CROPS

Winter Wheat Seedling Emergence from Deep Sowing Depths

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ABSTRACT

Growers in low-precipitation (<300 mm annual) dryland wheat–fallow areas of the inland Pacific Northwest need winter wheat (*Triticum aestivum* L.) cultivars that emerge from deep sowing depths in dry soils. Stand establishment is the most important factor affecting winter wheat grain yield in this region. Despite poor resistance to disease, modest grain yield potential, and other problems, the outdated soft white winter wheat (SWWW) cultivar Moro is widely sown in these dry areas, due to its excellent emergence ability. All other SWWW cultivars are semidwarfs that carry emergence-impeding Rht_1 or Rht_2 reduced-height genes. From 12 sowing trials at 2 locations over 4 yr, we compared the emergence capability of Moro to (i) 8 SWWW cultivars and (ii) 16 SWWW advanced experimental Moro-replacement lines. Under both wet and dry soil conditions (soil water content in the seed zone ranged from 11 to 19 mm^3 mm^{-3}), seeds were sown deep, with 110 to 160 mm of soil cover. Moro always emerged fastest and achieved the best final stand compared with the semidwarf cultivars. The advanced experimental lines, which contained either no reduced-height gene or a Rht_1, Rht_2, or Rht_8 reduced-height gene, had superior straw strength, disease resistance, and grain quality compared with Moro. The best-emerging advanced experimental lines had coleoptile lengths >100 mm. Coleoptile length was associated with emergence capability among both cultivars ($r^2 = 0.71$, $P < 0.004$) and advanced lines ($r^2 = 0.62$, $P < 0.001$). From deep sowing depths in this study: (i) cultivars and advanced lines with Rht_1 and Rht_2 reduced-height genes always emerged poorly compared with Moro; (ii) the Rht_8 reduced-height gene did not hamper emergence to the extent that Rht_1 and Rht_2 did; and (iii) several advanced experimental lines with long coleoptiles equaled or exceeded Moro for emergence.

Sixty percent of Washington's winter wheat production area receives an average annual precipitation of only 150 to 300 mm (Hasslen and McCall, 1995). Growers in this 1.5-million-hectare low-precipitation dryland region are unable to take full advantage of the extensive progress in soft white winter wheat (SWWW) improvement over that past 30 yr, because (except for Moro) all SWWW cultivars (both club and common types) in the Pacific Northwest are semidwarfs that carry Rht_1 or Rht_2 dwarfing genes (Allan, 1980). Semidwarfs have coleoptile lengths 30 to 40% shorter than nonsemidwarfs (Allan et al., 1962). Rate of coleoptile elongation and length of the coleoptile are significantly correlated with emergence capability (Allan et al., 1961, 1965; DeJong and Best, 1979).

Moro was released 32 yr ago by Oregon State University (Rohde, 1966). By today's standards, it has poor disease resistance, modest yield potential, and inferior grain quality; it is also difficult to thresh, and has weak straw that causes lodging. Despite these deficiencies, Moro is the number-one club-type SWWW grown in Washington (Hasslen and McCall, 1995), due to its ability to emerge from deep sowing depths through thick soil cover.

The climate of the inland Pacific Northwest is characterized by winter precipitation and dry summers. Successful establishment of winter wheat on fallow in late August or early September is dependent on carryover soil water from the previous winter. Seed-zone water content is the controlling factor for wheat seedling emergence, but soil temperature and depth of soil covering the seed are also important (Lindstrom et al., 1976). Seed-zone soil water content of 11 mm^3 mm^{-3} is considered the lower limit for winter wheat seedling emergence from deep sowing depths on silt loam soils in the inland Pacific Northwest (Schillinger and Papendick, 1997). In dry years, seed is placed as deep as 200 mm below the soil surface with deep furrow drills to reach adequate water for germination, and seedlings may emerge through 150 mm or more of dry soil cover. Under these deep sowing conditions, it is not the coleoptile that emerges from the soil (Simmons, 1987), but rather the first true leaf after pushing through the tip of the coleoptile.

Stand establishment is the most important single factor affecting winter wheat grain yield in low-precipitation dryland regions of the Pacific Northwest (Bolton, 1983). Fast-emerging cultivars are desirable, because rain soon after sowing causes surface soil crusting, and the emerging coleoptile or first leaf often cannot penetrate such crusts. In addition to increasing grain yield potential, successful establishment of winter wheat on fallow has a major influence on decreasing wind erosion in late summer to early fall and provides protection against water erosion during the winter (Papendick and McCool, 1994).

Our objective was to compare seedling emergence rate and final stand establishment of the standard cultivar Moro to (i) other SWWW cultivars available to growers in low-rainfall dryland areas of the Pacific Northwest and (ii) advanced experimental lines that are possible candidates for cultivar release to replace Moro. Our goal is to develop cultivars that emerge equal to or better than Moro and surpass it for other traits.

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Abbreviations: DAS, days after sowing; SWWW, soft white winter wheat.

MATERIALS AND METHODS

Two winter wheat seedling emergence studies were conducted during August and September of 1994, 1995, 1996, and 1997 at the Washington State University Dryland Research Station at Lind (240 mm average annual precipitation) and at the Robert and Mark Kramer farm near Harrington, WA (305 mm average annual precipitation). In Study 1, emergence of commercially available SWWW cultivars was evaluated from eight sowing dates at both Lind and Harrington over a 3-yr period. Cultivars were common types Eltan, Lewjain, Madsen, and Rod, and club types Hyak, Moro, Rely, Rohde, and Hiller. All cultivars are semidwarf types that carry either the *Rht₁* or *Rht₂* reduced-height gene, except Moro, which is standard height (i.e., with no reduced-height genes). Seed for sowing was obtained from newly harvested seed (i.e., harvested the same year) of all cultivars each year from a rainfed nursery at the Lind Dryland Research Station.

In Study 2, seedling emergence of 16 potential Moro-replacement advanced experimental lines was compared with that of Moro on four sowing dates in 1996 and 1997 at Lind. Ten lines were standard-height types (no dwarfing genes); three lines (ARS 96329, ARS 96339, and ARS 96342) carry the Rht_8 semidwarf gene; and three more lines (WA 7833, WA 7835, and WA 7752) that have either the Rht_1 or Rht_2 semidwarf gene were also included for comparison. The Rht_8 gene is reported not to reduce coleoptile length to the extent of the Rht_1 and Rht_2 genes (Konzak, 1981; Allan et al., 1996). Seed of advanced experimental lines and Moro was obtained both years from a rainfed nursery at Lion's Ferry, WA.

Field plots were established on summer-fallowed soils at both locations. The soil type at Lind is a Shano silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids) and at Harrington a Renslow silt loam (coarse-silty, mixed, superactive, mesic Calciargidic Argixerolls).

Seeds were lightly hand-screened to remove shriveled and broken kernels for sowing each year. Germination of seeds for all cultivars and experimental lines exceeded 95% in tests conducted in petri dishes at a constant 21°C temperature. One-thousand-kernel weight was measured for the 1997 advanced experimental lines. For each cultivar or advanced experimental line, 100 seeds were sown using a four-opener deep-furrow drill in 4.3 m-long rows with a 0.38-m spacing between rows. The drill delivered seed of individual entries to separate openers. In both studies, the design was a randomized complete block, with 12 replicates per entry.

Seeds were sown 160 to 210 mm below the soil surface all years, depending on the seed-zone water content (Fig. 1). The depth of soil covering the seed varied from 110 to 160 mm (Table 1). Soil volumetric water content in the seed zone was determined gravimetrically at time of sowing (Gardner, 1986). These measurements were obtained in 20-mm increments, avoiding wheel tracks, to a depth of 220 mm using an incremental soil sampler (Pikul et al., 1979). Mean water content values were determined from four soil cores taken at each location on each sowing date. Wheat seedling emergence (%) was determined by counting individual plants at 24-h intervals beginning 7 d after sowing (DAS).

Coleoptile length and first-leaf length measurements were obtained in 1996 and 1997 by growing 10 seedlings of each selection in shallow, 20-mm-deep flats filled with moist vermiculite. Entries from both cultivars and advanced experimental lines were replicated 10 times in a randomized complete block design. Flats were placed in a totally darkened enclosure at a constant temperature of 21°C. Coleoptile length was measured on five randomly selected plants 7 DAS. First-leaf length was measured from the seed to the leaf tip from the same plants selected for coleoptile measurement.

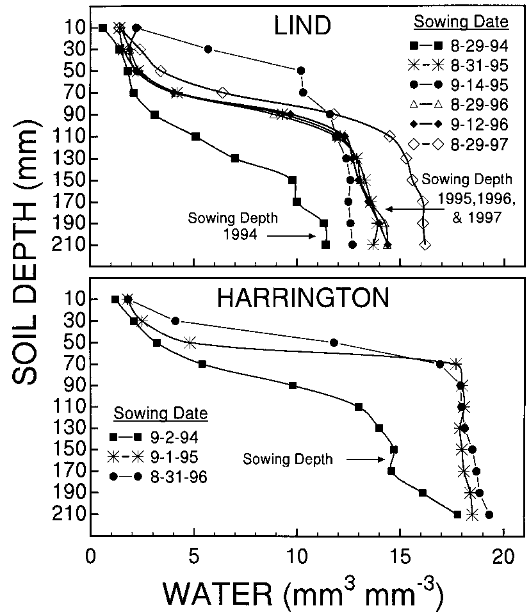

Fig. 1. Sowing depth and seed-zone soil water content on nine sowing dates in 4 yr (1994–1997) at Lind and Harrington, WA, to compare the emergence capability of soft white winter wheat cultivars and advanced experimental lines with Moro.

An analysis of variance (ANOVA) was conducted for (i) wheat seedling emergence percentage for every sampling date each year, as well as a combined analysis across years and locations, and for (ii) coleoptile and first-leaf lengths. Treatment means were separated by Fisher's protected LSD. Treatments were considered significantly different at $P < 0.05$. Simple linear regression and multiple regression models were calculated to determine the association of coleoptile length, first-leaf length, and seed weight to emergence for both cultivars and Moro replacement advanced experimental lines.

RESULTS

Sowing Conditions

Sowing conditions were dry in 1994, with soil water content in the seed zone of 11.5 $mm^3\ mm^{-3}$ at Lind and 14.6 $mm^3\ mm^{-3}$ at Harrington, but the seed zone was

Table 1. Soil covering seed, seed-zone soil water content, and amount and timing of rainfall between sowing and emergence for soft white winter wheat cultivars and advanced experimental lines sown on 10 dates at Lind and Harrington, WA (1994–1997).

Sowing date	Soil covering seed	Soil water content	Rainfall	
			Amount	Timing
	mm	$mm^3\ mm^{-3}$	mm	DAS†
Lind				
29 Aug. 1994	160	11.5	3	7
31 Aug. 1995	140	13.4	13	7
14 Sept. 1995	110	12.9	0	
29 Aug. 1996	150	13.4	1	11
12 Sept. 1996	140	13.4	4	8
29 Aug. 1997	155	15.4	8 + 2	5, 17
11 Sept. 1997	155	15.4	2 + 12	4, 6
Harrington				
2 Sept. 1994	130	14.6	5	7
1 Sept. 1995	120	18.3	19	6
31 Aug. 1996	140	18.9	3 + 4	7, 14

† DAS, days after sowing.

Table 2. Mean percent seedling emergence at 7 to 22 d after sowing of nine soft white winter wheat cultivars, combined across three sowing dates at Harrington, WA, and four sowing dates at Lind, WA (1994–1996).

		Seedling emergence								
Rank	Cultivar	7	8	9	10	11	12	14	15	22
		%								
1	Moro	5	15	27	36	42	45	48	48	48
2	Lewjain	2	7	13	21	27	32	35	35	36
3	Eltan	2	10	16	23	29	32	34	34	34
4	Rohde	1	4	13	20	26	29	31	32	32
5	Madsen	1	4	10	17	24	27	28	28	29
6	Rely	1	2	7	14	20	23	26	27	27
7	Rod	0	2	7	13	18	22	25	25	26
8	Hyak	1	4	9	14	19	23	24	24	24
9	Hiller	0	1	3	7	11	14	18	19	21
	LSD (0.05)	2	3	4	5	6	6	6	6	6

relatively wet at both locations in 1995, 1996, and 1997 (Fig. 1; Table 1). Seed-zone soil water content at Harrington in the dry 1994 sowing period exceeded that at Lind even during the wetter years, except in 1997 (Table 1), showing the wide difference in late-summer sowing conditions between the two precipitation zones (240 mm annual precipitation at Lind, and 305 mm at Harrington).

Cultivars

Moro emerged significantly faster and achieved the best final stand compared with the other cultivars (Table 2). Due to extremely dry sowing conditions at Lind in 1994, most seedlings either died before they reached the soil surface or were unable to penetrate a light soil crust caused by 3 mm of rain occurring 7 DAS (data not shown). Detailed descriptions of how surface soil crusts impede seedling emergence are provided by Arndt (1965) and Awadhwal and Thierstein (1985). Despite receiving 5 mm of rain 7 DAS at Harrington, Moro achieved a final stand of 61%, compared with 19% for the nearest competitor. Hiller, a 1995 Washington State University release, attained only a 1% final stand.

From the August 1995 sowing at Lind, a thick surface crust formed following 13 mm of rain 7 DAS, and Moro was the only cultivar to achieve a satisfactory (47%) stand. From the September 1995 sowing at Lind, after which no rainfall occurred, all cultivars emerged well (range: 61 to 80%), with no significant differences in final stand among Moro, Rohde, and Eltan. Stands were adequate for most cultivars at the 1995 Harrington site, despite heavy crusting, presumably favored by very wet seed-zone conditions and a relatively thin (120 mm) layer of soil covering seed (Table 1). A rough and cloddy seedbed was purposely prepared at Lind in 1996, to further hinder seedlings during emergence. Despite adequate seed-zone soil water and only trace rainfall occurring after sowing, stand establishment ranged from 4% for Hiller to 25% for Moro. Many seedlings died after failing to elongate around surface clods, some as large as 90 mm in diameter, in the furrow. At Harrington, emergence of all cultivars through thick (140 mm) soil cover in 1996 was reduced relative to 1995, despite excellent seed-zone water conditions and minimal soil crusting.

Final overall emergence ranking for cultivars averaged over both locations and years was (best to worst): Moro, Lewjain, Eltan, Rohde, Madsen, Rely, Rod, Hyak, and Hiller (Table 2). The mean emergence rate of Moro exceeded that of all other cultivars on all sampling dates, and Moro's final mean stand establishment (48%) was more than twice that of last-place Hiller. Coleoptile and first-leaf lengths of cultivars are shown in Table 3. The four top-emerging cultivars had the longest coleoptiles. Moro had both longer coleoptile ($P < 0.001$) and first-leaf ($P < 0.001$) lengths than any other cultivar. Lewjain, Rohde, Eltan, and Madsen had significantly longer first leaves than Rod, Rely, Hyak, and Hiller. Simple linear regression coefficients of determination for the relationship of coleoptile length to emergence ($r^2 = 0.71$, $P = 0.004$) and first-leaf length to emergence ($r^2 = 0.64$, $P = 0.009$) showed that either one, as a single independent variable, is a reasonable predictor of emergence capability. However, the significance level of coleoptile length and first-leaf length to emergence was not improved when both were included as independent variables in a multiple regression model ($R^2 = 0.66$, $P = 0.01$). This indicates a high degree of colinearity (i.e., similarity) between coleoptile length and first-leaf length as estimators of seedling emergence.

Advanced Experimental Lines

In 1996, nine advanced standard-height lines and three Rht_8 semidwarf lines were compared with Moro on two sowing dates. The trial sown in August was into

Table 3. Mean coleoptile length and first-leaf length of nine soft white winter wheat cultivars. Measurements were obtained after growing plants in darkness at a constant 21°C temperature for 7 d.

		Length	
Cultivar	Dwarfing gene	Coleoptile	First leaf
		mm	
Moro	None	90	207
Lewjain	Rht_1	75	131
Rohde	Rht_2	67	133
Eltan	Rht_1	65	154
Hyak	Rht_2	65	122
Rely	Rht_2	65	122
Hiller	Rht_2	63	116
Madsen	Rht_1	62	133
Rod	Rht_1 or Rht_2	60	126
LSD (0.05)		3	7
CV, %		1.3	2.0

Table 4. Mean percent seedling emergence at 8 to 20 d after sowing of advanced experimental soft white winter wheat lines, compared with cv. Moro, sown in late August and mid-September at Lind, WA (1996).

Rank	Treatment†	Seedling emergence 8	9	10	12	14	17	20
		%						
1	ARS 96344	0	6	13	28	32	33	35
2	ARS 96343	0	5	13	26	30	32	34
3	ARS 96338	0	6	8	18	23	25	29
4	ARS 96327	0	7	9	19	22	24	26
5	H91097-01	1	8	10	18	20	22	25
6	ARS 96328	0	5	10	16	19	20	23
7	ARS 96337	1	5	11	16	17	18	19
8	Moro	1	6	13	15	16	18	18
9	ARS 96329	1	7	8	15	16	17	18
10	WA 7834	0	3	8	12	17	17	18
11	ARS 96333	0	1	3	10	15	18	18
12	ARS 96342	0	7	10	14	15	15	17
13	ARS 96339	0	1	6	11	14	16	16
	LSD (0.05)	NS	5	7	7	7	8	8

Table 5. Mean percent seedling emergence at 8 to 17 d after sowing of advanced experimental soft white winter wheat lines, compared with cv. Moro, sown in late August and mid-September at Lind, WA (1997).

Rank	Treatment	Dwarfing gene	Seedling emergence 8	11	12	13	17
			%				
1	ARS 96343	None	2	31	37	39	41
2	ARS 96338	None	4	24	28	30	31
3	ARS 97327	None	3	23	27	26	31
4	ARS 96329	*Rht*$_8$	10	25	27	27	28
5	Moro	None	7	23	27	27	28
6	H91097-01	None	3	19	25	26	28
7	ARS 97222	None	3	17	22	23	25
8	WA 7834	None	3	16	20	22	24
9	WA 7833	*Rht*$_2$	1	6	15	17	19
10	WA 7752	*Rht*$_1$ or *Rht*$_2$	0	8	11	13	15
11	WA 7835	*Rht*$_2$	0	2	3	4	5
	LSD (0.05)		4	6	7	7	8

† ARS 96344 was not included in the 1997 study, as it is genetically similar to ARS 96343.

a rough, cloddy seedbed and emergence ranged from 20 to 42%. Six of the standard-height lines attained significantly better stands than Moro (data not shown). The September 1996 sowing was hampered by 4 mm of rain occurring 8 DAS, and emergence ranged from 10 to 30%, with three of the standard-height lines emerging better than Moro. Lines ARS 96344, ARS 96343, and ARS 96338 were the top emergers, respectively, from both 1996 sowings. Average emergence rates across 1996 sowing dates are shown in Table 4. The three semidwarf lines with the *Rht*$_8$ gene (ARS 96329, ARS 96339, and ARS 96342) attained stands similar to Moro (Table 4), providing further evidence that *Rht*$_8$ does not impede emergence to the extent of *Rht*$_1$ and *Rht*$_2$ genes.

In 1997, advanced experimental entries were six standard-height, one *Rht*$_8$, and three *Rht*$_1$ or *Rht*$_2$ lines. Seven of the 1996 entries were repeated in 1997. Although sowing conditions were very wet, rain showers prior to seedling emergence occurred on both August and September sowings (Table 1). Final emergence percentage among lines ranged from 6 to 40% and 5 to 43% for August and September sowings, respectively. Averaged across 1997 sowing dates, the only line to exceed Moro for final stand was ARS 96343 (Table 5). The three advanced lines carrying the *Rht*$_1$ or *Rht*$_2$ reduced-height genes had the lowest rate and extent of emergence (Table 5). The 1000-kernel weight of ARS 96343 was 54.3 g, more than 13 g heavier than any other 1997 entry (Table 6).

Advanced experimental lines that emerged better than Moro on any of the four sowing dates in 1996 and 1997 had longer coleoptiles than Moro (Table 6). As with the comparison of cultivars, coleoptile length as a single independent variable in simple linear regression models proved better related to emergence ($r^2 = 0.63$, $P < 0.001$ in 1996; $r^2 = 0.62$, $P < 0.001$ in 1997) than to first-leaf length ($r^2 = 0.24$, P = NS in 1996; $r^2 = 0.61$, $P < 0.001$ in 1997). Prediction of emergence was not improved using a multiple regression model containing

Table 6. Coleoptile length, first-leaf length, and kernel weight of advanced experimental soft white winter wheat lines, compared with Moro, in 2 yr. Measurements were obtained after growing plants in darkness at a constant 21°C temperature for 7 d.

Line†	1000-kernel wt. (1997)	Dwarfing gene	Coleoptile length 1996	Coleoptile length 1997	First-leaf length 1996	First-leaf length 1997
	g		mm			
ARS 96327	30.4	None	119	106	172	164
H91097-01	37.6	None	112	108	184	169
ARS 96343	54.3	None	109	116	189	174
ARS 96344	—†	None	105	—	188	—
ARS 96338	32.4	None	103	111	181	164
ARS 96333	—	None	101	—	161	—
WA 7834	37.1	None	100	102	180	166
ARS 96328	—	None	93	—	212	—
Moro	34.6	None	90	105	202	194
ARS 96329	28.7	*Rht*$_8$	87	98	214	201
ARS 96337	—	None	87	—	210	—
ARS 96339	—	*Rht*$_8$	86	—	204	—
ARS 96342	—	*Rht*$_8$	84	—	201	—
ARS 97222	32.9	None	—	99	—	169
WA 7833	38.9	*Rht*$_2$	—	67	—	136
WA 7752	32.0	*Rht*$_1$ or *Rht*$_2$	—	66	—	114
WA 7835	40.6	*Rht*$_2$	—	49	—	115
LSD (0.05)			18	4	10	10
CV, %			6.6	4.7	2.0	7.0

† Missing values: Some lines were entered in only a single year, and 1000-kernel weight was measured in 1997 only.

both coleoptile length and first-leaf length as independent variables. Although the best-emerging 1997 entry (ARS 96343) had the heaviest kernels, kernel weight was not related to emergence ($r^2 = 0.04$, P = NS).

SUMMARY AND CONCLUSIONS

Winter wheat grown in the low-precipitation dryland region of the Pacific Northwest must be able to emerge under stress conditions from deep sowing depths for adequate stand establishment. Growers continue to sow the outdated SWWW club cultivar Moro because it emerges well from deep sowing depths in dry soils. All other SWWW cultivars in the Pacific Northwest carry Rht_1 or Rht_2 dwarfing genes that impede both the rate and extent of emergence, which affects yield potential.

From deep sowing depths, Moro consistently emerged fastest and achieved the best final stand under both wet and dry seed-zone conditions compared with other SWWW cultivars. Six advanced experimental standard-height lines with coleoptiles >100 mm in length were superior to Moro for emergence on one or more sowing dates, but only one advanced line surpassed Moro when averaged across years and sowing dates.

Coleoptile length was significantly related to emergence ability, accounting for 62 and 71% of the variability in emergence for advanced experimental lines and cultivars, respectively. Coleoptile length was a better estimator of seedling emergence than first-leaf length. Kernel weight of advanced experimental lines was not significantly related to emergence.

Results from this study highlight progress in developing SWWW cultivars specifically for deep sowing conditions in low-precipitation dryland areas in the inland Pacific Northwest. Recent changes in SWWW breeding objectives, in response to the expressed needs of growers, have made these advances possible.

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