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Short Communication

Root Architecture Variation in Small Grain Cultivars

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 root:shoot 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 measured root:shoot 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 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 root to shoot 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 root:shoot 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 root:shoot 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*

11 1. INTRODUCTION

12

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

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

37 2. MATERIALS AND METHODS

38

39 2.1 Cultivar selection

40 Heirloom and commercial cultivars of hard red spring wheat (*Triticum aestivum* L.) and
41 barley (*Hordeum vulgare* L.) that performed well (i.e., high yield, protein content, and
42 disease resistance) in cultivar trials [5] were selected for root architecture experiments.
43 These included five wheat cultivars (commercial cvs. 'Scarlet' and 'Norwell' and heirloom
44 cvs. 'Red Fife', 'Glenn', and 'Reward') and four barley cultivars (commercial cvs. 'Oxbridge'
45 and 'Camus' and heirloom cvs. 'Dolma' and 'Jet').
46

47 2.2 Seed treatment

48 Seeds were surface sanitized in 70% ethanol for 5 minutes followed by rinsing thrice with
49 distilled water under aseptic conditions. After rinsing, seeds were left to imbibe in distilled
50 water for 12 hours.
51

52 2.3 Study design and set-up

53 We used a completely randomized design (CRD) with five replications for each cultivar.
54 Seedlings were grown on germination paper (10"x10", Anchor Paper Co. Seed Solution,
55 Saint Paul, MN) following a modified version of B Snyder and J Lynch (Department of
56 Horticulture, Penn State University, PA, USA, personal communication). In brief, we used
57 two sheets of blotting paper (Anchor Paper Co., St. Paul, MN, USA) and cut a notch (1 cm
58 wide and 4 cm long) at the center of the top edge of each sheet. Then, we placed two pieces
59 of paper without notches on top. These layers were then placed in a large, clear bag
60 (10"x11", SC Johnson and Son Limited, Brantford, ON, Canada) and moistened completely
61 with 0.5 mM CaSO₄ (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 25°C and 60% relative humidity and grown for 10 days. Light was provided using fluorescent lights at an intensity of 90 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for 16 hours each day. All germination units were periodically moistened with 0.5 mM CaSO_4 to prevent drying.

2.4 Root architecture 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 WinRHIZO software (WinRHIZO Pro 2009c, Regent Instruments Inc.). WinRHIZO data were transferred to MSTAT-C for statistical analyses [6]. Metrics calculated with WinRHIZO 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 70°C for 48 hours, and then weighed them to calculate dry root weight, dry shoot weight, and subsequently root to shoot 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 root to shoot 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 root:shoot 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)	Root:Shoot 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 ($\pm$)	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 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 than 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.

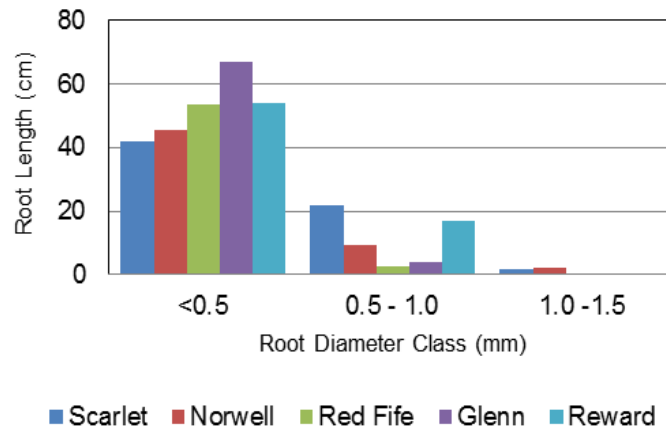


Fig. 1: Root length distribution in diameter classes in wheat cultivars

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 root:shoot ratio compared to all other 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)	Root:Shoot Ratio
Oxbridge-C	80.3	8.19	0.33	0.07	139	34.8	7.4	1.09
Camus-C	73.4	9.68	0.42	0.10	250	34.3	8.1	1.15
Jet-H	100	11.1	0.35	0.10	197	36.2	7.2	0.83
Dolma-H	84.6	8.50	0.43	0.09	137	35.4	10	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 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 (0.5-1.0 mm) compared to either heirloom cultivar.

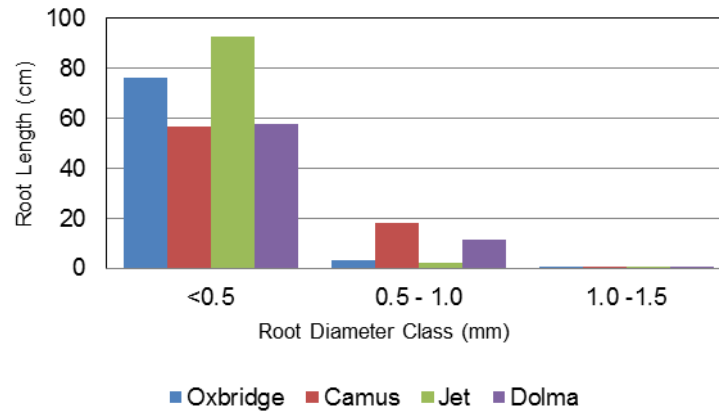


Fig. 2: Root length distribution in diameter classes in barley cultivars

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 root:shoot 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
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
Reward (H)	127	5.2	32.5	41
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
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 Mean, and LSD indicates Least Significant Difference

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

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

161 **4. CONCLUSION**

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

176 **COMPETING INTERESTS**

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179 Authors have declared that no competing interests exist.

180 **CONSENT (WHERE EVER APPLICABLE)**

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183 N/A

184 **ETHICAL APPROVAL (WHERE EVER APPLICABLE)**

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187 N/A

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226 DEFINITIONS, ACRONYMS, ABBREVIATIONS

227 N/A

230 APPENDIX

231 N/A