

Interaction between root architecture, soil moisture and phosphorus placement on cereal productivity

F van der Bom¹, A Williams², and M Bell^{2,3}

¹ School of Agriculture and Food Sciences, The University of Queensland, St Lucia, QLD 4072, Australia

² School of Agriculture and Food Sciences, The University of Queensland, Gatton, QLD 43432, Australia

³ Queensland Alliance for Agriculture and Food Innovation, The University of Queensland, Gatton, QLD 4343, Australia

Abstract

Root architecture is considered a promising breeding target for developing resource-efficient crops. Currently, genotypes of winter and summer cereals are being screened for traits such as narrow seminal root angles, with the goal of enhancing access to deep soil water. These developments may deliver improvements for crop water use efficiency; however, topsoil nutrient stratification is an emergent profile characteristic for many soils in the northern region of Australia, leading to spatial separation of water and nutrients such as phosphorus (P) as the soil profile dries. To date, little is known about how ‘designer’ root systems respond to and interact with this separation of resources. We investigated the effect of P placement on crop and root growth of durum wheat genotypes defined by contrasting root traits (narrow/broad seminal root angle), with or without the influence of a drying soil profile and observed spatio-temporal interactions between root system architecture, P placement, and moisture availability. Differences in root distribution were related to plant capacity to take up P from different locations in the profile. Successful deployment of genotypes with pre-defined root architecture will depend on local conditions including rainfall patterns and soil P distribution.

Keywords

Phosphorus placement, drought, resource interactions, root ideotypes, root angle, root plasticity

Introduction

Plant roots are receiving increased attention in regard to efficient capture of soil resources (Lynch 2019). Breeders are currently trying to develop ideotypes that have 1) narrow, deep root systems, which are assumed to improve water and nitrate capture in dryland environments, and 2) wide, shallow root systems for better uptake of less mobile nutrients that tend to be more concentrated in the topsoil, such as phosphorus (P). Because phenotype selection of root system architecture (RSA) is extremely difficult under field conditions, breeders focus on easily measurable ‘proxy’ traits that correlate with the broader RSA instead. An example of this is root angle, which correlates with rooting depth in a range of crops (Lynch 2013; Manschadi et al. 2008). These developments may deliver improvements for crop water use efficiency but much uncertainty remains about how root traits (or RSA) affect uptake patterns in more complex soil environments (van der Bom et al. 2020).

Topsoil nutrient stratification is an emergent profile characteristic for many soils in the northern region of Australia, leading to spatial separation of water and nutrients such as P as the soil profile dries (Angus et al. 2019). In these systems, P fertiliser is increasingly applied in concentrated ‘deep bands’ that prolong crop access to P because they remain moist for a longer period of time. How crop root systems respond to this heterogeneous distribution of P and to the separation between moisture and P placement will determine productivity in any given set of seasonal conditions. Roots are also known to exhibit highly localised, plastic responses to spatial variation in soil, e.g. by proliferating in P ‘hotspots’ such as a P band (Hodge 2004). To date, little is known about how this plasticity and root-P interactions relate to the broader expression of root traits and RSA.

We conducted a series of experiments with durum wheat (*Triticum durum*) genotypes characterized by contrasting root systems (narrow or broad seminal root angle). Our goals were to investigate 1. the effect of stratified and banded P on crop growth and root distribution, and 2. how drying conditions influence root growth and utilization of P placed in different locations in the soil profile.

Methods

The soil used in the experiments was a Grey Vertosol with a low P status (8 mg kg⁻¹ Colwell P), representing a major cropping soil across the region. We used two experimental durum genotypes defined by a contrasting seminal root angle (1-63 wide; 6-17 narrow). These lines have previously been described by Alahmad et al. (2019).

Rhizobox experiment

A rhizobox (60 × 40 × 4 cm) experiment was conducted in a temperature-controlled glasshouse (22/17°C day/night) in a randomized block design with five replicates. Each rhizobox was filled with 10 kg of air-dry soil. Basal nutrients, except P, were supplied at the following levels (mg kg⁻¹ soil): 100.0 N, 166.2 K, 123.7 S, 20.4 Ca, 40.0 Mg, 2.0 Zn, 36.2 Cl, 3.4 Mn, 0.5 Cu, 0.1 Mo. The P placement treatments included: 1. a control with no P added; 2. a P band, placed at 25cm depth and 10cm off-centre; 3. Topsoil P, applied in the top 10 cm of the rhizobox; and 4. Mixed P, dispersed throughout the entire profile. For the Band, P was applied as a single spot of 100 mg P, corresponding to approx. 50 kg P ha⁻¹ under field conditions. The same amount was mixed through to the top 10 cm for the Topsoil P treatment and for the Mixed treatment this was repeated throughout the entire profile. The P fertiliser was applied as either mono-ammonium P (MAP) or monocalcium P (MCP) with additional ammoniumsulfate to ensure an equivalent N application between the two fertiliser types. We observed no statistical differences between the two P types therefore we present the mean of both fertiliser types.

We grew one plant per rhizobox, with moisture levels maintained between 60-70% of WHC by intermittent watering. After 38 days all shoots were harvested. Each rhizobox was placed on a pinboard and the soil was carefully washed away to expose the intact root system. The root system was photographed, and root properties evaluated using WinRhizo Pro 2019a.

Lysimeter experiments

A lysimeter experiment was conducted with 70 cm × 30 cm diameter cores (60 kg of dry soil). Three irrigation probes were inserted in different depths of the soil profile. A 1.5 cm layer of pebbles placed at 10 cm depth prevented water movement from the subsoil to the topsoil. We used two moisture regimes: 1. stable moisture maintained between 60 % and 80 % of WHC, and 2. a drying topsoil, for which the top 10cm of the profile up to the pebble layer was allowed to dry out after four weeks.

The experiment was a randomized block design with four replicates. Basal nutrients except P, were supplied at the following levels (mg kg⁻¹ soil): 154 N, 150 K, 37 S, 2 Zn, 150 Cl, using commercial fertilisers in the forms of urea, muriate of potash, Ammonium sulfate and zinc sulfate hepta hydrate. Fertiliser P (60 mg P kg⁻¹) was applied as MAP in four treatments: 1. A low-P control, 2. a deep band (25cm depth), 3. Topsoil-P (dispersed in the top 10cm layer), and 4. Mixed P (dispersed throughout the profile). Differences in nitrogen due to the ammonium content in MAP were compensated by the adding variable amounts of ammonium sulfate. We grew seven plants per core, corresponding to a commercial planting density of 100 plants m⁻². Shoots were harvested after 68 days, around anthesis.

Analyses, calculations and statistics

Dry matter weights of shoot and root samples were determined after drying at 60°C until constant weight. Shoot samples were ground, and P concentration was determined on ICP-OES after digestion with a mixture of hydrogen peroxide and nitric acid (McQuaker 1979). Phosphorus uptake was calculated by multiplication of P concentration and biomass. Treatment effects were analysed using linear mixed models. Pairwise comparisons were made using Tukey's HSD method.

Results

In the rhizobox experiment, we observed clear responses to P placement, with a strong increase in shoot biomass particularly for the topsoil and mixed P treatments and a smaller but still significant response to banded P ($P < 0.01$, Figure 1). The wide genotype tended to produce less biomass than the narrow one when P was banded, which corresponded to a clear response of root intensity at the 'band

zone' ($P < 0.05$). Root intensity at depth was also generally greater for the narrow genotype ($P < 0.05$), except for in the low-P control. Conversely, the wide genotype displayed overall greater root intensity in the top 10 cm ($P < 0.001$). These data corroborate information from literature that 'wide' genotypes tend to have shallower rooting, whereas 'narrow' genotypes tend to go deeper (Lynch 2019).

For both genotypes, root intensity in the topsoil was largest when P was placed in this zone and not elsewhere (i.e. the Topsoil P treatment, ($P < 0.001$)). This was in stark contrast to where P was mixed throughout the profile, which produced the lowest topsoil root intensity amongst all treatments. We believe this reflects that the plants grown in this treatment had available P in luxury supply in any location in the soil profile, and therefore there was no need for them to proliferate roots in a specific zone. P availability was also generally associated with more roots in medium to deep zones, as indicated by improved root intensity in layers > 30 cm deep ($P < 0.001$).

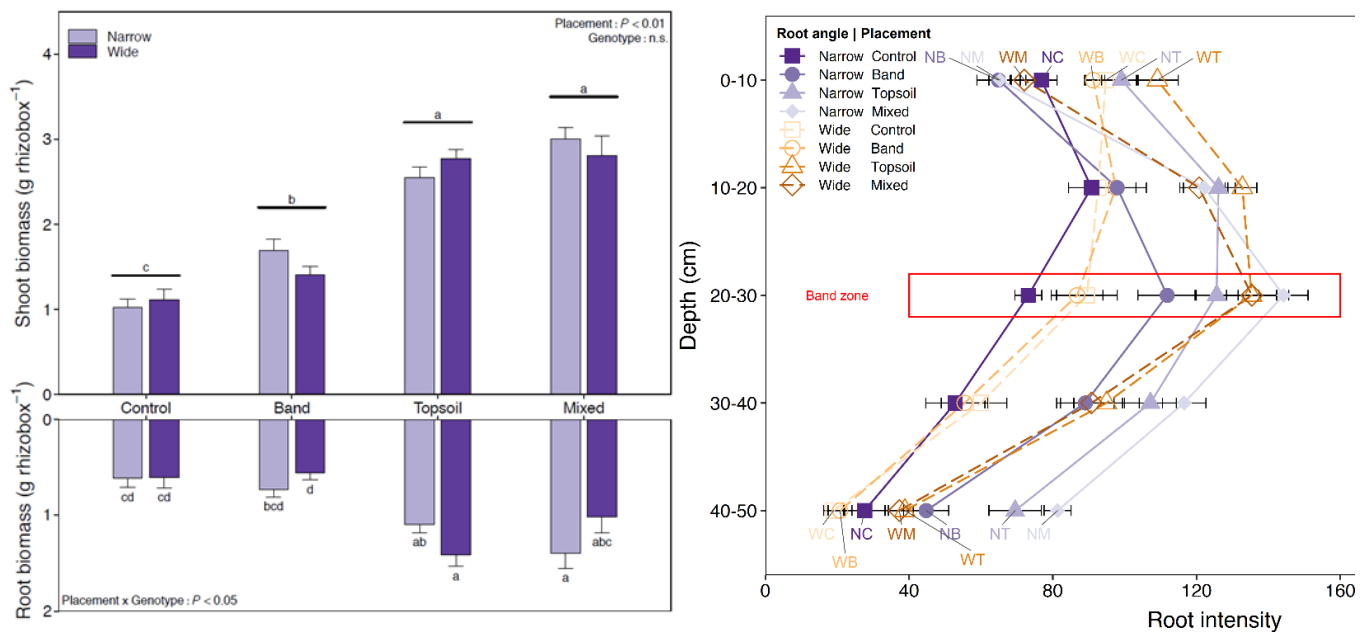


Figure 1. Left: Plant biomass in response to P placement in the rhizobox experiment. Right: Root intensity (visible root area on the pinboard in cm²) in the rhizoboxes.

We found clear crop responses to both P placement and moisture regime for the lysimeter experiment (Figure 2, $P < 0.001$) supporting those observed in the rhizoboxes. For example, under well-watered conditions, the wide genotype outperformed the narrow one in the Topsoil P treatment. However, the genotypic difference in biomass was not reflected in total P uptake. This may reflect timing of P uptake, in which the wide genotype was better able to scavenge the topsoil for P early on but as P uptake continued over time, the narrow genotype took up a total amount of P close to that of the wide genotype.

When P was banded, both genotypes took up similar amounts of P and produced a similar amount of biomass. However, the wide genotype had a lower number of flowering tillers, with a substantial proportion of them still developing ($P < 0.001$, data not shown). Thus, the wide genotype had a delayed phenology, presumably because it took longer to develop sufficient roots around the band and acquire P, as suggested by the observations of early root growth in the rhizoboxes.

Overall, a drying topsoil reduced shoot growth and P uptake compared with the well-watered treatments, with differences in magnitude depending on where P was placed in the profile. Drying reduces the volume from which the root system can take up P, so P located in the topsoil would effectively have become unavailable (Angus et al. 2019). In agreement, the Topsoil P treatment showed the proportionally greatest decrease in both biomass and P uptake, and the advantage of the wide genotype was diminished, presumably because it could not take advantage of its ability to better

scavenge the P rich topsoil. In contrast, the P band located in the subsoil remained moist, resulting in a relatively smaller effect of a drying topsoil because P uptake from the band was not affected. As a result, the total amount of P taken up by the crop tended to be greater when P was banded than when it was located in the topsoil.

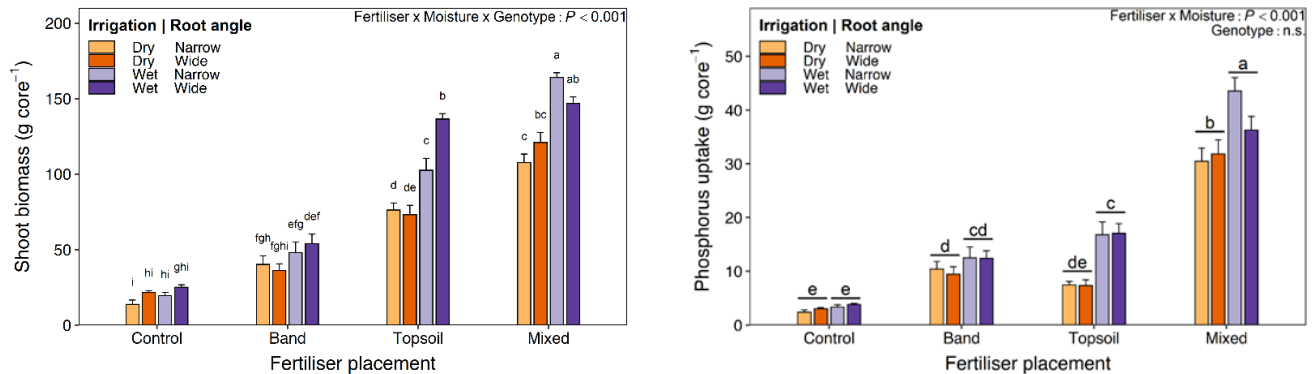


Figure 2. Crop responses to P placement and moisture in the lysimeter experiment. Left: Shoot biomass, Right: P uptake

Conclusion

Our data suggest that root architecture will interact the distributions of P and soil moisture, with RSA affecting how resources are used in a heterogeneous soil environment. In the current experiments, narrow and wide root angles were associated with deep and shallow RSA, affecting spatial exploration of the profile, but these genotypically defined root patterns required P nutrition to be reliably expressed. As such, the utility of ‘designer’ ideotypes (genotypes with a specific set of architectural root traits), will likely depend on the environment to which they are deployed. There is a need to further identify and better understand the trade-offs involved in the efficient capture of multiple, spatially disjunct soil resources.

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