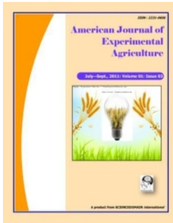

American Journal of Experimental Agriculture
4(7): 849-856, 2014

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Root Architecture Variation in Wheat and Barley Cultivars

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Authors' contributions

Author T.C. designed the study, performed WinRHIZO scans and statistical analysis, and produced the first draft of the manuscript. Author L.S. assisted with the study design, implemented the protocols, collected and organized the data, and helped with writing the manuscript. Author A.R. supervised and guided each aspect of the research. All authors have read and approved the final manuscript.

Original Research Article

Received 11th February 2014
Accepted 7th March 2014
Published 18th March 2014

ABSTRACT

Aims: We analyzed root architecture variation among heirloom and commercial cultivars of wheat and barley to improve our understanding of the quantitative variation present within small grain root architectures. We also compared lab-based root architecture measures with cultivar shoot:root ratios and field data.
Study Design: This study had a completely randomized design (CRD) with five replications of 5 heirloom and 4 commercial genotypes.
Place and Duration of Study: The study was conducted in Plant Science Laboratory, Faculty of Land and Food Systems, The University of British Columbia, Canada, during May-June, 2012.
Methodology: Wheat and barley seeds were grown on specific germination paper in a controlled environment, and were assessed for root architecture parameters: total root length, surface area, average diameter, root volume, number of tips, and branching angle (WinRHIZO Pro 2009c, Regent Instruments Inc.). Fisher's least significant differences were calculated in MSTAT-C to assess genotypic variation of these parameters. We also calculated shoot:root ratios. These root architecture results were compared to parameters measured in the field for these cultivars.
Results: Differences between wheat genotypes were identified among the cultivars with heirloom cultivars developing relatively larger and deeper root systems compared to the

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commercial cultivars (i.e., longer and thinner roots, more surface area, higher number of tips, and greater branching angle). Commercial wheat cultivars showed coarser roots (i.e., greater root diameters), more root volume, higher dry weight, and shoot to root ratios compared to the heirloom cultivars with cv. 'Scarlet' showing the highest values. Among barley cultivars, heirloom 'Jet' had the highest values for parameters (i.e., length, area, volume, and branching angle) and the lowest shoot:root ratio compared to the commercial cvs. 'Oxbridge' and 'Camus'. The commercial wheat cv. 'Scarlet' showed a positive association between grain yield, under low input organic conditions, and root diameter whereas the heirloom barley cv. 'Jet' had positive associations between grain yield, root length and surface area.

Conclusion: The root architectures of the heirloom wheat and barley cultivars indicate they may be better suited for low phosphorus and/or drought conditions, typical of low input or organic production. The root architectures of the commercial cultivars, on the other hand, were deemed more suitable for high input conditions. There exists a positive association between root length, surface and yield potential when heirloom wheat cultivars were grown under low input conditions. Longer and finer roots, and the lower shoot:root ratio in some heirloom cultivars further suggest breeding potential for improved nutrient uptake efficiency and drought tolerance in wheat and barley.

Keywords: Root architecture; heirloom and commercial cultivars; intraspecific variation; grain yield.

1. INTRODUCTION

The geometry of a plant's root system is an important determinant of crop performance. It affects drought tolerance, nutrient and water uptake efficiency, lodging resistance, and tolerance to mineral toxicity [1]. As root architecture is under genetic control, it can be manipulated for adaptation to marginal environments [1], with different root parameters varying in importance depending on the context. For example, wheat and barley plants with a higher percentage of roots in the upper soil layer will naturally absorb a higher percentage of nutrients from that area, as where typically applied in conventional agriculture [2]. However, a plant with this architecture will be less drought tolerant as water reserves are typically located deeper in the soil profile. In addition, different root architectures explore soil volumes to varying degrees and can impact a plant's ability to exploit limited resources. For example under phosphorus (P) stressed conditions, roots proliferate within a specific area with higher P contents [3]. Therefore, a root system that explores a greater soil volume, i.e., longer and thinner roots, will have a greater chance of encountering and exploiting resources.

As root architecture strongly affects plant performance, understanding the inherent variation among cultivars is important for both plant breeders and farmers. There remains a great need to accurately characterize and associate root architectures with both inheritance and production performance. In addition, characterizing root architecture variation can help link our fundamental knowledge across plant science disciplines, e.g., plant ecology, plant physiology, and agronomy [4]. Finally, significantly more research has been conducted on the above-ground plant parts compared with below-ground parts, despite its accepted importance [1]. Therefore, we assessed heirloom and commercial cultivars of wheat and barley to improve our understanding of the variation in small grain root architecture and to assess their potential for low input sustainable agriculture.

2. MATERIALS AND METHODS

2.1 Cultivar Selection

Heirloom and commercial cultivars of hard red spring wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) that performed well (i.e., high yield, protein content, and disease resistance) in cultivar trials [5] were selected for root architecture experiments. These included five wheat cultivars (commercial cvs. 'Scarlet' and 'Norwell' and heirloom cvs. 'Red Fife', 'Glenn', and 'Reward') and four barley cultivars (commercial cvs. 'Oxbridge' and 'Camus' and heirloom cvs. 'Dolma' and 'Jet').

2.2 Seed Treatment

Seeds were surface sanitized in 70% ethanol for 5 minutes followed by rinsing thrice with distilled water under aseptic conditions. After rinsing, seeds were left to imbibe in distilled water for 12 hours.

2.3 Study Design and Set-up

We used a completely randomized design (CRD) with five replications for each cultivar. Seedlings were grown on germination paper (10"x10", Anchor Paper Co. Seed Solution, Saint Paul, MN) following a modified version of B Snyder and J Lynch (Department of Horticulture, Penn State University, PA, USA, personal communication). In brief, we used two sheets of blotting paper (Anchor Paper Co., St. Paul, MN, USA) and cut a notch (1cm wide and 4cm long) at the center of the top edge of each sheet. Then, we placed two pieces of paper without notches on top. These layers were then placed in a large, clear bag (10"x11", SC Johnson and Son Limited, Brantford, ON, Canada) and moistened completely with 0.5mM $CaSO_4$ (MW 136) solution. Next, a germination cradle was prepared; this was achieved by pressing the paper without notches into the underlying notch. One seed was then placed embryo side down into the germination cradle. This germination unit (i.e., bag, moistened paper and seed) was then secured with two binder clips to a similar sized sheet of plexiglass, and held at a 45 degree angle. The germination units were kept in a growth chamber (Controlled Environments Ltd., Winnipeg, MB, Canada) set at 25ºC and 60% relative humidity and grown for 10 days. Light was provided using fluorescent lights at an intensity of 90µmols m^{-2} s^{-1} for 16 hours each day. All germination units were periodically moistened with 0.5mM $CaSO_4$ to prevent drying.

2.4 Root Measurement and Data Analysis

After 10 days, the paper and seedlings were removed from the bags and scanned on a calibrated, lighted flatbed scanner at 300 dpi. Scans were then analyzed by Win RHIZO software (Win RHIZO Pro 2009c, Regent Instruments Inc.). Win RHIZO data were transferred to MSTAT-C for statistical analyses [6]. Metrics calculated with Win RHIZO include: total root length, surface area, average diameter, root volume, number of tips, and branching angle. We also dried samples, in a drying oven at 70ºC for 48 hours, and then weighed them to calculate dry root weight, dry shoot weight, and subsequently shoot to root ratios. These results were compared to parameters previously measured in the field for these cultivars in performance trials [5].

3. RESULTS AND DISCUSSION

Wheat: Root architecture metrics for commercial and heirloom wheat are shown (Table 1). In general, heirloom cvs. 'Glenn' and 'Reward' displayed notable differences (i.e., longer root, greater surface area and higher number of tips) compared with the commercial cvs. 'Scarlet' and 'Norwell'. Overall, the commercial cultivars showed coarser roots (i.e., higher root diameter), greater volume, and higher dry root weight, and shoot to root ratios compared to the heirloom cultivars, with cv. 'Scarlet' displaying the highest values. There is significant variation among the heirloom cultivars with cv. 'Reward' displaying the highest surface area, diameter, root volume, and number of tips compared to cv. 'Red Fife' and cv. 'Glenn'. The lowest shoot:root ratio was observed in heirloom wheat cv. 'Reward' indicating the greatest biomass partitioning to the roots among all cultivars and a trait associated with drought tolerance potential [7]. The commercial cultivars were more uniform for a number of parameters including surface area, diameter, volume, and angle of branching (Table 1). Heirloom cultivars with typically longer and thinner roots, greater surface area, more tips, and higher branching angles, are predicted to have larger and deeper root systems than the commercial cultivars.

Table 1. Root architecture metrics for heirloom and commercial wheat cultivars

Cultivars	Root Length (cm)	Surface Area (cm^2)	Average Diameter (mm)	Root Volume (cm^3)	No. of Tips	Branching Angle (degrees)	Dry Root Weight (mg)	Shoot:Root Ratio
Scarlet-C	64.8	9.43	0.47	0.11	85	35.7	11.4	1.41
Norwell-C	57.0	7.92	0.46	0.09	52	34.7	8.6	1.05
Red Fife-H	65.6	5.81	0.33	0.05	87	37.2	7.0	1.07
Glenn-H	75.5	8.18	0.34	0.07	66	35.0	9.7	1.22
Reward-H	71.4	9.62	0.43	0.10	103	35.6	9.7	0.88
SEM (±)	1.69	0.87	0.04	0.01	4.0	0.62	0.76	0.11
$LSD_{0.05}$	4.80	2.47	0.11	0.03	11.37	1.76	2.16	0.31

C indicates commercial cultivar, H indicates heirloom cultivars, SEM indicates standard error of the mean, and LSD indicates least significant difference

Root length distribution across diameter classes in heirloom and commercial wheat cultivars is shown (Fig. 1). Heirloom cultivars produced thinner roots then commercial cultivars with 75-95% of all roots within the <0.5 mm diameter class compared with 50-75% in commercial cultivars. Cultivar 'Glenn' possessed the highest percentage (95%) of thin roots while the commercial cvs. 'Scarlet' and 'Norwell' displayed the lowest percentage, i.e., coarsest.

Barley: Barley cultivars also showed significant variation in most root parameters including length, area, volume, and angle of branching (Table 2). No trends differentiating commercial and heirloom cultivars are identified. The heirloom cv. 'Jet', however, produced the longest roots with the greatest surface area along with the highest branching angle and the lowest shoot:root ratio compared to all other cultivars.

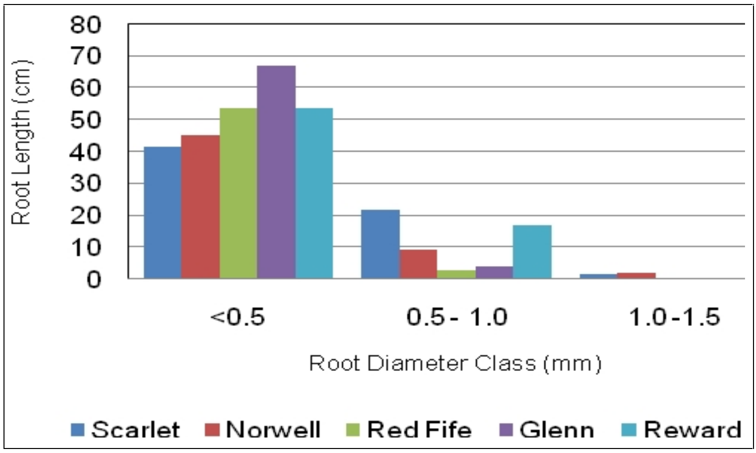

Fig. 1. Root length distribution in diameter classes in wheat cultivars

Table 2. Root architecture metrics for heirloom and commercial barley cultivars

Cultivars	Root Length (cm)	Surface Area (cm^2)	Average Diameter (mm)	Root Volume (cm^3)	No. of Tips	Branching Angle (degrees)	Dry Root Weight (mg)	Shoot:Root Ratio
Oxbridge-C	80.3	8.2	0.33	0.07	139	34.8	7.4	1.09
Camus-C	73.4	9.7	0.42	0.10	250	34.3	8.1	1.15
Jet-H	100.1	11.1	0.35	0.10	197	36.2	7.2	0.83
Dolma-H	84.6	8.5	0.43	0.09	137	35.4	10.0	1.06
SEM (±)	3.40	0.62	0.03	0.01	12.1	0.64	0.59	0.09
$LSD_{0.05}$	9.67	1.76	0.08	0.28	34.4	1.82	1.67	0.25

C indicates commercial cultivar, H indicates heirloom cultivars, SEM indicates standard error of the mean, and LSD indicates least significant difference

Fig. 2 shows root length distribution by diameter class (mm) in barley cultivars. The heirloom barley cv. 'Jet' produced the finest roots with almost 100% roots falling in <0.5 mm diameter class followed by the commercial cv. 'Oxbridge' (>90%). Commercial barley cv. 'Camus' displayed the coarsest roots (0.5-1.0mm) compared to either heirloom cultivar.

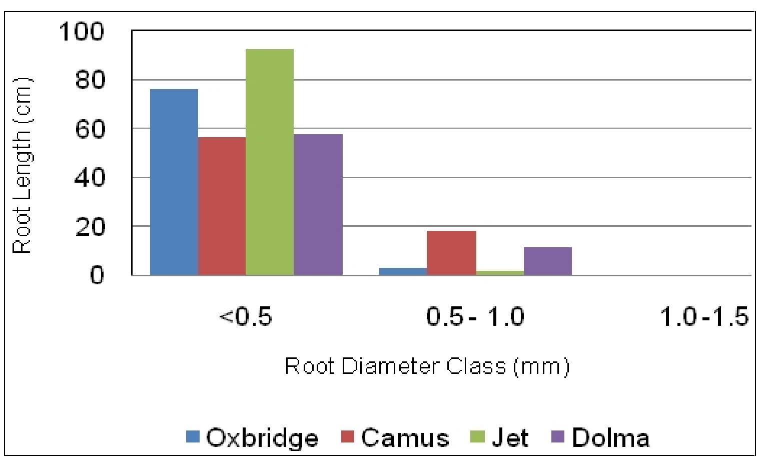

Fig. 2. Root length distribution in diameter classes in barley cultivars

Root architecture association with field performance: Field performance of both heirloom and commercial cultivars, grown under low input organic conditions, are presented (Table 3). There exists variation for the association between wheat root architecture (Table 1, Fig. 1) and plant performance metrics (Table 3). In general, the heirloom wheat cultivars produced tall plants with long internodes (Table 3) and longer finer more branched root systems (Table 1) compared to the commercial cultivars. However, they also tended to lodge more than the commercial cultivars due to their taller culms. The commercial cultivar cv. 'Scarlet', with its greatest root diameter, root volume, dry root weight and shoot:root ratios (Table 1) produced higher grain yield, harvest index [HI, defined as a ratio of economical yield (grain yield) to the total above ground biomass (grain yield + plant biomass)], and 1000 seed test weight (Table 3) compared to the heirloom cultivars suggesting that cultivars with the shorter (i.e., more feeder or surface) roots are also suitable under organic systems.

Table 3. Field performance of small grain cultivars grown under low input conditions; republished with permission [5]

Cultivars	Plant Height at Harvest (cm)	Grain Yield (t/ha)	Harvest Index (%)	1000 Seed Weight (g)
Wheat				
Scarlet (C)	103	5.4	48.4	48.0
Norwell (C)	114	5.3	42.7	44.7
Red Fife (H)	135	4.1	37.4	43.7
Glenn (H)	109	5.1	42.4	40.0
Reward (H)	127	5.2	32.5	41.0
SEM (±)	3.67	0.31	2.66	2.82
$LSD_{0.05}$	7.35	0.65	5.32	5.65
Barley				
Oxbridge (C)	65	5.8	53.8	55.3
Camus (C)	81	5.0	53.8	54.0
Jet (H)	75	5.5	29.2	48.5
Dolma (H)	78	4.9	41.7	36.3
SEM (±)	3.49	0.29	3.12	3.22
$LSD_{0.05}$	7.0	0.6	6.25	6.45

C indicates commercial cultivar, H indicates heirloom cultivars, SEM indicates standard error of the mean, and LSD indicates least significant difference

Unlike wheat, barley did not show any meaningful associations between root metrics and field performance (Tables 2, 3).

Among the few heirloom and commercial wheat and barley cultivars assessed in this study, significant variation was observed for many root architectural parameters. A number of reports link root architecture with traits associated with low-input production including nutrient uptake efficiency, culm strength, and drought tolerance. Jones et al. [8] showed that root diameter is one of the most important determinants of nutrient uptake efficiency with thinner roots having greater efficiency. Furthermore, several reports support the association between thinner roots and improved P and water uptake [8,9]. In wheat, it has been reported that many wild forms and landraces possess large root systems with thin roots, but tend to lodge because of their tall culms [10,11]. Last, Bernier et al. [7] suggested that plants with low shoot:root ratio possess a water stress avoidance potential while plants with a higher ratios are more likely to suffer from water stress. The variation observed among these few heirloom and commercial cultivars indicates significant variation persists in these germ-plasm pools, and is available to breeders interested in developing cultivars for low-input agriculture.

4. CONCLUSION

This study assessed the variation among heirloom and commercial cultivars of wheat and barley for several root architectural traits. Our assessment showed significant variation among heirloom and commercial wheat cultivars and between root and agronomic performance traits. Overall, heirloom wheat cultivars displayed longer and thinner roots, more surface area, higher number of tips, and greater branching angle compared to commercial cultivars. These traits are often associated with resistance to drought stress and improved P uptake. The commercial cultivars, on the other hand, generally displayed coarser roots and greater shoot:root ratios. There exists variation between heirloom and commercial wheat cultivars for the association between root architecture and plant performance. Barley, however, did not show any meaningful associations between root metrics and field performance. Overall, the longer and finer roots, and the lower shoot:root ratio of some heirloom cultivars suggest they may be useful candidates for inclusion in breeding programs designed to improve nutrient uptake efficiency and drought tolerance.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
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