Root2Res

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

Priority list of root/rhizosphere ideotype traits

Summary

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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

Root2Res 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) grant No. 23.00050.

INTRODUCTION

The aim of this activity was to ascertain which below ground crop traits confer tolerance against water and phosphorus stress and therefore which traits are likely to be involved in resilience to environmental change.

BACKGROUND TO THE WORK

This task defines the high-level root and rhizosphere traits important for enhancing and sustaining crop performance in different agroclimatic regions and environments. Root traits are those that relate to the plant root system, including architectural traits (such as root depth/angle and root length density) and morphological traits (such as root hairs, root diameter, aerenchyma/cell size). The rhizosphere is the region of soil/substrate surrounding the root that is directly influenced by root growth and activity. Rhizosphere traits include for example root exudates and mucilage, and microbiome traits (bacteria & fungi). The output produces a list of root and rhizosphere traits to mitigate against water and nutrient stress

METHODOLOGY

The work involved assessment of scientific literature and consultation with industry stakeholders. The literature was reviewed via two methods; firstly, a quick scoping review (QSR) was undertaken to provide a 'balanced assessment' of the literature, including project reports. Secondly, a review of published reviews of belowground crop traits was undertaken.

Primary and secondary questions

Primary Questions:

1. What root traits are important for resilience to water stress?
2. What rhizosphere traits are important for resilience to water stress?
3. What root traits are important for resilience to phosphorus stress?
4. What rhizosphere traits are important to phosphorus stress?

Secondary Questions Maximum of 2:

1. What specific root or rhizosphere traits are identified as important for aiding crop performance (yield/biomass) if measured in an environment with water or phosphorus stress, or for improving water uptake/use efficiency or P uptake/use efficiency?
2. Are there any systematic differences in root traits that are identified as important in (1) between the different Agroclimatic Zones (ACZs)?

Crop species to be included in the review

Barley (*Hordeum vulgare*), Wheat (*Triticum*), bean (*Vicia faba*), Pea (*Pisum sativum*), Lentil (*Lens culinaris*), potato (*Solanum tuberosum*) and sweet potato (*Ipomoea batatas*).

Expert Elicitation

The project consortia supplied references relevant to their expertise and the topic of the review. This list of references was also screened as part of the review process.

Reviews and opinion papers were excluded from the QSR, but used in the 'review of reviews'. There was a total of 53 resources of the type review or opinion paper' supplied by the consortia. Resources dating back 5 years, (to 2018) were included, which left 31. In total, 25 were subject to data extraction.

Additionally, the EoRNA Barley expression database was searched to identify relevant candidate genes with putative functions, which provided clues about possible metabolic and biochemical pathways which may be involved in the development of relevant root traits.

Stakeholder Workshops

Stakeholder workshops were organised to consult breeders,growers and agronomists about the most important root and rhizosphere traits for their crops and growing environment, the format consisted of both online and in person meetings. It was decided to hold four meetings corresponding to the four field trial hubs within the Root2Res project.

Not all workshops had taken place by the deliverable date. The first stakeholder workshop, Agroclimatic Zone 1 (ACZ1) Oceanic Climate, was held as an online event on the 24th of February. The second workshop, ACZ 2 Humid continental climate, was held as a hybrid in person and online event at the Agricultural Institute of Slovenia, Jabile on May 11th 2023. Both of these workshops followed a similar format with an introduction and discussion on 5 points (see below) followed by feedback and conclusions.

Questions for discussion:

- Which environmental stresses are relevant to the local environment?
- What would help to mitigate these? What rooting traits would help to mitigate these?
- How would you know/assess if rooting is adequate?
- What phenotyping tools would be useful for assessing root traits?
- What are the priority traits? Pick a top one or two.

The other two workshops were planned as in person events as follows:

- ACZ 3 Mediterranean Climate: May 2023;
- ACZ Transitional point 15th June 2023 in France.

Feedback from these will be included in analysis and interpretation of priority traits even if they are collated after submission of the deliverable.

Results summary & Conclusions

The combination of literature review and stakeholder workshops allowed the project to arrive at list of target root traits which will be relevant to the industry and help develop cultivars which are more resilient to environmental stresses.

Stakeholder summary – what are the priority traits? Pick a top one or two

The feedback from the discussion groups on the final point of selecting one or two priority traits:

ACZ1:

- Root system size and proportionality
  - Root density without aboveground biomass trade-off
- Resilience to multiple stresses – Plasticity
  - Depends on the stress
  - Lateral roots to respond to the environment
  - Plasticity to overcome multiple stresses
- Nutrient uptake
  - Scavenging ability
  - Root exudates to increase nutrient availability
  - Ability to take up nutrients in both wet and dry conditions
- Healthy microbiome
- Overcoming strong soil
- Resistance to soil borne fungi

ACZ2:

- Deeper roots and bigger root biomass
- Early vigour and faster growth
- Nodulation at legumes

Literature summary

This work allowed the project to produce a priority list of target belowground crop traits that confer tolerance to water and phosphorus stress, which was divided into architectural/developmental root traits, anatomical root traits and rhizosphere traits.

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

	Traits	Water logging	Water deficit	Phosphorus deficit
Root Traits – Architectural/developmental	**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			✓
R o o	**Aerenchyma formation**	✓	✓	✓

	Traits	Water logging	Water deficit	Phosphorus deficit
	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 ✓denotes if the trait contributes resilience towards one of the abiotic stresses addressed in the review (water logging, water deficit or phosphorus stress). Traits listed were identified at least three times and those traits in bold were identified at least 5 times.

None of the target traits identified have been unexpected or surprising. The root and rhizosphere traits most frequently identified in the literature searched and combined with stakeholder input are listed in Table 1

Greater root dry weight was identified as an important root trait for resilience to both water deficit and phosphorus deficit. Deeper rooting was identified as important for coping with water deficit.

Aerenchyma formation was identified as an important target anatomical root trait for resilience to not only water logging but also water and phosphorus deficit. Aerenchyma formation is linked to higher adventitious root porosity.

Root hairs were also identified as important for resilience to abiotic stresses. An increased number of root hairs helps to cope with both water and phosphorus deficit and longer root hairs specifically with phosphorus deficit.

Rhizosphere traits which were frequently reported to aid in crop resilience to water and phosphorus deficit included associations with AMF and specific elite strains of rhizobia (for leguminous crops), which had specific functions, such as increasing osmoprotectant accumulation or high potential solubilization of inorganic P. While phosphate solubilizing bacteria (PSB) or phosphate solubilizing microorganisms (PSM) were reported to help with phosphorus deficit. However, it should be noted that a relatively recent review concluded that “PSM do not mobilise sufficient P to change the crops’ nutritional environment under field conditions” (Raymond, et al., 2021). The authors suggest that further ‘mechanistic understanding’ is required to understand how PSM mobilise P as part of the whole soil community and how this can be

manipulated to promote the mobilisation and cycling of P. This is congruent with a proposed research track for AMF, that envisages AMF, along with other soil biota, in an agricultural system that uses more sustainable options in terms of inputs and biodiversity (Rillig, et al., 2019). These authors also highlight the need for more critical research approaches and new methods.

The information extracted does not indicate that different traits are more suited to a particular ACZ, however it should be noted that this is likely to be due to the balance of data extracted within the QSR, in which no information for root traits in the field was found for ACZ2 and ACZ3. Additionally, no major differences between the crop types have been identified, with the caveat of the pulse crop ideotype. A pulse ideotype of 'wide, shallow & fine' (Rao, et al., 2021) to compliment the 'steep, cheap and deep' ideotype which has been proposed in cereal crops.

POINTS TO NOTE:

One important factor which was raised during the ACZ1 stakeholder workshop and has also been noted during the review process is the issue of compacted soils and the need for roots to penetrate strong soils.

Several of the target traits may well be correlated with other identified traits which had fewer mentions, for example 'greater root dry weight' could easily be related to increased root length, or root:shoot ratio. An increased surface area could be achieved via increased root hairs number and length or increased lateral roots.

For the rhizosphere traits, it is noted that there is a need for more understanding of how the manipulation of one or two factors affects the microbial community as a whole (especially for root exudates and their interactions with the rhizobiome) and then in turn to confer the desired benefit to the plant.

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1. References

Rao, S. et al., 2021. Pulse Root Ideotype for Water Stress in Temperate Cropping System. *Plants,* 10(4), p. 692.

Raymond, N. et al., 2021. Phosphate-solubilising microorganisms for improved crop productivity: a critical assessment.. *New Phytol,* Volume 229, pp. 1268-1277.

Rillig, M. et al., 2019. Why farmers should manage the arbuscular mycorrhizal symbiosis. *New Phytol,* Volume 222, pp. 1171-175.

2. Appendix I

2.1. Web of Science Search Terms

1. **Primary Question 1: What root traits are important for resilience to water stress?**

Barley

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("Barley") OR TS=("Hordeum vulgare"))

Wheat

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("wheat") OR TS=("Triticum"))

Bean

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("Bean") OR TS=("Field bean") OR TS=("Vicia faba"))

Pea

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("Pea") OR TS=("Pisum sativum"))

Lentil

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("lentil*") OR TS=("Lens culinaris"))

Potato

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("potato") OR TS=("solanum tuberosum"))

Sweet potato

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("sweet potato") OR TS=("yam") OR TS=("Ipomoea batatas"))

2. Primary Question 2: What rhizosphere traits are important for resilience to water stress?

Barley

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("Barley") OR TS=("Hordeum vulgare"))

Wheat

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("wheat") OR TS=("Triticum"))

Bean

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("Bean") OR TS=("Field bean") OR TS=("Vicia faba"))

Pea

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth

promoting bacteria")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("Pea") OR TS=("Pisum sativum"))

Lentil

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND ((TS=("lentil") OR TS=("Lens culinaris"))

Potato

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("potato") OR TS=("solanum tuberosum"))

Sweet potato

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("water") OR TS=("water stress") OR TS=("water deficit") OR TS=("waterlogging") OR TS=("drought*") OR TS=("flood*")) AND (TS=("sweet potato") OR TS=("yam") OR TS=("Ipomoea batatas"))

3. Primary Question 3: What root traits are important for resilience to phosphorus stress?

Barley

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("Barley") OR TS=("Hordeum vulgare"))

Wheat

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("wheat") OR TS=("Triticum"))

Bean

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("Bean") OR TS=("Field bean") OR TS=("Vicia faba"))

Pea

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("Pea") OR TS=("Pisum sativum"))

Lentil

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("lentil") OR TS=("Lens culinaris"))

Potato

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("potato") OR TS=("solanum tuberosum"))

Sweet potato

(TS=("root*") OR TS=("root length") OR TS=("root architecture") OR TS=("root depth") OR TS=("root angle") OR TS=("root length density") OR TS=("root diameter") OR TS=("aerenchyma") OR TS=("lateral root") OR TS=("primary root") OR TS=("root cap") OR TS=("root system")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("sweet potato") OR TS=("yam") OR TS=("Ipomoea batatas"))

4. Primary Question 4: What rhizosphere traits are important to phosphorus stress?

Barley

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("Barley") OR TS=("Hordeum vulgare"))

Wheat

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("wheat") OR TS=("Triticum"))

Bean

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("Bean") OR TS=("Field bean"))

Pea

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("Pea") OR TS=("Pisum sativum"))

Lentil

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("lentils") OR TS=("Lens culinaris"))

Potato

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth

promoting bacteria")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("potato") OR TS=("solanum tuberosum"))

Sweet potato

(TS=("rhizosphere") OR TS=("exudate*") OR TS=("mucilage") OR TS=("microbiome") OR TS=("mycorrhizal symbiosis") OR TS=("mycorrhiza*") OR TS=("rhizobi*") OR TS=("seed pericarp") OR TS=("bacteria*") OR TS=("fung*") OR TS=("PGPR") OR TS=("plant growth promoting bacteria")) AND (TS=("Phosphorus") OR TS=("phosphorus dynamics") OR TS=("low soil phosphorus") OR TS=("phosphorus stress") OR TS=("phosphorus deficit*") OR TS=("phosphorus index")) AND (TS=("yam") OR TS=("Ipomoea batatas"))

2.2. Google Scholar Search terms

1. **Primary Question 1: What root traits are important for resilience to water stress?**

Barely 187 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("Barley" OR "Hordeum vulgare")

Wheat 179 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("wheat" OR "Triticum")

Bean 180 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("Bean" OR "Vicia faba")

Pea 182 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("Pea" OR "Pisum sativum")

Lentil 187 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("lentil*" OR "Lens culinaris")

Potato 189 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("potato" OR "solanum tuberosum")

Sweet potato 193 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("sweet potato" OR "Ipomoea batatas")

2. Primary Question 2: What rhizosphere traits are important for resilience to water stress?

Barley 194 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobiumum*" OR "bacteria*" OR "fungi*") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("Barley" OR "Hordeum vulgare")

Wheat 186 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("wheat" OR "Triticum")

Bean –187 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("Bean" OR "Vicia faba")

Pea - 189 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("Pea" OR "Pisum sativum")

Lentil 193 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("lentil" OR "Lens culinaris")

Potato 196 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("potato" OR "solanum tuberosum")

Sweet potato 200 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("water" OR "waterlogging" OR "drought*" OR "flood*") AND ("sweet potato" OR "Ipomoea batatas")

3. Primary Question 3: What root traits are important for resilience to phosphorus stress?

Barley 149 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("Phosphorus") AND ("Barley" OR "Hordeum vulgare")

Wheat 141 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("Phosphorus") AND ("wheat" OR "Triticum")

Bean 142 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("Phosphorus") AND ("Bean" OR "Vicia faba")

Pea 144 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("Phosphorus") AND ("Pea" OR "Pisum sativum")

Lentil 148 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("Phosphorus") AND ("lentil" OR "Lens culinaris")

Potato 151 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("Phosphorus") AND ("potato" OR "solanum tuberosum")

Sweet potato 155 characters

("root*" OR "root angle" OR "root hair*" OR "aerenchyma" OR "lateral root" OR "primary root") AND ("Phosphorus") AND ("sweet potato" OR "Ipomoea batatas")

4. Primary Question 4: What rhizosphere traits are important to phosphorus stress?

Barley 156 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("Phosphorus") AND ("Barley" OR "Hordeum vulgare")

Wheat 148 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("Phosphorus") AND ("wheat" OR "Triticum")

Bean – 149 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("Phosphorus") AND ("Bean" OR "Vicia faba")

Pea - 151 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("Phosphorus") AND ("Pea" OR "Pisum sativum")

Lentil 155 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("Phosphorus") AND ("lentil" OR "Lens culinaris")

Potato 158 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("Phosphorus") AND ("potato" OR "solanum tuberosum")

Sweet potato 162 characters

("rhizosphere" OR "exudate*" OR "mucilage" OR "mycorrhiza*" OR "rhizobium*" OR "bacteria*" OR "fungi*") AND ("Phosphorus") AND ("sweet potato" OR "Ipomoea batatas")

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