Root2Res
Root phenotyping and genetic improvement for rotational crops resilient to environmental change

Policy Brief

The Role of Plant Roots in Soil Health

Key messages

- Soil health is critical for sustainable agriculture, climate resilience, food security and biodiversity.
- Roots play a key role in soil carbon storage, water retention, structure formation, resilience and biodiversity — yet they're often overlooked in policy and research.
- We need targeted investment in root trait research, breeding, and field trials to unlock their full potential.
- Support policies are needed that reward living root systems — through the CAP, national soil strategies and new incentives for farmers

Introduction

Soil health — commonly defined as the continued capacity of soil to function as a living ecosystem that sustains plants, animals, and humans — is fundamental to sustainable agriculture, climate resilience, and ecosystem services [1,2]. The European Union's (EU) Soil Strategy for 2030 underscores the urgency of preserving soil functions, as they are vital for food security, biodiversity, and climate change mitigation [3]. However, inappropriate agricultural practices and climate change have led to soil degradation, declining levels of soil organic carbon, and loss of plant, soil fauna and microbial diversity [4,5,6].

Several EU initiatives emphasise the importance of soil health, including the EU Mission: A Soil Deal for Europe, the Soil Monitoring Law, the Nature Restoration Law and the Common Agricultural Policy (CAP). Climate-smart strategies such as carbon farming also recognise the role of soils in climate change mitigation through carbon sequestration and improved management practices.

In agricultural soils, plant roots are a key driver of soil processes and overall soil health, yet they have been largely overlooked in research. Plant roots transfer carbon into the soil through exudation and decomposition, and play a crucial role in shaping soil structure, nutrient cycling, water retention, microbial interactions and disease suppression. These functions are essential for maintaining healthy, productive soils [7].

This policy brief reviews the current scientific understanding of roots and soil health, highlights key knowledge gaps and explores policy opportunities to unlock the potential of root systems in tackling soil-related challenges.

Key scientific insights on root–soil interactions

Soil carbon

Roots play a key role in the soil carbon cycle, an increasingly important aspect of climate mitigation [8]. Plants allocate up to 60% of their fixed carbon belowground, bringing it into the soil through root biomass and crop residues. Unlike shoot residues, roots place carbon deeper into the soil, without requiring transport by soil fauna. Additionally, root exudates — carbon compounds released into the soil by roots — support microbial communities whose necromass contributes significantly to the cycling and stabilisation of soil carbon [9]. However, our understanding of which specific root traits most effectively support these processes is limited and further research is needed to fully uncover the potential of roots in enhancing soil carbon storage, while also considering potential trade-offs between allocating carbon to roots versus aboveground biomass.

Soil structure

Roots and their carbon inputs contribute to the physical arrangement of soil particles, known as soil structure, both directly by creating biopores and indirectly by promoting the formation of soil organic matter. Both pathways, in turn, play a crucial role in improving soil stability and fertility. Root exudates contribute to this process by nourishing soil microbes and promoting the growth of beneficial fungi and bacteria [10,11].

The physical influence of roots is particularly significant [12]. Root systems increase cohesion and overall mechanical strength of soil, reducing the risk of erosion. They promote aggregate formation that enhance structural integrity and they can penetrate compacted or hardened soil layers, creating pore spaces and improving aeration and drainage. However, soil compaction remains a widespread and serious issue in modern agriculture, restricting root development and compromising many of the soil functions described above [13]. Plant species have varying abilities to overcome compacted layers. Identifying root traits that most effectively support structural improvements remains a key research need [14,15,16].

Water retention

Good soil structure, supported by living roots, enables water infiltration, storage and retention, making it available to plants and other living organisms in the soil while also reducing runoff and erosion. Deep roots enable plants to access water stored in the lower layers of the soil, improving their resilience to drought and potentially making some moisture accessible to nearby species with shallower roots [17]. In contrast, shallow and fibrous roots enhance surface soil porosity, promoting water infiltration and helping soils recover from waterlogging through improved drainage and aeration.

More insights are needed to guide root trait selection and management to optimise drought resistance and mitigate excess water in agricultural systems.

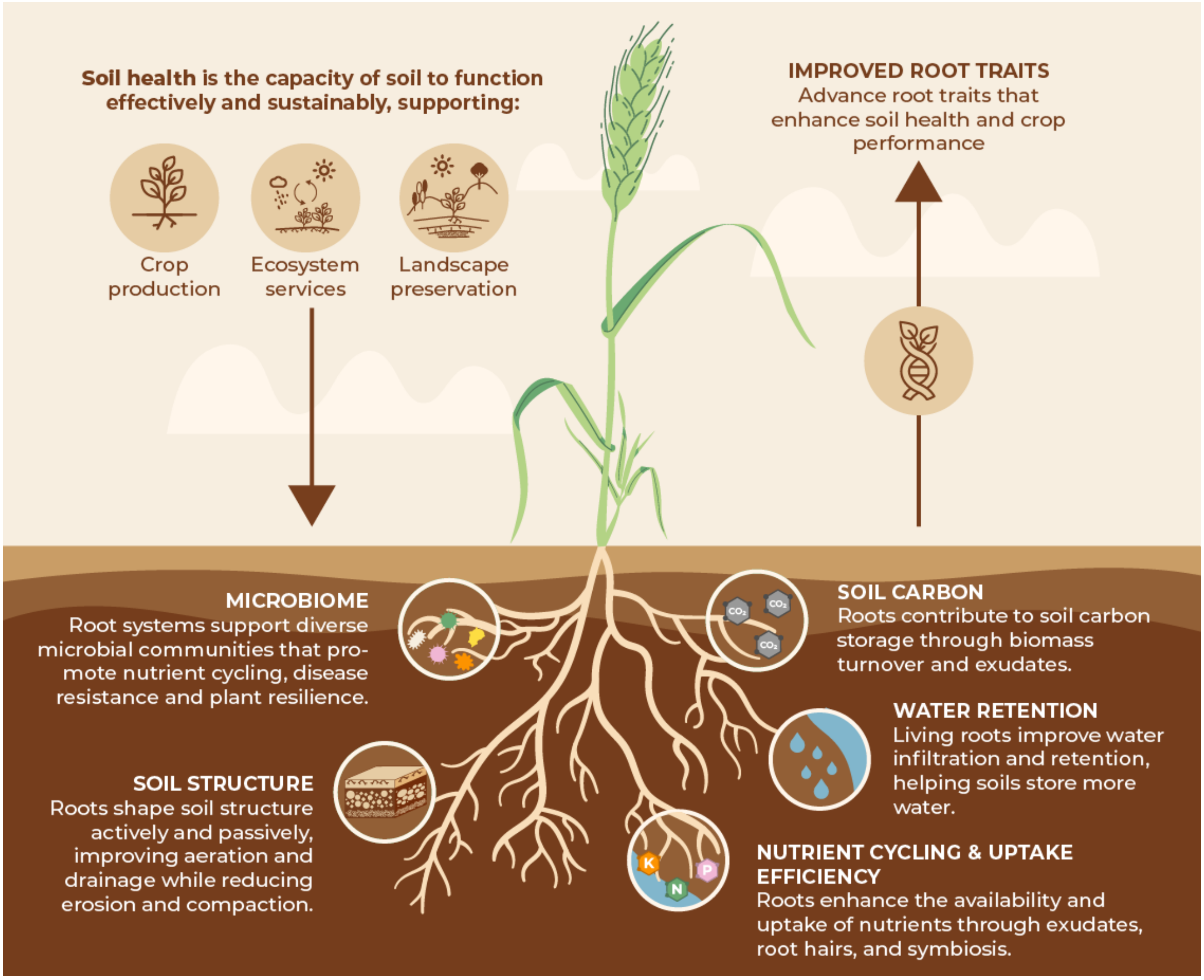

Figure 1: The importance of root traits in increasing resilience and mitigating environmental stresses.

Nutrient cycling and uptake efficiency

Crop root systems play a vital role in nutrient cycling and mitigating environmental impacts from nutrient loss. Nitrogen is particularly significant because it is widely used in agriculture and is highly susceptible to leaching due to its solubility. Deep-rooted cereal crops can access nitrogen that has leached into deeper soil layers, increasing nitrogen uptake and reducing environmental losses [18,19]. Also, root system plasticity, i.e., their ability to adapt to current environmental conditions, may offer promising opportunities to improve the efficiency of fertiliser, e.g., reducing phosphorus loss to the soil. Further research is needed to identify which root traits most effectively enhance nutrient acquisition and efficiency, and how these traits can be bred or managed within diverse cropping systems.

Microbiome

Plants actively shape the surrounding soil environment, known as the rhizosphere. The composition of the soil microbiome directly impacts soil health. While some microbes suppress pathogens, others can promote disease under certain conditions. A diverse and balanced microbial community supports plant resilience, nutrient cycling and long-term soil fertility. Genotype specific root exudation patterns can influence the surrounding microbiome, which may help mitigate challenging periods, such as drought. Such adaptive responses demonstrate the dynamic role of roots in mediating interactions between soil, plants and microbes. Yet the soil–root–microbiome interface likely holds many unknown functions, making it a crucial research focus for sustainable agriculture and soil health.

Conclusions and policy recommendations

Living roots play a vital role in promoting soil health. Using nature-based solutions, including a combination of cash crops and multi-service plants such as cover crops, green manure and inter-cropping, ensures year-round living root systems. This boosts short-term productivity while providing a long-term investment in ecosystem sustainability.

Despite significant advances in understanding root biology, substantial knowledge gaps remain in applying this knowledge to concrete, evidence-based guidelines, policy frameworks and agricultural practices that optimise both productivity and ecosystem services, such as soil health.

Advancing our understanding of the soil–root–microbiome interface can transform agriculture, enhancing productivity, resilience, and sustainability. Investing in this research is essential to drive science-based innovation in soil management and climate action.

Specifically, we recommend that you:

1. **Maintain and strengthen EU Framework Programme funding** for collaborative, public-good research. Support pan-European consortia and living labs to enable robust, system-level assessments of root traits and their contributions to climate-smart, regenerative agriculture.
2. **Increase investment in interdisciplinary research** on root traits, root plasticity, and their influence on soil functions across different farming systems.
3. **Expand and/or strengthen below-ground phenotyping networks** to lower costs and improve research efficiency, e.g., networks like "PHENOME EMPHASIS" that focus on roots.
4. **Support long-term field studies** to evaluate root systems' effects on soil structure, carbon storage, water regulation and nutrient use efficiency. These studies should include both controlled trials and on-farm research.
5. **Strengthen on-farm research** to help growers understand which management practices (e.g. reduced tillage, cover crops) enhance root system development, how these practices interact with soil conditions, and how benefits can be quantified and integrated into existing production systems.
6. **Improve breeding programmes** to select beneficial root traits, including root–microbe interactions. This could involve incorporating root traits into Value for Cultivation and Use assessments, and expanding trait evaluation to include non-cash crops (e.g., cover crops and intercrops), which contribute to year-round root presence and provide system-wide benefits.
7. **Include root-centric strategies** in national and regional policies for soil health, climate resilience and sustainable agriculture — recognising root systems as drivers of change.
8. **Create incentives to maintain living roots in the soil year-round** through practices like cover cropping, including perennials and minimising fallow periods, as part of regenerative and climate-smart agricultural policies.

References

[1] Tahat MM, Alananbeh MK, Othman AY, Leskovar ID. Soil health and sustainable agriculture. 2020. Sustainability 12(12):4859. https://doi.org/10.3390/su12124859

[2] Davis AG, Huggins DR, Reganold JP. Linking soil health and ecological resilience to achieve agricultural sustainability. 2023. Frontiers in Ecology and the Environment 21(3): 131–139. https://doi.org/10.1002/fee.2594

[3] European Commission: Directorate-General for Environment, EU soil strategy for 2030 – Towards healthy soils for people and the planet. 2021. Publications Office. https://data.europa.eu/doi/10.2779/02668

[4] Kraamwinkel CT, Beaulieu A, Dias T, Howison RA. Planetary limits to soil degradation. 2021. Communications Earth & Environment 2, 249. https://doi.org/10.1038/s43247-021-00323-3

[5] Lal R. Climate change and soil degradation mitigation by sustainable management of soils and other natural resources. 2012. Agricultural Research 1:199-212. https://doi.org/10.1007/s40003-012-0031-9

[6] Oishy MN, Shemonty NA, Fatema SI, Mahbub S, Mim EL, Raisa MB, Anik AH. Unravelling the effects of climate change on the soil-plant-atmosphere interactions: A critical review. 2025. Soil & Environmental Health 13:100130. https://doi.org/10.1016/j.seh.2025.100130

[7] George TS, Bulgarelli D, Carminati A, Chen Y, Jones D, Kuzyakov Y, Schnepf A, Wissuwa M, Roose T. Bottom-up perspective–The role of roots and rhizosphere in climate change adaptation and mitigation in agroecosystems. 2024. Plant and soil 500(1):297-323. https://doi.org/10.1007/s11104-024-06626-6

[8] Kell, DB. Large-scale sequestration of atmospheric carbon via plant roots in natural and agricultural ecosystems: why and how. 2012. Philosophical Transactions of the Royal Society B: Biological Sciences 367, 1589–1597. https://doi.org/10.1098/rstb.2011.0244

[9] Panchal P, Preece C, Peñuelas J, Giri J. Soil carbon sequestration by root exudates. 2022. Trends in Plant Science 27, 749–757. https://doi.org/10.1016/j.tplants.2022.04.009

[10] Bonkowski M, Villenave C, Griffiths B. Rhizosphere fauna: the functional and structural diversity of intimate interactions of soil fauna with plants roots. 2009 Plant Soil 321: 213-233. http://dx.doi.org/10.1007/s11104-009-0013-2

[11] Hermans SM, Lear G, Case BS, Buckley HL. The soil microbiome: An essential, but neglected, components of regenerative agroecosystems. 2023. iScience 26. https://doi.org/10.1016/j.isci.2023.106028

[12] Angers DA, Caron J. Plant-induced Changes in Soil Structure: Processes and Feedbacks. 1998. Biogeochemistry 42, 55–72. https://doi.org/10.1023/A:1005944025343

[13] Giuliani LM, Hallett PD, Loades KW. Effects of soil structure complexity to root growth of plants with contrasting root architecture. 2024. Soil and Tillage Research 238: 106023. https://doi.org/10.1016/j.still.2024.106023.

[14] Reubens B, Poesen J, Danjon F, Geudens G, Muys B. The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: a review. 2007. Trees 21(4), 385-402. https://doi.org/10.1007/s00468-007-0132-4

[15] Gyssels G, Poesen J, Bochet E, Li Y. Impact of plant roots on the resistance of soils to erosion by water: a review. 2005. Progress in physical geography 29(2), 189-217. https://doi.org/10.1191/0309133305pp443ra

[16] Loades KW, Bengough AG, Bransby MF, Hallett PD. Reinforcement of soil by fibrous roots. 2013. Enhancing Understanding and Quantification of Soil–Root Growth Interactions 4, 197-228. https://doi.org/10.2134/advagricsystmodel4.c9

[17] Uga Y, Sugimoto K, Ogawa S et al. Control of root system architecture by DEEPER ROOTING 1 increases rice yield under drought conditions. 2013. Nature Genetics 45, 1097–1102. https://doi.org/10.1038/ng.2725

[18] Ordone A, Popovic O, Thorup-Kristensen K. Deep roots: implications for nitrogen uptake and drought tolerance among winter wheat cultivars. 2024. Plant Soil 500: 13-32. https://doi.org/10.1007/s11104-023-06255-5

[19] Liu H, Colombi T, Ortrud J, Westerbergh A, Weih M. Linking wheat nitrogen use to root traits: Shallow and thin embryonic roots enhance uptake but reduce conversion efficiency of nitrogen. 2022. Field Crops Research 285. https://doi.org/10.1016/j.fcr.2022.108603

About this policy brief and Root2Resilience

Publisher: ARVALIS

Authors: Nina Gallmann (FiBL), Jean-Pierre Cohan (ARVALIS), Tim George (JHI), Laura Kemper (FiBL), Christina Baxter (ADAS), Lionel Dupuy (NEIKER), Johannes Postma (FZJ) and Doris Vetterlein (UFZ)

Contact: Jean-Pierre Cohan, jp.cohan@arvalis.fr and Tim George, tim.george@hutton.ac.uk

Review: Eva Oburger (BOKU), Pierre Rochepeau (ARVALIS)

Image by Freepik

Permalink: https://zenodo.org/records/16911590

This policy brief was elaborated in the Root2Resilience project.

Root2Resilience: The project is running from September 2022 to August 2027. The overall goal of Root2Resilience – Root phenotyping and genetic improvement for rotational crops resilient to environmental change – is to develop root phenotyping, genetic and modelling tools and use them to define and test innovative genotype ideotypes able to enhance the tolerance to abiotic stress and carbon sequestration in soils

Project website: root2res.eu

Funding

Funded by the European Union

UK Research and Innovation

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

Root2Resilience has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101060124. Its work is supported by Innovate UK through the Horizon Europe Guarantee scheme Grant Agreement No. 101060124 and by the Swiss State Secretariat for Education, Research and Innovation (SERI) under grant No. 23.00050. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, UK Research and Innovation ((UKRI), European Research Executive Agency (REA) or the Swiss State Secretariat for Education, Research and Innovation (SERI). Neither the European Union nor any other granting authority can be held responsible for them. The authors and editors do not assume responsibility or liability for any possible factual inaccuracies or damage resulting from the application of the recommendations in this practice abstract.