Roots in policy: How to encourage breeding for root-related traits and more resilient crops

Key messages

- Roots are important for climate resilience.

- Novel crop cultivars are needed that are more resilient to environmental stress, through improved root traits and interactions with the soil.

- These cultivars will be critical to support the EU Green Deal goals and the Farm to Fork and Biodiversity strategies.

- Breeding for root-related traits should be incentivised through initiatives to promote the use of resilient crops with better root systems.

Introduction

The evidence for climate change is unequivocal. Changing climate patterns are already affecting agricultural eco-systems (Muluneh 2021; Malhi et al. 2020) and a higher frequency of extreme weather events in the future (Pugnaire et al. 2019) will increase the instances of droughts, flooding and heatwaves, and reduce winter frosts (Dempewolf et al. 2014; Calleja-Cabrera et al. 2020). Therefore, while the unpredictability of the environment will increase, it is predictable that these changes will have consequences on productivity, sustainability, biodiversity conservation, and other functions in agricultural ecosystems.

Crops need to be adapted to this changing climate and contribute to mitigation of resulting effects. While research and breeding efforts have often focused on aboveground traits, **we highlight that many of the environmental stresses associated with climate change will be most acutely perceived by the plant at the root-soil interface and are also likely to be mitigated at this globally important interface** (figure 1). Plants have various root-

based strategies to adapt and to compensate the negative effects of different stresses and constraints. Such adaptations may involve changes in how roots grow, how they function and how they take up water and nutrients (Hazman and Brown, 2018; Klein et al. 2020; Li et al. 2022a; Deng et al. 2021). However, breeders often lack effective and scalable tools to select for varieties with such traits.

Society needs us to use and expand this knowledge to develop crops for the future which are resilient to environmental stresses. However, this is not currently being incentivised. In many countries in the EU and beyond, decisions on which cultivars to use in a specific region are often based on performance indicators from optimal conditions. Varieties are mostly chosen based on high yield, tolerance to a set of mandatory crop diseases and post-harvest quality for feed or food. Varieties that are added to these recommended lists are more likely to secure a large market share. This system incentivises breeding companies to develop new cultivars with greater yield under optimal conditions. It does less to incentivise breeding
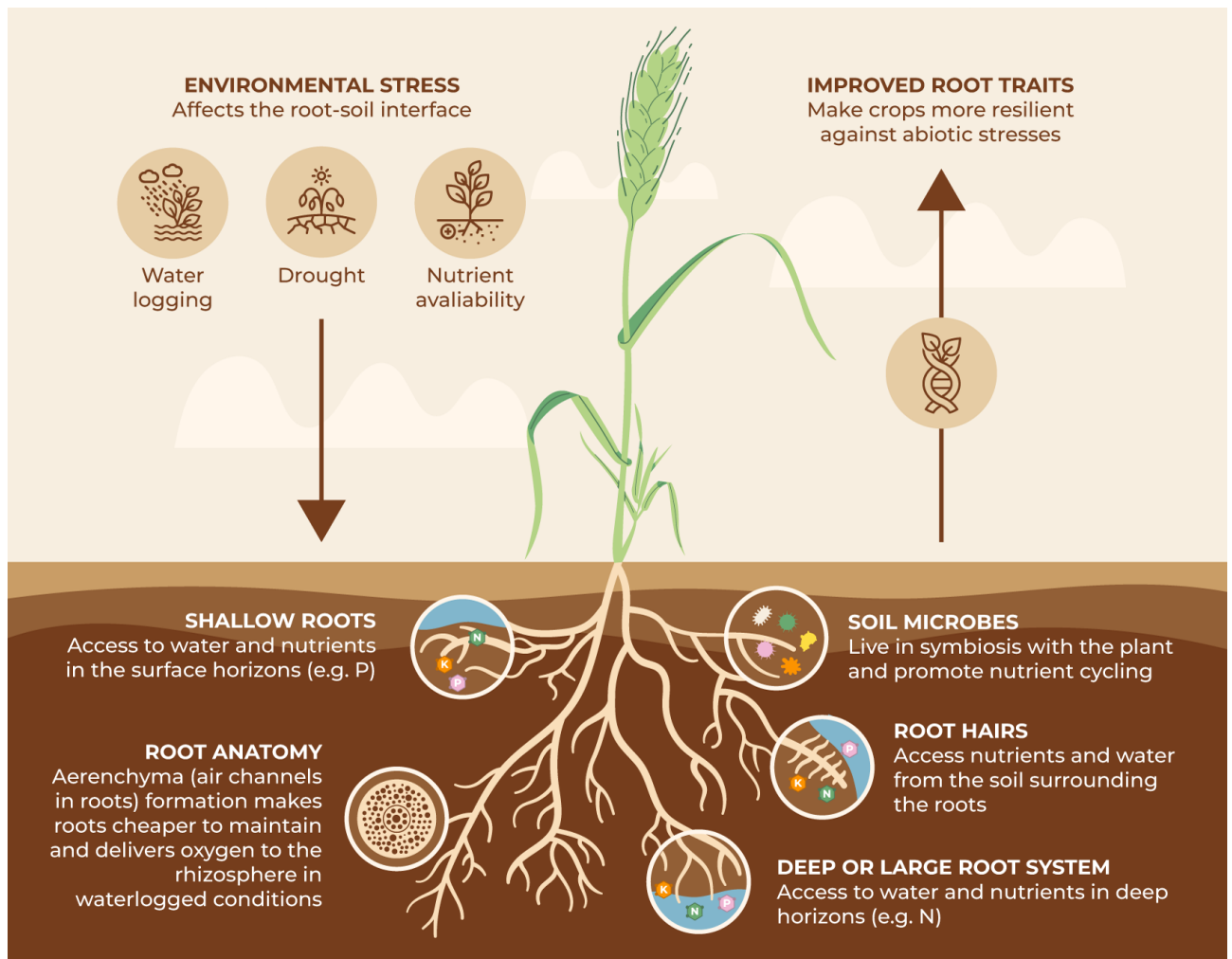
Figure 1. The importance of root traits in increasing resilience and mitigating environmental stresses

for increased stress conditions caused by climate change (drought, heat, waterlogging etc), and utility in sustainable systems (e.g., reduced tillage, reduced fertiliser input, intercropping, cover crop systems). Such incentives could be promoted through legislation being developed for Plant Reproductive Material (PRM) and Value for Sustainable Use or Cultivation (VSCU) currently. While breeding for root related traits is difficult, a more nuanced approach to trialling new varieties for a range of environmental and sustainable management systems will help identify new cultivars with better below ground traits.

The European Green Deal, the Farm to Fork Strategy, the biodiversity strategy and other policies that aim to reduce fertilizer and pesticide use are already changing the breeding focus. Integrating these policies and ensuring policy coherence will be key to incentivising the development of root- specific traits by referencing them in different policy mechanisms e.g., CAP Ecoschemes, carbon removal certification framework, etc.

Results

Root2Res is using a combination of novel and existing data, which will be supported by mathematical modelling and the literature to identify ideal sets of below-ground traits. Improving root traits in this way is not only expected to increase resilience to environmental stress but also help improve nutrient uptake efficiency, thereby reducing the risk of nutrient run-off and direct and indirect GHG emissions by reducing fertilizer requirements, and contributing to the Farm to Fork goals.

The ideal root traits identified from the first round of development are listed in Table 1. In summary, the ideal traits presented include root architectural traits (larger and deeper root systems), root anatomical traits (more and longer root hairs and aerenchyma formation) and rhizosphere traits (more mycorrhizae, elite rhizobia strains and phosphate solubilising bacteria). These traits will now be used to interrogate the available genetic material, both genotypically and phenotypically, to identify existing individuals which best embody the ideal traits and adaptability.

These will be trialled in multiple environments and assessed for their impact on resilience to stress, but also the ability to mitigate against climate change by reducing GHG emissions, reliance on external inputs, and sequestering carbon to soil. Once the ideotypes are validated, there will be an opportunity to exploit this information by designing a translational pipeline for breeding which will have the aim of generating novel cultivars of key crops which have the ideal traits. A number of routes can be taken including conventional breeding and gene editing, should the policy environment allow it.

In order to help speed this process up, Root2Res is also developing phenotyping tools for below-ground traits that can be used to create a more nuanced trialling and recommendation system in EU Member States and beyond. Including these phenotyping tools in selection of cultivars under a wider range of environmental and management systems will create a system that encourages the delivery of new crops for resilient to environmental change.

Table 1: Target root and rhizosphere traits divided into architectural/developmental root traits, anatomical root traits and rhizosphere traits.

	Traits	Environmental stresses		
		Water logging	Water deficit	Phosphorus deficit
Architectural and developmental Root Traits	**Greater root dry weight**		✔	✔
	Deeper rooting		✔	
	Increased lateral root number		•	•
	Early root vigour		•	•
	Increased distribution of roots at depth		•	
	Root surface area			•
	Increased root length density			•
Anatomical Root Traits	**Aerenchyma formation**	✔	✔	✔
	More root hairs (inc. density)		✔	✔
	Greater root hair length			✔
	Greater adventitious root porosity	•	•	•
Rhizosphere Traits	**Arbuscular mycorrhizal fungi**		✔	✔
	Rhizobia – elite strains with specific functionality		✔	✔
	Phosphate solubilizing bacteria			✔
	Root exudates		•	•
	Increased rhizospheric phosphatase activity			•

A ✔ or • denotes if the trait contributes resilience towards one of the abiotic stresses addressed in the review (water logging, water deficit or phosphorus stress). A • indicates that traits were identified at least three times and a ✔ indicates they were identified at least 5 times. Results were identified in a literature review.

Conclusion

Despite the current focus on aboveground traits, roots and their interaction with soil play a crucial role in mitigating climate change. Novel crop cultivars that are resilient to environmental stress, through improved root traits and interactions with the soil, will be critical to support the EU Green Deal goals and the Farm to Fork and Biodiversity strategies, including:

- ensure food security in the face of geopolitical uncertainties, climate change and biodiversity loss;

- reduce the environmental and climate footprint of the EU food system;

- strengthen the EU food system's resilience;

- improve positive economic and social externalities from farming systems, and

- lead a global transition towards competitive sustainability from farm to fork.

Breeding companies need to deliver these novel crop varieties to ensure that farmers have the genetic tools necessary to deliver food security and environmental stewardship in more extreme and variable climate. Root2Res is contributing to this goal by developing tools and knowledge that will help breeders to deliver new crop varieties, with improved root traits, that are resilient to environmental stresses. However, policy incentives are essential to ensure this.

Policy recommendations

It is essential to support breeding for root-related traits which foster resilience to environmental change. This should be incentivised through initiatives to promote the use of resilient crops with better root systems.

Policies should:

1. Diversify cultivar trialling and recommendation systems in EU member states:
   a. Expand systems that mainly promote the release of crop varieties only if they are superior to existing varieties (i.e., higher yielding and other single factor criteria) under optimal conditions. Instead, advocate for and subsidise evaluation criteria such as yield stability and adaptability under a range of stress conditions and variable environments to simulate future climate conditions. This should be addressed through legislation, such as the plant reproductive material (PRM) legislation.
   b. Include the selection of crop varieties for sustainable systems including reduced tillage, cover crops, intercropping, etc.
   c. Specify which cropping systems should be tested in trialling and recommendation systems (i.e., lower nitrogen in potato production; use of intercropping with legumes, etc).
   d. Increase focus on the interaction between the plant genetics, the environmental conditions and the management practices applied to cultivate it from breeding programmes to practical recommendations for farmers via an advisory network.

2. Provide impartial, non-commercial "advisory" positions to serve as intermediaries between breeding programmes and farm practices. These positions should champion varieties that are adapted to local conditions and challenges, which will in turn incentivise seed merchants to provide varieties adapted to local conditions and markets.

3. Foster public-private partnerships that facilitate breeding for sustainable objectives that promote positive externalities.

References

Calleja-Cabrera J, Boter M, Oñate-Sánchez L, Pernas M (2020) Root growth adaptation to climate change in crops. Front Plant Sci 11:544.

Dempewolf H, Eastwood RJ, Guarino L, Khoury CK, Müller JV, Toll J (2014) Adapting agriculture to climate change: a global initiative to collect, conserve, and use crop wild relatives. Agroecol Sustain Food Syst 38:369–377.

Deng L, Peng C, Kim DG, Li J, Liu Y, Hai X, Liu Q, Huang C, Shangguan ZP, Kuzyakov Y (2021) Drought effects on soil carbon and nitrogen dynamics in global natural ecosystems. Earth-Sci Rev 214:103501.

Hazman M, Brown KM (2018) Progressive drought alters architectural and anatomical traits of rice roots. Rice 11:62.

IPCC (2023) AR6 Synthesis Report. https://www.ipcc.ch/report/ar6/syr/ last accessed 24/03/2023

Klein SP, Schneider HM, Perkins AC, Brown KM, Lynch JP (2020) Multiple integrated root phenotypes are associated with improved drought tolerance. Plant Physiol 183:1011–1025.

Li J, Wang J, Liu H, Macdonald CA, Singh BK (2022a) Application of microbial inoculants significantly enhances crop productivity: A meta-analysis of studies from 2010 to 2020. J Sustain Agric Environt 1:216–225

Malhi Y, Franklin J, Seddon N, Solan M, Turner MG, Field CB, Knowlton N (2020) Climate change and ecosystems: threats, opportunities and solutions. Phil Trans R Soc B3752019010420190104

Muluneh MG (2021) Impact of climate change on biodiversity and food security: A global perspective. Agric Food Secur 10:36.

Pugnaire FI, Morillo JA, Peñuelas J, Reich PB, Bardgett RD, Gaxiola A, Wardle DA, Van Der Putten WH (2019) Climate change effects on plant-soil feedbacks and consequences for biodiversity and functioning of terrestrial ecosystems. Sci Adv 5:eaaz1834.

About this policy brief and Root2Resilience

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 too 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 wevbsite: root2res.eu
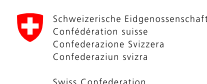
Funding

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**

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.