An in-field high-throughput root phenotyping method using electromagnetic induction method

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Abstract

Root systems determine crop's capacity to take up water for growth and yield production, underpinning agricultural productivity. In this study, we aim to i) test a new approach for high-throughput phenotyping of root growth and function in the field using electromagnetic induction (EMI) coupled with a quasi-2D inversion algorithm, and crop canopy sensing technologies, ii) study how do genetic (G), environmental (E) and management (M) factors and their interactions, affect functional root traits?, and (iii) present results from two seasons of multi-environments field experimentations on the role of root traits on sorghum yield and yield stability. A 3D root activity factor (R) was calculated as a function of crop water use, soil water availability, and crop canopy size. The maximum rooting depth (RD) and a root architecture index (RA) was calculated from the R profiles in soil depth. The R was validated for the presence of roots using the root length density measured from root cores. The results showed that R was closely related to measured root length density under diverse environmental conditions. The calculated root functional traits (i.e., RD and RA) can capture ExM effects on root traits. Hybrids with high root phenotypic plasticity in RD and RA had more stable yields and yield components. We conclude that the proposed root phenotyping approach can provide a rapid and efficient option to phenotype crop rooting system in the field and can be used to study both mean traits and plasticity of the rooting system.

Keywords

Field root phenotyping, electromagnetic induction, functional root traits, root activity, rooting depth

Introduction

Root system determines the capacities of crops to take up water for growth and producing yield, underpinning agricultural productivity (Tracy et al., 2019). Identifying desirable root phenotypes directly in the field could be the short route to help identify and incorporate traits that enhance drought tolerance in breeding programs, and to inform more resilient agricultural management strategies.

Most root studies have been limited to inferring root function from costly and laborious 2D and 3D visualisations of the root system architecture, usually from growing single plants under controlled conditions. This is extrapolating root function from root form. An important constraint of these methods is that they do not represent the real root performance under real field environments.

Zhao et al. (2022) have developed a method using electromagnetic induction (EMI) coupled with inversion algorithms to rapidly characterize root growth and water use functions in the field. Advantages of this method are it is non-destructive and it overcomes typical artifacts of alternative methods, such as, the preferential root pathways generated by roots growing against a glass wall in a rhizo-box or hard surfaces in pots or soil columns.

In this study, we aim to (i) test the new root phenotyping method using EMI proposed in Zhao et al. (2022) based on field collected root cores, (ii) study how do genetic (G), environmental (E) and management (M) factors and their interactions, affect functional root traits?, and (iii) explore how does plasticity in root traits affect crop yield and yield stability?.

Methods

Two field trials were conducted in Queensland, Australia. The first trail was at a commercial farm in Nangwee, (27°3'2.73" S, 51°18'34.36" E) in 2020/21, and the second one was at the Gatton Research Station (27°32'44.19" S, 52°19'50.72" E) in 2021/22. The soils at both sites were uniform, black self-mulching cracking clay Vertosols (Isbell 2021). Both trials consisted of a factorial combination of three times of sowing (TOS, late winter, early spring and summer), two levels of irrigation (rainfed and supplementary irrigation), four sowing densities (3, 6, 9 and 12 plants m^{-2}), and six commercial hybrids coded as A, B, C, D, E, and F. Root cores down to 1.5 m were collected at hybrid E plots at one plant density (9 plants m^{-2}) for validating the EMI derived R. For more detailed information on the experiment design can be found in Zhao et al. (2024).

Two consecutive EMI surveys were conducted to determine R at each soil layer (down to 1.8m with 0.3m increments) in a 10-day dry window around flowering for each of the times of sowing. During these periods there was no rainfall or irrigation applied. A detailed description on EMI calibration and R calculation can be found in Zhao et al. (2022). Here, a proxy of rooting depth (RD) at flowering is calculated as the deepest soil depth at which no root activity (R=0) is detected over the two consecutive EMI surveys (Fig. 1). The root activity index (RA) is a proxy for the proportion of root activity in the top 0.5 m soil profile ($R_{0\text{-}0.5m}$) relative to the total root activity in the whole soil profile down to RD ($R_{0\text{-}RD}$). Larger values of RA indicate larger water use from the topsoil layers, and smaller values of RA indicate a larger proportion of total crop water use from the deeper soil layers:

$$RA = \frac{R_{0-0.5m}}{R_{0-RD}} \qquad (1)$$

Phenotypic plasticity for each trait was calculated as the slope of the reaction norm between the trait for each hybrid and the mean of the trait across hybrids for each environment. Conditional inference trees were used to untangle interactions and explore the effects of the factorial combinations of season, time of sowing, irrigation, plant population density and hybrid on RA and RD. The conditional inference trees were produced using the R package ‘partykit’.

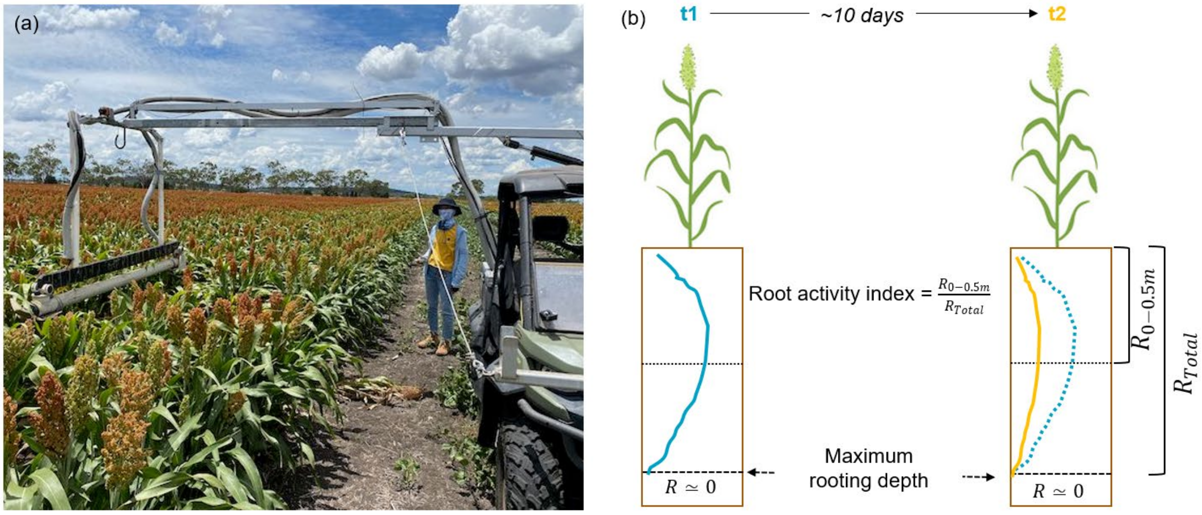

Figure 1 (a) Soil water surveying using an electromagnetic induction (EMI) instrument - DUALEM-21S (Dualem Inc., Milton, ON, Canada) shown over the crop canopy though the sensor is traversed on the soil surface in between the crop rows, and (b) calculation of root activity index (RA) and maximum rooting depth (RD, m) during a 10-day window around flowering.

Results

Linear relationships were observed between the EMI derived R and values of root length density (cm cm^{-3}) measured from the root cores (Fig 2). Fig. 2 also shows that for similar values of root length density, the dryland plots had larger values of root activity than the supplementary irrigated plots. In the dryland plots, the relationship did not hold for the topsoil layer (0.3-0.5m) as in the top layers the main limiting factor to water uptake was plant available water.

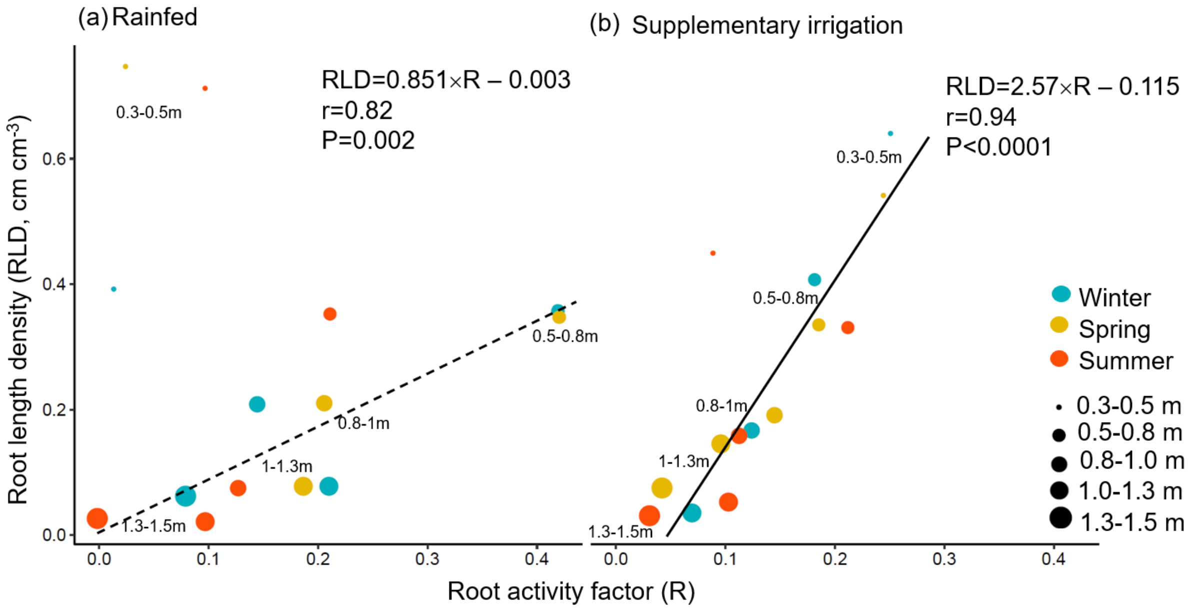

Figure 2. Relationship between the root length density (RLD, cm^3 cm^{-3}) and root activity factor (R) at flowering for the rainfed/dryland (a) and irrigated (b) plots. The data is for genotype E, sown at 9 pl m^{-2} in the 2020/21 season. Blue, orange, and red dots indicate the late winter, spring, and summer sown crops, respectively, and the size of the points indicate the soil layer. The linear relationships were not fitted to the data from the 0–0.3 m and 0.3–0.5 m depths, as those layers were close to wilting point, particularly in the rainfed treatment.

Fig. 3 shows that there are significant E×M effects on RA and RD. Differences in RD at flowering were mainly driven by the time of sowing (Fig 3), with summer-sown crops generally having a deeper RD at flowering (1.27-1.45 m) than crops sown in late winter or spring (1.18-1.36 m). RD at flowering tended to be deeper (1.45 m) during the first drier season, and with high plant population densities (i.e. 9, 12 plants m^{-2}). For crops sown in late winter and spring the irrigation regime was the main driver of differences in RD, with the rainfed plots having deeper RD (1.36 m) than the irrigated plots (1.18 m in 2020/21 and 1.32 m in 2021/22).

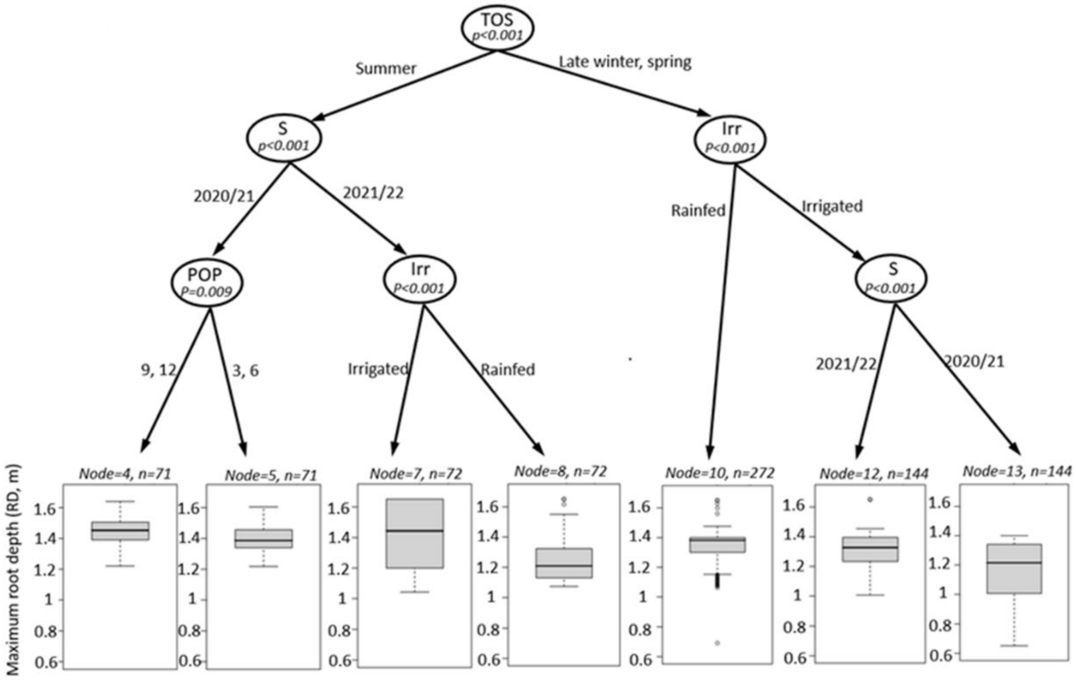

Figure 3. Conditional inference trees explaining the variation in maximum rooting depth (RD, m) for the contrasting seasons (S; 2020/21 and 2021/22) by time of sowing (TOS; later winter, spring and summer), irrigation (Irr; rainfed and supplementary irrigated) and plant density (POP; 3, 6, 9 and 12 plant m^{-2}) interactions.

In terms of yield plasticity (Fig. 4a) across the studied environments (Season*TOS), hybrids A and B (slope <1) were generally the most stable, while hybrid C (slope = 1.53) was the most plastic.

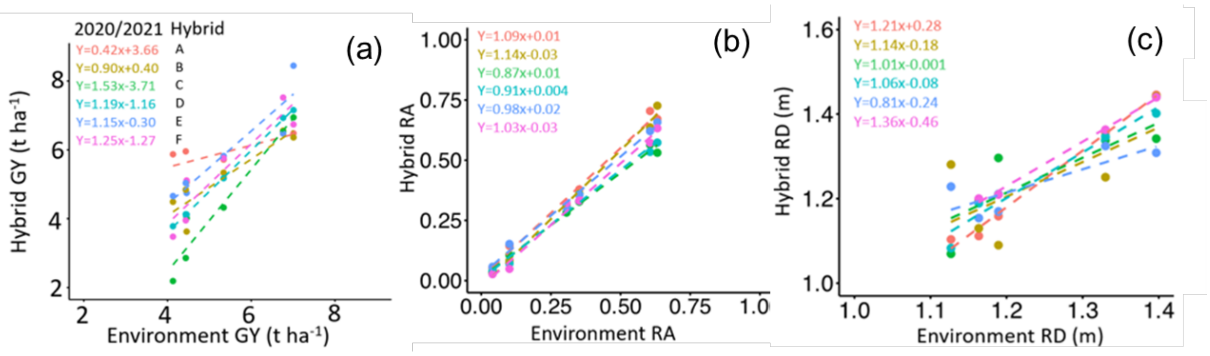

Figure 4. Reaction norms of grain yield (GY), root activity index (RA) and maximum rooting depth (RD, m) for the six sorghum commercial hybrids (A-F) in the 2020/21 season. Results for the 2021/22 season can be found in Zhao et al. (2024).

In contrast, hybrid A (slope =1.09) and B (1.14) had the most plastic RA (Fig. 4b) across the studied environments (Season*TOS), while hybrid C (0.87) had the most stable RA. Similar trends can also be observed for the RD. A larger root plasticity was associated with a deeper RD and a larger root activity in the deeper soil layers in the drier environments, and a shallower rooting depth and a larger superficial root activity in the hallower soil layers in the wetter environments.

In general, there was a negative association between the plasticity of grain number and plasticity of RA (Fig. 5b), and a strong negative correlation between the plasticity of grain weight and the plasticity of RD (Fig. 5f).

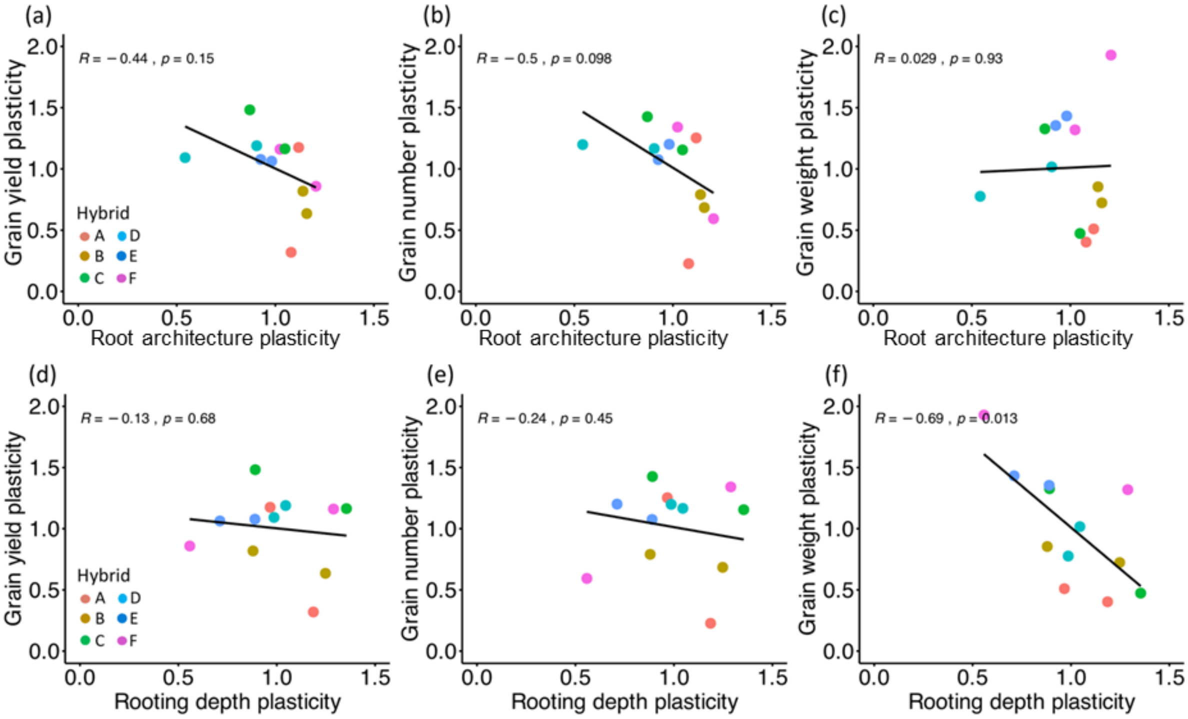

Figure 5. Relationships between the plasticity of grain yield, grain number and grain weight to root architecture index (RA, a, b and c) and maximum rooting depth (RD, d, e, and f) for six sorghum hybrids (A-F) over both the 2020/21 and 2021/22 seasons.

Conclusion

The EMI-derived R was closely related to the distribution of root length density of sorghum in the soil profile down to 1.5m across diverse environment scenarios. The phenotyping approach captured ExM effects on the functional root traits i.e., RD and RA. Hybrids with high root phenotypic plasticity had more stable yields and yield components. These results highlight the potential of the proposed EMI method for high-throughput phenotyping of both root traits and root phenotypic plasticity in the field. The approach needs to be scaled to a population of materials as used in pre-breeding trials.

References

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