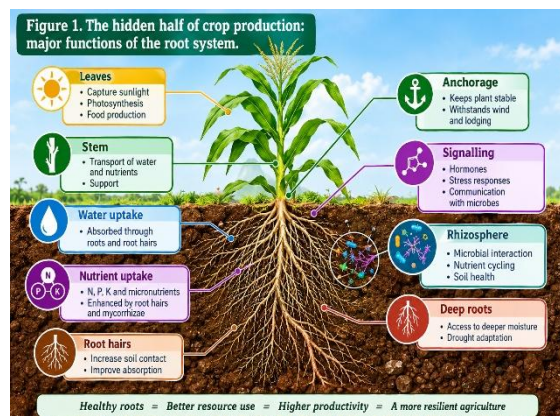
the soil and roots are the plant's main interface with that soil.

ROOTS ARE NOT SIMPLY UNDERGROUND PIPES

A common perception is that roots have only three jobs: holding the plant in the soil, absorbing water and taking up nutrients. These functions are certainly fundamental, but roots are much more dynamic than this simple description suggests. Roots continuously sense their surrounding environment. They encounter differences in moisture, oxygen, nutrient concentration, soil strength, temperature and microbial activity. In response, they modify their growth and architecture.

A root system is therefore not a fixed structure. It develops according to the interaction between genotype, soil conditions, water availability, nutrients and management practices. The spatial arrangement of roots is commonly described as root system architecture (RSA). It includes characteristics such as rooting depth, growth angle, root length, branching pattern, root diameter and the distribution of roots within different soil layers. This flexibility is one reason why two plants of the same crop growing in different fields can develop remarkably different root systems (Gusain *et al.*, 2024; Kalra *et al.*, 2024). A crop growing in a well-watered, loose soil may develop a different root system from the same crop exposed to drought or soil compaction. Similarly, nutrient-rich patches

can alter root proliferation, while hard soil layers can restrict penetration.



THE HIDDEN ENGINE OF CROP GROWTH

The root system acts as the plant's underground resource-acquisition network. It explores the soil and brings water and mineral nutrients into the plant. Water is particularly important because almost every physiological process associated with crop growth depends on adequate water supply. Roots absorb water from soil pores and transport it towards the shoot, where it supports photosynthesis, nutrient transport, cooling and cell expansion.

Nutrients also differ greatly in their movement through soil. Some nutrients are relatively mobile, whereas others move only short distances. Therefore, the ability of roots to explore an appropriate volume of soil becomes critical.

A root system with extensive lateral branching can explore more soil near the surface, whereas deeper roots can access water and nutrients from lower soil layers. Root hairs increase the effective contact between roots and soil particles and can improve nutrient and water acquisition. This is why root architecture must be viewed in relation to the environment. There is no single root system that is ideal for every crop, soil and climate (Lynch, 2013; Meister *et al.*, 2014).

For example, in a drought-prone environment, deeper rooting may allow a crop to access moisture that remains available below a drying surface layer. In contrast, in a shallow soil with limited depth, extensive deep rooting may provide little additional benefit. The most useful root system is therefore the one that matches the distribution of available resources (Richards, 2008; Wasson *et al.*, 2012; Zhang *et al.*, 2025).

DEEP ROOTS AND THE BATTLE AGAINST DROUGHT

Among all the functions of roots, their role in drought adaptation has attracted particular attention. As a crop grows, the upper layers of soil can lose water through evaporation and plant uptake. Rainfall or irrigation may temporarily replenish the surface, but during prolonged dry periods, deeper layers can retain useful moisture. A root system capable of reaching these layers may help a crop maintain water uptake when the surface becomes dry.

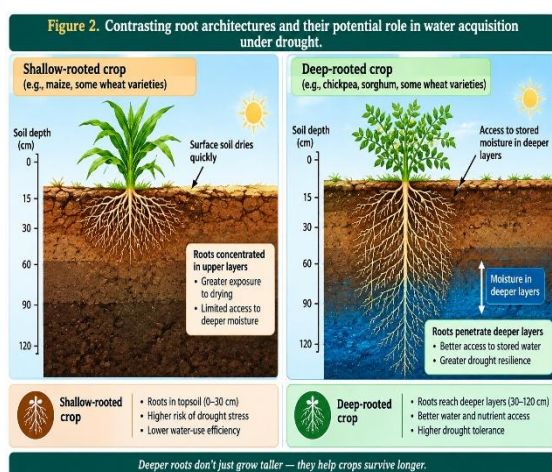
Research on drought adaptation has shown that root depth, root angle, root density and root hydraulic characteristics can contribute to maintaining crop performance under water-limited conditions (Wasson *et al.*, 2012; Zhang *et al.*, 2025).

Rice is generally associated with wet conditions, but drought can seriously reduce its productivity. Uga *et al.* (2013) identified DEEPER ROOTING 1 (DRO1), a genetic factor associated with root growth angle. Introducing a deeper-rooting form into a shallow-rooting rice background increased downward root growth and improved drought avoidance while maintaining yield performance under drought conditions.

This discovery changed the way researchers looked at drought tolerance. Instead of focusing exclusively on leaves, stomata or biochemical responses, it demonstrated that where the roots grow can itself become a

major component of drought adaptation. However, deeper roots should not automatically be considered better roots.

Deep rooting requires carbon and energy. Roots must grow, respire and maintain their tissues. If deep soil contains little available water or nutrients, excessive investment in deep roots may not provide sufficient benefit. Recent research therefore emphasises the importance of matching root architecture with the target environment rather than simply selecting for maximum rooting depth. The real goal is not “deep roots at any cost”, but efficient roots in the right place (Lynch, 2013; Meister *et al.*, 2014).



CHICKPEA PROVIDES AN IMPORTANT LESSON

The importance of roots is especially relevant to chickpea production in semi-arid and drought-prone regions. Chickpea is frequently exposed to terminal drought, particularly when rainfall becomes inadequate during reproductive development. Research has shown that root development can influence the ability of chickpea to use water stored deeper in the soil. Kashiwagi *et al.* (2015) and related studies have highlighted the contribution of root traits to drought adaptation in chickpea, with water available in the approximately 15–30 cm soil layer being particularly relevant under certain terminal-drought environments.

This has an important agronomic implication. A farmer may see a chickpea crop looking satisfactory during the early vegetative period, but the crop's ability to maintain growth and seed filling later in the season may depend partly on what happened underground earlier. A well-developed root system established early can become a kind of underground insurance policy against later moisture shortage.

This does not mean that root development alone can overcome severe drought. Weather, soil depth, rainfall amount, sowing date, variety and crop management all interact. But it does mean that agronomic decisions made during early crop establishment can influence the crop's capacity to use water later.

ROOTS AND NUTRIENTS: SEARCHING RATHER THAN SIMPLY ABSORBING

Water is not the only resource roots seek. Nitrogen, phosphorus, potassium and micronutrients are distributed unevenly through agricultural soils. Fertilizer application can create nutrient-rich zones, while repeated cropping can produce nutrient-depleted areas. Root systems can alter their growth and branching according to nutrient availability. This plasticity allows plants to invest roots where resources are potentially available. Root architecture therefore has a direct connection with nutrient-use efficiency.

Nitrogen is a good example. Nitrogen can move through soil and its availability changes over time because of processes such as mineralization, immobilization, leaching and plant uptake. Root distribution therefore influences how efficiently a crop captures available nitrogen. Phosphorus presents a different challenge because it is relatively immobile in soil. Root hairs, fine roots, mycorrhizal associations and localized root proliferation can all contribute to phosphorus acquisition. This is why simply applying more

fertilizer is not always the solution to poor nutrient uptake. The crop must also have an effective root system capable of accessing the nutrient (Lynch, 2013; Meister *et al.*, 2014).

Lynch (2013) proposed the concept of a “steep, cheap and deep” root ideotype for maize, linking root architecture with efficient acquisition of water and nitrogen. The concept illustrates a broader principle: roots should acquire resources efficiently without consuming excessive amounts of plant carbon in the process.

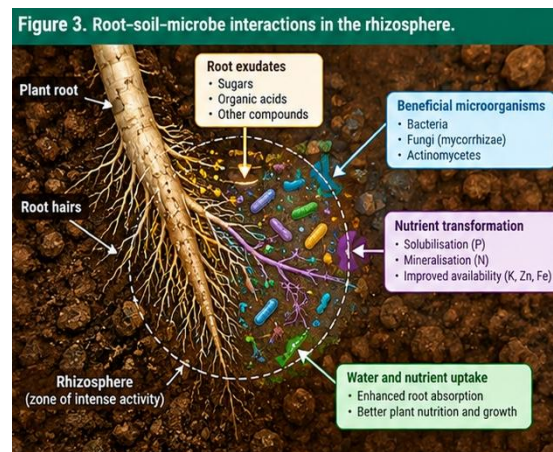
The future of nutrient management may therefore depend not only on deciding how much fertilizer to apply, but also on understanding how the crop's root system can access that fertilizer.

THE RHIZOSPHERE: WHERE THE REAL UNDERGROUND ACTIVITY HAPPENS

The narrow region of soil directly influenced by roots is known as the rhizosphere. It is one of the most biologically active zones of the soil. Roots release compounds known as root exudates, including sugars, organic acids and other molecules. These compounds can influence microbial populations around the root. In return, microorganisms can affect nutrient availability, plant growth and stress responses.

This creates a complex relationship between the plant, soil and microorganisms. Beneficial microbial associations can improve nutrient acquisition, influence root development and contribute to plant health. Mycorrhizal fungi, for example, can extend the effective soil-exploring network beyond the physical root surface. Therefore, when we talk about “root health”, we should not think only about root length or biomass. We should also consider the biological environment surrounding the root. A healthy root system is better understood as a

living interface between the plant and the soil ecosystem.



SOIL STRUCTURE CAN MAKE OR BREAK A ROOT SYSTEM

Roots cannot explore soil freely if the soil itself prevents them from doing so. Compaction is one of the major physical barriers to root growth. Repeated movement of heavy machinery, inappropriate tillage and traffic when soil is wet can increase soil compaction. Dense soil can restrict root penetration, reduce pore space and interfere with water and air movement. A crop may receive adequate fertilizer and rainfall but still perform poorly if its roots cannot effectively explore the soil.

Soil structure is therefore an important part of root management. Organic matter, residue retention, appropriate tillage, controlled traffic and avoidance of unnecessary soil disturbance can help maintain a soil environment that supports root growth. The objective is not to make soil simply “loose”; rather, it is to maintain a balance of pores that permits root penetration, water storage and adequate aeration.

The relationship works in both directions. Roots also influence soil. Growing roots create channels, release organic compounds and contribute organic material when they die. Root residues become a source of carbon for

soil organisms. In this way, roots are not merely users of soil, they are also builders of soil structure and biological activity.

TILLAGE AND ROOTS: A RELATIONSHIP OFTEN OVERLOOKED

Tillage is usually discussed in terms of seedbed preparation, weed control and residue management. Its influence on roots deserves equal attention. Excessive soil disturbance can disrupt soil structure and biological habitats, whereas well-managed reduced-tillage or conservation systems can encourage continuity of soil pores and biological activity. At the same time, no-tillage is not automatically suitable for every soil and environment. Poor drainage, severe compaction or particular weed problems may require carefully designed management.

The important point is that tillage should be evaluated not only by what happens to the soil surface immediately after the operation, but also by what happens to the root zone during the entire crop season. A good seedbed is not simply one that looks fine from above. It is one in which young roots can rapidly establish, penetrate and explore the available soil.

CROP ESTABLISHMENT BEGINS UNDERGROUND

The first few days after germination are critical. A seedling has limited stored resources and must establish a functional root system quickly. Poor soil moisture, crusting, compaction, excessive salinity or unsuitable sowing depth can restrict early root development. This is why seed placement and sowing conditions matter so much. Uniform sowing depth helps create uniform emergence. Appropriate soil moisture supports germination and early root growth. Suitable plant spacing reduces excessive competition among neighbouring root systems.

Plant population also influences root distribution. At very high population, individual plants may have less soil volume available for resource acquisition. At very low population, available resources may not be fully exploited. The optimum population is therefore not simply a number of plants per hectare, it represents a balance between above-ground canopy development and below-ground resource competition.

AGRONOMIC MANAGEMENT OF ROOTS

Although roots remain hidden beneath the soil surface, their growth and functioning can be influenced considerably through appropriate agronomic practices. Root management essentially involves creating favourable conditions for root growth, soil exploration, water acquisition and nutrient uptake.

1. Crop establishment

Uniform emergence provides seedlings with an early opportunity to develop healthy roots. Appropriate sowing depth, soil moisture and seed quality are fundamental.

2. Avoid unnecessary soil compaction

Restricting machinery movement, avoiding field operations on excessively wet soil and maintaining suitable soil structure can help roots explore a greater soil volume.

3. Manage irrigation carefully

Excessive irrigation can encourage shallow root development in some situations, while appropriate irrigation scheduling can encourage the crop to use available soil water more effectively. Irrigation should therefore be considered in relation to the crop's root zone rather than simply the soil surface.

4. Apply nutrients according to crop demand

Balanced nutrition supports root development, while both nutrient deficiency and excessive fertilization can disturb crop growth. Placement and timing can also influence how roots encounter nutrients.

5. Maintain organic matter and residues

Crop residues and organic amendments contribute to soil organic matter and can improve the physical and biological environment of the root zone when appropriately managed.

6. Reduce unnecessary disturbance

Tillage should have a clear agronomic purpose. Repeated operations that provide little additional benefit can increase costs and disturb the soil environment.

7. Select varieties with suitable root traits

Varieties differ in root architecture. Under drought-prone conditions, traits associated with deeper water acquisition may be valuable; under other environments, different root characteristics may be more appropriate.

BREEDING THE CROP BENEATH THE CROP

Crop breeding has traditionally focused on visible traits such as plant height, flowering time, grain number, grain size and disease resistance. Root traits have received less attention because they are hidden underground and are strongly influenced by soil conditions. Advances in root phenotyping, digital imaging and high-throughput screening are now making root traits easier to study.

Researchers are increasingly developing root ideotypes suited to particular environments. Deep and efficient roots may be valuable under drought, while different root

architectures may be better suited to shallow soils or nutrient-poor conditions. Thus, future crop improvement may increasingly focus on selecting varieties with root systems suited to specific soils and climates (Meister *et al.*, 2014).

BRINGING ROOTS INTO THE DIGITAL AGE

Root measurement is difficult because roots are hidden in soil. Traditional methods require excavation, washing and manual measurement. Modern imaging, three-dimensional analysis, automated phenotyping and artificial intelligence are making it possible to study root architecture more rapidly and accurately (Gusain *et al.*, 2024; Kalra *et al.*, 2024). These technologies could help breeders screen large numbers of plants for useful root traits and develop crops that use soil resources more efficiently.

ROOTS AND CLIMATE RESILIENCE

Changing rainfall, drought, heat and irregular soil moisture are increasing the importance of root traits. Root plasticity allows plants to modify root growth according to environmental conditions. Deep roots can access water from lower soil layers, while lateral roots can improve nutrient exploration near the surface (Farooq *et al.*, 2024). Therefore, climate-resilient agriculture needs to consider both the visible canopy and the hidden root system.

FROM ROOT SIZE TO ROOT EFFICIENCY

A larger root system is not necessarily a better one. Excessive root growth can require substantial carbon investment without providing proportional benefits. Traits such as root depth, diameter, angle, distribution, root hairs and specific root length are increasingly being considered when evaluating root efficiency (Lynch, 2013; Meister *et al.*, 2014).

The goal is to develop root systems that acquire sufficient water and nutrients with an appropriate investment of plant resources.

CONCLUSION

Roots may remain hidden, but their contribution to crop productivity is fundamental. They determine how effectively a crop explores the soil, captures water and nutrients, interacts with beneficial microorganisms and withstands environmental stresses. As agriculture faces increasing challenges from drought, soil degradation, nutrient limitations and climate variability, greater attention to the below-ground part of the crop is becoming essential. Future crop production should therefore combine better varieties with better root-zone management. Root traits, soil health, irrigation, nutrient management and suitable agronomic practices need to be considered together rather than separately. By bringing roots into mainstream agronomy, farmers and researchers can improve resource-use efficiency and strengthen crop resilience. The real potential of a crop is not determined only by what appears above the soil. Healthy roots provide the foundation for healthy plants, efficient resource use and sustainable crop production.

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