Field Crops Research 168 (2014) 57–64

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Wide row spacing for deep-furrow planting of winter wheat

William F. Schillinger[a,*], Stewart B. Wuest[b]

[a] Department of Crop and Soil Sciences, Washington State University, Dryland Research Station, Lind, WA 99341, USA
[b] USDA-ARS, Columbia Plateau Conservation Research Center, Pendleton, OR 97801, USA

ARTICLE INFO

Article history:
Received 9 July 2014
Received in revised form 16 August 2014
Accepted 17 August 2014

Keywords:
Winter wheat
Summer fallow
Wide row spacing
Conservation farming
Grain yield components
Weeds

ABSTRACT

A tillage-based winter wheat (*Triticum aestivum* L.)-summer fallow rotation is practiced on 1.56 million cropland hectares in the low-precipitation (<300 mm annual) region of the Inland Pacific Northwest of the United States (PNW). Farmers use deep-furrow drills with rows spaced 40–45-cm apart to plant winter wheat (WW) as deep as 20 cm below the soil surface to reach moisture in summer fallow (SF). Conservation tillage methods have been successfully developed that preserve ample residue during SF to control wind erosion, but existing drills cannot pass through heavy residue without plugging; thus farmers are reluctant to adopt conservation-tillage practices. We conducted field experiments over 3 years at three sites using the same number of seeds row^{-1} (8 site years) and same number of seeds ha^{-1} (3 site years) with row spacing of 40, 45, 50, 55, 60, and 80 cm and measured effects on grain yield, grain yield components, straw production, and weed dynamics. With same number of seeds row^{-1} (seeding rate declined as row spacing widened) the highest average grain and straw yield was achieved with the 40 and 45-cm spacing with gradual decline as row spacing widened due to fewer spikes unit area^{-1} (SPU) and despite increased kernels spike^{-1} (KPS). Kernel weight (KW) was not a factor. With same number of seeds ha^{-1} (more seeds row^{-1} as row spacing widened) there were no overall differences in SPU, KPS, KW, and straw production among treatments and only a slight grain yield reduction at the two widest spacing treatments. Weeds were not an agronomic problem with any spacing treatment due to timely and effective in-crop herbicide application although weed dry biomass did increase slightly as row spacing widened. Our research suggests that row spacing for WW production in the dryland PNW can be widened to at least 50 cm and most likely 55 cm to facilitate conservation-tillage farming with equal grain and straw production compared to narrower row spacing currently used by farmers.

1. Introduction

The 2-year winter wheat-summer fallow (WW-SF) rotation is practiced on >90% of rainfed cropland in the dry region of the PNW because it is more stable and profitable than any other crop rotation scheme yet tested (Schillinger and Papendick, 2008). Tillage is used during the spring of the SF year to break soil capillary continuity to reduce water evaporation during the dry summer (Papendick et al., 1973; Wuest, 2010) to allow planting of WW into carryover soil moisture in late August or early September. Farmers use specially designed "deep-furrow" drills to push dry surface soil into ridges between furrows to place wheat seed into moist soil and to reduce the thickness of the soil layer through which WW seedlings must emerge. In order to place seed into moisture below the tillage layer without having it covered by more than 9–13 cm of soil, the row spacing must be wide enough to provide ample room for stacking dry soil into tall furrow ridges. Essentially all farmers in the region use either John Deere™ HZ or International Harvester™ 150 deep-furrow drills with 40 and 45 cm row spacing, respectively. When WW stands are successfully achieved from late-summer planting, plants have ample time to produce tillers before the onset of cold weather, and will grow rapidly when temperatures warm in late winter-early spring.

The sandy-loam and silt-loam soils found throughout the region are low in organic matter and susceptible to substantial wind erosion and dust emission during high-wind events when SF fields are pulverized from excessive tillage and lacking in surface residue (Sharratt et al., 2010). Conservation tillage methods that retain equal soil moisture as traditional tillage during SF have been successfully developed, but farmers are reluctant to practice conservation tillage due to fear their drills will plug from too much residue during planting. The ability of a drill to function well under high-residue conditions in tilled SF is improved when the row

Abbreviations: KPS, kernels per spike; KW, kernel weight; PNW, Inland Pacific Northwest of the United States; SPU, spikes per unit area; SF, summer fallow; WW, winter wheat.

* Corresponding author. Tel.: +1 509 235 1933.
E-mail address: william.schillinger@wsu.edu (W.F. Schillinger).

http://dx.doi.org/10.1016/j.fcr.2014.08.006
0378-4290/

spacing is widened. This makes it important to understand the relationship between row spacing and WW grain yield potential under PNW growing conditions.

The literature on row spacing and spacing between seeds within rows for wheat often indicates a decrease in grain yield as row spacing gets wider. For spring wheat, or in short season winter environments like the Canadian Great Plains, a decrease in grain yield is often measured as row spacing is increased from about 16–32 cm, and an even greater decrease as row spacing is widened further (Kleemann and Gill, 2010; Tompkins et al., 1991a,b; Xie et al., 1998). In the same environment there can be a decrease in grain yield when seeds are closer together within a row (Boström et al., 2012). Maximum grain yield is generally achieved when the greatest number of productive spikes are realized at harvest (Lloveras et al., 2004; Tompkins et al., 1991a), and more equidistant within-row seed spacing often augments grain yield due to reduced inter-species competition and better light interception (Anderson and Barclay, 1991). Similarly, some wheat grain yield decrease has been credited to crowding of seeds within the row (Boström et al., 2012). In that case, drills that spread seed in a band within each row has been credited with increasing yield (Amjad and Anderson, 2006), but seed spreading and paired rows are not practical for deep-furrow planting.

In several studies, especially where water stress is experienced, increasing row spacing from 10 to 30 cm had little or no effect on grain yield (Chen et al., 2010; Hiltbrunner et al., 2005; Lafond and Derksen, 1996; McLeod et al., 1996). In drier environments with long growing season and lower grain yield potential, the number of productive spikes required to maximize yield is lower and there is more time for tillering if individual plants have the water and fertility resources to do so. It is also possible for higher density plantings to experience early senescence or loss of productive tillers during grain fill because more water has been used earlier (Benbella and Paulsen, 1998; Hiltbrunner et al., 2005).

In the studies cited above, 30 cm was considered wide row spacing. Given that the narrowest row spacing of the deep-furrow drills used in the PNW is wider than most of the row spacing widths reported in the literature, one might assume that any further widening of row spacing would cause a decrease in WW grain yield potential. For example, Kleemann and Gill (2010) calculated a decrease in yield of 5–8% when the rows were widened from 18 to 36 cm, and a 16–26% reduction when the rows were widened from 18 to 54 cm. Under low-moisture conditions, width of row spacing may not adversely affect WW grain yield (Ketata et al., 1976; Vander Vorst et al., 1983), but no such experiments have previously been conducted in the dryland PNW.

The hypothesis for our experiment was that row spacing can be widened to some given distance beyond the 40 and 45 cm of existing commercial drills without adversely affecting WW grain yield, straw production, and weed control. The objective was to promote conservation-tillage farming by providing scientific evidence of little to no grain yield reduction using new deep-furrow drill prototypes that employ row spacing >45 cm in order to pass through and retain high quantities of surface residue in tilled SF during planting without drill plugging. Specific objectives were to determine the effects of wider row spacing on: (i) grain yield, (ii) grain yield components, (iii) straw production, and (iv) weed dynamics.

2. Materials and methods

2.1. Establishment of treatments

A 3-year experiment was conducted at three sites during the 2011–2013 crop years to determine if row spacing could be widened from the traditional 40–45 cm used by farmers throughout the low-precipitation region of the PNW for deep-furrow planting of WW. The three study sites were representative of those found throughout the WW-SF region (Fig. 1). Soils at all sites are sandy silt loam in texture, more than 180 cm deep, with no rocks or restrictive layers. Slope at all sites was <2%. Long-term average annual precipitation is 242, 280, and 266 mm at Lind, Ritzville, and Echo, respectively.

Soil management during the 13-month SF period differed somewhat across sites. At all sites, WW stubble was left standing from harvest in July through the winter to trap snow and otherwise increase over-winter soil water storage (Williams, 2004), although at Ritzville, aqua NH_3—N and thiosol S was knifed into WW stubble at a 15-cm depth with narrow shanks spaced 30 cm apart in early November after the onset of fall rains. Glyphosate [*N*-(phosphonomethyl) glycine] herbicide was applied at all sites in late March–early April to control volunteer WW and other weeds.

Primary spring tillage was conducted at an average depth of 10 cm in late April. At Lind, primary spring tillage and simultaneous fertilizer injection was conducted with a wide-blade undercutter sweep with attached rotary hoe for soil clod sizing. The undercutter implement causes minimal soil lifting or disturbance and is considered a best management conservation tillage practice for WW-SF farming in the region (Papendick, 2004). At Ritzville, a field cultivator with attached Phoenix™ rolling harrow was used for primary spring tillage. Although a field cultivator causes considerably more soil disturbance and residue burial compared to an undercutter sweep, primary spring tillage implements used at Lind and Ritzville are considered "conservation tillage" because WW grain yield and straw production is considerably higher at Ritzville compared to Lind and practices used at these sites typically retain approximately 30% surface residue cover after deep-furrow planting of WW into SF. However, WW stubble is generally cut at a height of 30 cm or shorter to minimize the risk of drill plugging at planting as already discussed. Retention of much higher quantities of surface residue in SF is possible; thus, the need for the present study. Traditional tillage practices were used at the Echo site. A tandem disk was used for primary spring tillage followed soon after with a field cultivar plumbed to inject fertilizer. Although not measured, very little residue remained on the soil surface after deep-furrow planting of WW at Echo.

An across-site and year average of 56 kg aqua NH_3—N + 11 kg thiosol S ha^{-1} was injected into the soil during the field operations discussed above. Following primary spring tillage, the soil was rodweeded once or twice as need from June to August at a depth of 8 cm to control Russian thistle (*Salsola kali* L.) and other weeds.

Row spacing treatments were 40, 45, 50, 55, 60, and 80 cm. Experimental design was a randomized complete block with four replications. Individual plots were 2.4 m × 30 m. The same 2.4-m-wide John Deere HZ split-packer deep-furrow drill was used at all sites. The factory row spacing of this drill is 40 cm. We modified the row spacing to the desired treatment widths by moving the seed boots and placing different-length spacers between the packer wheels. Changing the row spacing width for each treatment was easily accomplished in the field by two people within 30 min, thus the experiment was always planted at a given site in one day. During the 3 years, the experiments were planted between August 31–September 6 at Lind, September 9–16 at Ritzville, and September 22–October 4 at Echo. These dates are considered optimum WW planting windows at each of the sites.

There were two separate studies. In study #1, which was conducted during all 3 years, all row-spacing treatments had the same number of seeds per row; thus, the default 56 kg ha^{-1} seeding rate for the 40-cm spacing treatment was reduced to 28 kg ha^{-1} for the 80-cm spacing. Data from Lind in the 2013 crop year was not collected due to plugging of one of the drill openers in two of the 80-cm plots, therefore 8 site years of data were obtained for this

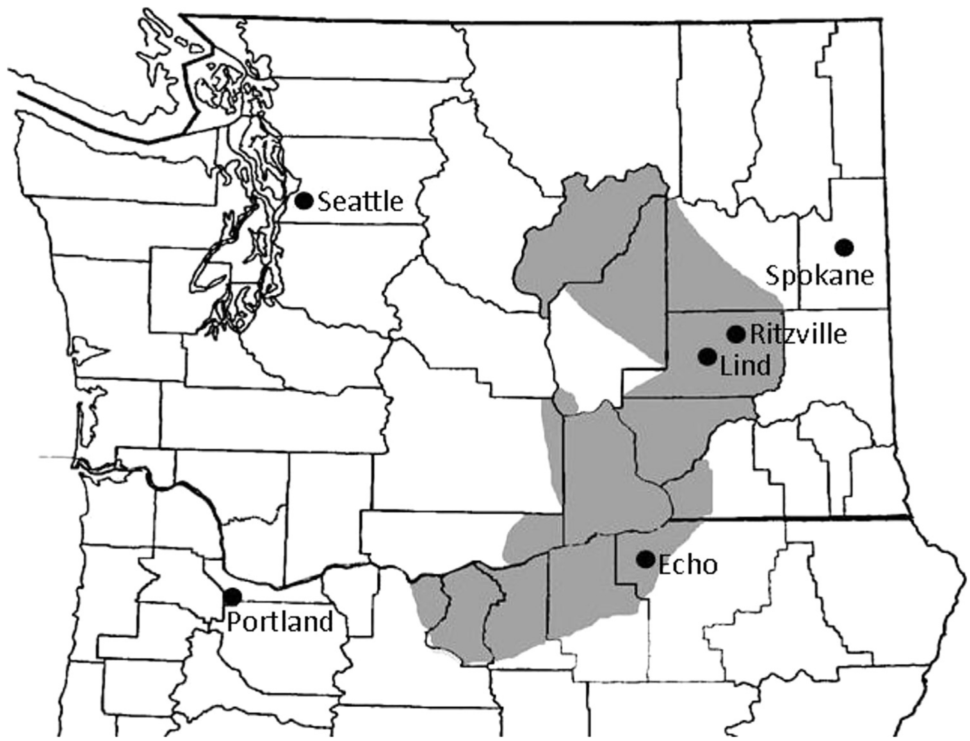

Fig. 1. The low (150–300-mm annual) precipitation zone of east-central Washington and north-central Oregon (shaded area) covers 1.56 million cropland hectares and is the largest contiguous cropping zone in the western United States. A 2-year winter wheat-summer fallow rotation is practiced by essentially all dryland farmers in this zone.

experiment. Study #2 was conducted during the 2013 crop year (total = 3 site years) when we procured a specialized and highly accurate seed metering devise to allow a seeding rate of 56 kg ha^{-1} for all treatments; this meaning that the 80-cm spacing had twice the number of seeds per unit length of row as the 40-cm treatment.

Winter wheat cultivars used were Xerpha and Bruehl at Lind and Ritzville, and ORCF 102 and Northwest 533 at Echo. These cultivars are widely planted by farmers throughout the region. Certified seed of cultivars was treated with CruiserMaxx®, which contains an insecticide (thiamethoxam) for protection against wireworm (*Agriotes lineatus*) as well as fludioxonil and mefenoxam fungicides for disease control. This seed treatment is commonly used for wheat production in the PNW. Seed was placed deep into moisture in SF with an average of 11 cm of soil covering the seed. Seed-zone water content was adequate for germination and emergence of WW at all sites every year as evidenced by full and vigorous plant stands within 10 days after planting. Damage to plants due to cold during the winter months was minimal.

In-crop broadleaf herbicides were used at all sites every year, and in-crop grass-weed herbicides were used at some sites in certain years, by application of labeled rates of the herbicides in April. The types and rates of herbicides used were typical of those commonly used by wheat farmers in the region. At Lind and Ritzville, broadleaf herbicides used were Brox M®(bromoxyniloctanoate + MCPA isooctyl ester), Brox M + Ally®(metsulfuronmythel), or Huskie®(pyrasulfotole + bromoxynil). At Echo, in-crop broadleaf herbicides used were Huskie, 2,4-D ester (2-ethylhexyl ester of 2,4-dichlorophenoxyacetic acid), and Dicamba (dimethylamine salt of Dicamba) + Harmony Extra®(thifensulfuron methyl + tribenuron methyl). In-crop grass-weed herbicides used were Maverick®(sulfosulfuron) at Ritzville in 2011 and Beyond®(imazamox) at Echo in 2010 and 2011. In-crop grass-weed herbicides were tank mixed with the in-crop broadleaf herbicides. Tilt®(propiconazole) fungicide for stripe rust (*Puccinia striiformis* Westend) control was also tank mixed with the in-crop herbicides at all sites every year.

2.2. Measurements

Grain yield was determined in mid-to-late July by harvesting the grain from plants in a swath through each 30-m-long plot with a plot combine with 1.5-m-wide cutting platform, collecting grain in a paper sack, and weighing grain on a digital scale. When all spikes from a particular row could not entirely be fed into the cutting platform (due to the varying row spacing among treatments), wheat in that row was manually flattened on the soil surface and, therefore, not included when that plot was harvested. Grain yield for all treatments reported here was adjusted to accurately reflect the actual surface area harvested per unit area of land (i.e., kg ha^{-1}).

Spike density and total above-ground dry biomass production were measured by hand-cutting plants from a representative 1-m-long row segment in each plot just prior to harvest. Unit area for the clipped row of each treatment was then calculated based on drill row spacing. Whole-plant samples were placed in a low-humidity greenhouse for 7 days before weighing. Kernels spike^{-1} was calculated based on spikes m^{-2} and thousand kernel weight after passing spikes though a hand-fed thresher. Straw production was determined by subtracting the weight of the grain from the weight of the above-ground whole plant.

Dry biomass of individual weed species (Lind and Ritzville) and total combined dry biomass of weeds (all sites) was determined in all treatments prior to grain harvest by first counting (Lind and Ritzville only), then clipping and gathering the above-ground portion of weeds between two representative rows from the entire 30-m-length of the experiment. Weeds were placed in paper bags and allowed to air dry in a low-humidity greenhouse before weighing on a digital scale.

2.3. Analysis of data

Analysis of variance was conducted for grain yield, SPU, KPS, KW, straw production, and weed populations. Tukey's honest significance test was used to detect statistical differences in treatment means for all data. Treatment means were considered significantly different if the *P*-value was <0.05. Data from Study #1 (same number of seeds row^{-1}) were analyzed within site for each year, over years at each site, and across sites (i.e., combined 8 site years). In Study #2 (same number of seeds ha^{-1}), data were analyzed within site as well as across sites for the 3 site years.

3. Results and discussion

3.1. Weeds

Weeds were not problematic with any row spacing treatment at any site. Downy brome (*Bromus tectorum* L.), a winter annual grass weed with a similar life cycle as WW, produced the most dry biomass of any weed present at all three sites (Table 1). There was a general trend for downy brome dry biomass to increase as row spacing widened (Table 1), but these levels could be considered very low compared to other studies that measured infestation of this weed in the WW–SF rotation in the PNW (Thorne et al., 2007; Young and Thorne, 2004).

Russian thistle, the most problematic broadleaf weed throughout the WW–SF region, and prickly lettuce (*Lactuca serriola* L.) produced far less dry biomass compared to downy brome (Table 1). There were no significant differences in Russian thistle dry biomass with any spacing, and only at 80 cm were significant differences in prickly lettuce dry biomass measured (Table 1). Other minor broadleaf weeds measured were tumble mustard (*Sisymbrium altissimum* L.), tansy mustard (*Descurainia pinnata* Walt.), and western salsify (*Tragopogon dubius* L.). Total weed dry biomass generally increased at all three sites as row spacing widened but, as mentioned above, these levels are considered relatively low. We attribute the low weed pressure to uniform WW stands at all sites every year and to timely and effective application of in-crop herbicides. In situations where weed control was not as effective, we would expect greater weed pressure with wider row spacing compared to narrower spacing.

3.2. Grain yield, yield components, and straw production

3.2.1. Study #1: Same number of seeds per row

With the same number of seeds per row, there were never any within-year grain yield differences between the 40 and 45 cm row spacing treatments and a statistically significant decline in yield with 50-cm spacing only occurred in one of the 8 years (Table 2). Grain yield slowly and progressively declined during most years with 55, 60, and 80-cm row spacing. When averaged over the 8 site years, the 40 and 45 cm treatments had the highest grain yields, with small but statistically significant declines in yield as row spacing widened (Table 2). The average grain yield from narrowest to widest row spacing over the 8 sites years was 4000–3390 kg ha^{-1}. Gradual grain yield decline with widening row spacing was due to fewer SPU (Figs. 2a, 3a and 4a), despite a partially compensating tendency for more KPS with wider rows (Figs. 2b, 3b and 4b). Kernel weight was never a factor (Figs. 2c, 3c and 4c). Straw production declined with wider rows, becoming especially apparent with the 80-cm row spacing (Figs. 2d, 3d and 4d).

3.2.2. Study #2: Same number of seeds per hectare

When planting more seeds per unit length of row with the wider spacing treatments (i.e., same number of seeds ha^{-1}), there were no significant grain yield differences among treatments at Lind or Echo and, at Ritzville, there were no differences in grain yield until row spacing reached 60 cm (Table 3). When averaged across the three sites, there was no difference in grain yield among the 40, 45, 50, and 55 cm spacing treatments, and with a narrow range of only 3310–3000 kg ha^{-1} (i.e., 9% difference) from the 40- to 80-cm treatments (Table 3). Averaged over the three sites, there were no differences in spikes m^{-2} (Fig. 5a), kernels spike^{-1} (Fig. 5b), kernel weight (Fig. 5c) or straw production (Fig. 5d).

Table 1
Dry biomass of three weed species as well as total weed biomass with six row spacing treatments at three sites averaged over 3-year experiment.

Site and row spacing (cm)	Weed species			
	Russian thistle	Downy Brome	Prickly lettuce	Total weeds[a]
	kg ha^{-1}			
Lind, WA				
40	0	3 b[b]	0 b	3 c
45	1	8 b	0 b	10 c
50	3	8 b	0 b	12 bc
55	0	17 b	1 b	20 bc
60	4	22 b	1 b	31 b
80	19	73 a	7 a	112 a
Ritzville, WA				
40	0	4 b	1 b	17 ab
45	1	17 ab	1 b	19 ab
50	0	11 ab	1 b	12 b
55	1	7 ab	3 ab	20 ab
60	0	45 a	2 ab	47 ab
80	1	44 ab	6 a	50 a
Echo, OR[c]				
40				44
45				63
50				47
55				54
60				27
80				72

[a] Total weeds include tumble mustard, tansy mustard, and western salsify.
[b] Within-site and within-column means followed by the same letter are not significantly different at $P < 0.05$.
[c] Dry biomass of Individual weed species was not determined at Echo.

Table 2
Winter wheat grain yield at three sites (8 site-years) as affected by six row spacing treatments with the same number of seeds per row (i.e., declining number of seeds ha^{-1} as row spacing widened).

	Row spacing (cm)					
	40	45	50	55	60	80
	Grain yield (kg ha^{-1})					
Lind, WA						
2011	2350	2330	1950	1970	1900	2170
2013	2920	3110	2630	2690	2720	2680
2-yr avg.	2640 ab[a]	2720 a	2290 b	2330 b	2310 b	2430 ab
Ritzville, WA						
2011	5060 a	5090 a	4580 b	4360 bc	4120 c	4220 bc
2012	5450 a	5450 a	5320 a	4910 b	4660 bc	4420 c
2013	5240 a	4810 abc	5200 ab	5200 ab	4700 bc	4620 c
3-yr avg.	5250 a	5120 a	5030 a	4800 b	4490 bc	4420 c
Echo, OR						
2011	4910 a	4870 a	4870 a	4720 a	4700 a	4190 b
2012	4050 a	3870 ab	3820 b	3580 c	3590 c	2890 d
2013	2030	2010	1980	1990	1960	1940
3-yr avg.	3660 a	3580 ab	3560 abc	3430 bc	3420 c	3010 d
8-site-year avg.	4000 a	3940 a	3790 b	3680 c	3540 c	3390 d

[a] Within-row means followed by the same letter are not significantly different at $P < 0.05$.

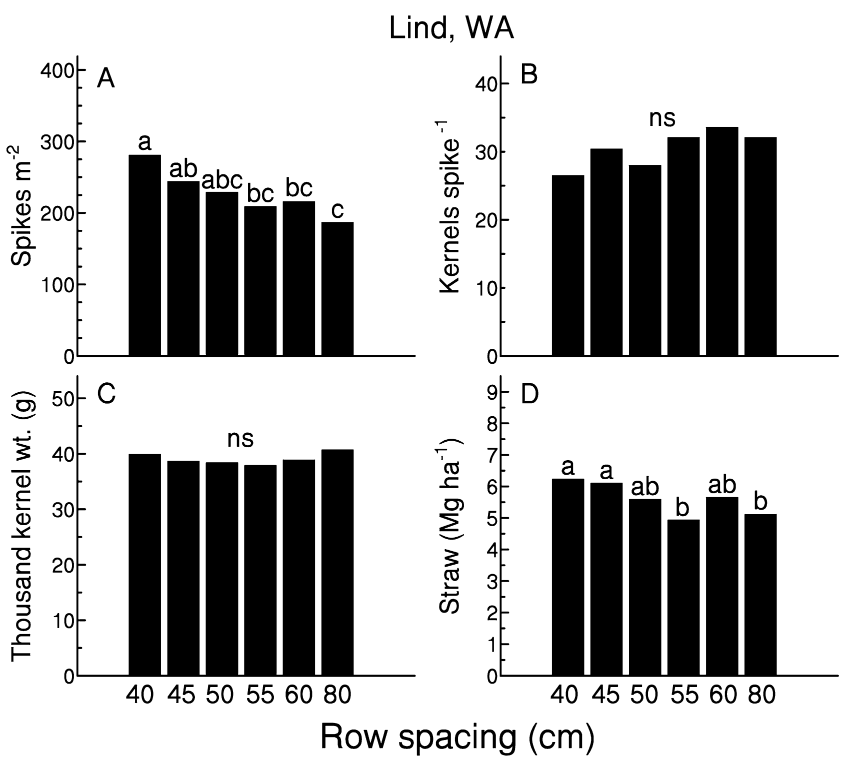

Fig. 2. Grain yield components and straw production of six row spacing treatments with the same number of seeds row^{-1} (i.e., declining seeds ha^{-1} as row spacing widened) averaged over 2 years at Lind, WA. Means followed by the same letter are not significantly different at $P < 0.05$.

Table 3
Winter wheat grain yield at three sites (3 site-years) as affected by six row spacing treatments with the same number of seeds ha^{-1} (i.e., number of seeds per unit length of row increased as row spacing widened).

	Row spacing (cm)					
	40	45	50	55	60	80
	Grain yield (kg ha^{-1})					
Lind, WA	2730	2780	2600	2620	2630	2530
Ritzville, WA	5240 a[a]	5020 ab	5200 a	4970 ab	4740 bc	4590 c
Echo, OR	1960	1990	2010	1950	1920	1890
3-Site avg.	3310 a	3260 a	3270 a	3180 ab	3100 bc	3000 c

[a] Within-row means followed by the same letter are not significantly different at $P < 0.05$.

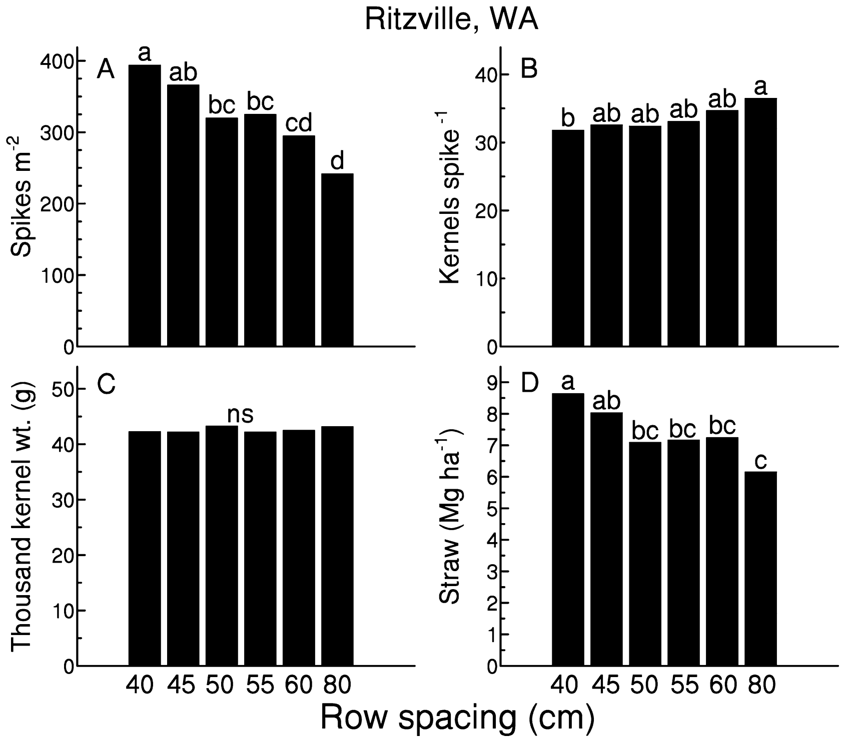

Fig. 3. Grain yield components and straw production of six row spacing treatments with the same number of seeds row^{-1} (i.e., declining seeds ha^{-1} as row spacing widened) averaged over 3 years near Ritzville, WA. Means followed by the same letter are not significantly different at $P < 0.05$.

3.3. When is row spacing too wide?

Compared to previous findings in the literature, we found smaller wheat grain yield penalties as row spacing widened. Essentially all drills used for wheat production around the world have narrower spacing between openers than any of the row spacing treatments in our study. Perhaps grain yield potential in the dryland PNW could be enhanced with rows spaced <40 cm apart, but 40 cm is the minimum row spacing considered feasible for planting deep to reach moisture and simultaneously stack dry soil in furrows

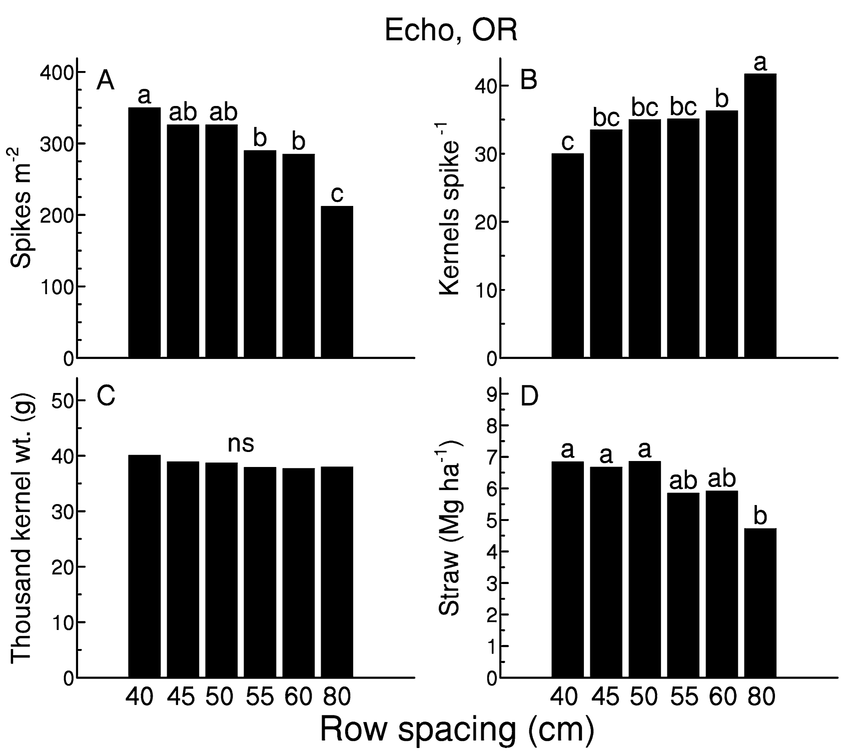

Fig. 4. Grain yield components and straw production of six row spacing treatments with the same number of seeds row^{-1} (i.e., declining seeds ha^{-1} as row spacing widened) averaged over 3 years near Echo, OR. Means followed by the same letter are not significantly different at $P < 0.05$.

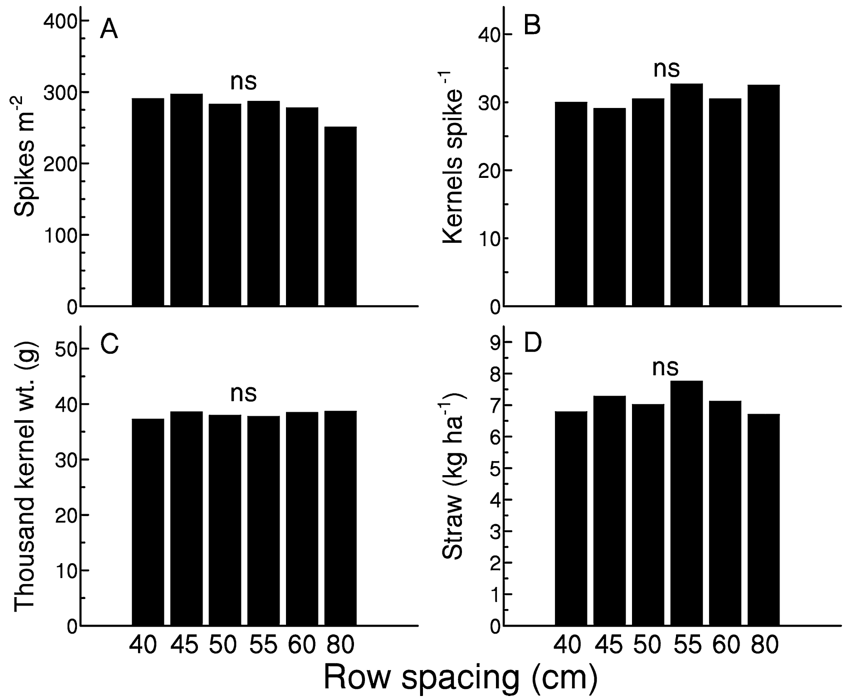

Fig. 5. Grain yield components and straw production of six row spacing treatments with the same number of seeds ha^{-1} (i.e., increasing number of seeds row^{-1} as row spacing widened) averaged over 3 sites in 2013. ns = no significant differences at $P < 0.05$.

to reduce the thickness of soil covering seed. If WW stands cannot be successfully established into carryover seed-zone water in fallow in late August–early September and, instead, seed is placed at a shallow depth with narrow (i.e., 15–25-cm) row spacing on October 15 or later after the onset of fall rains, grain yield will be reduced by an average of 36% (Higginbotham et al., 2011).

Data from Study #1 (Table 2) and Study #2 (Table 3) show that grain yield decline with row spacing >40 cm was mostly at the higher yielding sites. Removing Lind data and the data from Echo in 2013 (i.e., all the site-years with yields below 3500 kg ha^{-1}), we performed a simple linear regression to obtain the relationship Yield = 5830 − 21.6 × row spacing, ($P < 0.01$). This means that grain yield is predicted to decline by 21.6 kg ha^{-1} for every 1-cm increase in row spacing beyond 40 cm when grain yield potential is >3500 kg ha^{-1}. This equation is similar to that referenced by Kleemann and Gill (2010) for dry Australian conditions. We must emphasize, however, that (i) long-term average grain yield from most farms in the WW–SF region of the PNW is considerably below 3500 kg ha^{-1} and, (ii) the majority of wind erosion and blowing dust problems occur from farms with grain yield potential below this level.

4. Conclusions

Wheat growers in the dry WW-SF region of the PNW are reluctant to retain high quantities of surface residue in fallow fields due to concerns about plugging their deep-furrow drills during planting. Planting WW is the most time-critical and important field operation of the entire year. Deep-furrow drills with wider row spacing than models currently in use would enhance residue clearance and likely lead to wide adoption of thoroughly tested high-residue conservation tillage practices that significantly reduce wind erosion with no grain yield penalty. Data from our study indicate that, in the dry WW-SF region of the PNW where yield potential is below 3500 kg ha^{-1}, row spacing can be widened to 55 cm with little to no decline in grain yield and negligible increase in weed pressure compared to the 40- and 45-cm row spacing of drills currently used by farmers.

Acknowledgements

The authors gratefully acknowledge the excellent technical assistance by WSU agricultural research technician John Jacobsen, WSU technical assistant Steven Schofstoll, and USDA-ARS technicians Tami Johlke and Robert Correa. Appreciation is extended to wheat farmer Derek Schafer for providing land for the experiment at the Ritzville site and Brett Rohde for land at Echo. Funding for this study was provided by Washington State University through Hatch Project 0250, USDA-ARS, Washington Grain Commission, and the Soil Conservation Districts in Franklin and Benton Counties in Washington.

References

Amjad, M., Anderson, W.K., 2006. Managing yield reductions from wide row spacing in wheat. Aust. J. Exp. Agric. 46, 1313–1321.
Anderson, W.K., Barclay, J., 1991. Evidence for differences between three wheat cultivars in yield response to plant population. Aust. J. Agric. Res. 42, 701–713.
Benbella, M., Paulsen, G.M., 1998. Efficacy of treatments for delaying senescence of wheat leaves: II. Senescence and grain yield under field conditions. Agron. J. 90, 332–338.
Boström, U., Anderson, L.E., Wallenhammar, L.E.A.C., 2012. Seed distance in relation to row distance: effect on grain yield and weed biomass in organically grown winter wheat, spring wheat and spring oats. Field Crops Res. 134, 144–152.
Chen, S., Zhang, X., Sun, H., Wang, Y., Ren, T., 2010. Effects of winter wheat row spacing on evapotranpsiration, grain yield and water use efficiency. Agric. Water Manage. 97, 1126–1132.
Higginbotham, R.W., Jones, S.S., Carter, A.H., 2011. Adaptabilty of wheat cultivars to a late-planted no-till fallow production system. Sustainability 3, 1224–1233.
Hiltbrunner, J., Liedgens, M., Stamp, P., Streit, B., 2005. Effects of row spacing and liquid manure on directly drilled winter wheat in organic farming. Eur. J. Agron. 22, 441–447.
Ketata, H., Edwards, L.H., Morrison, R.D., 1976. Response of three hard red winter wheat cultivars to four planting arrangements. Agron. J. 68, 428–429.
Kleemann, S.G.L., Gill, G.S., 2010. Influence of row spacing on water use and yield of rain-fed wheat (*Triticum aestivum* L.) in a no-till system with stubble retention. Crop Pasture Sci. 61, 892–898.

Lafond, G.P., Derksen, D.A., 1996. Row spacing and seeding rate effects in wheat and barley under a conventional fallow management system. Can. J. Plant Sci. 76, 791–793.
Lloveras, J., Manent, J., Viudas, J., López, A., Santiveri, P., 2004. Seeding rate influence on yield and yield components of irrigated winter wheat in a Mediterranean climate. Agron. J. 96, 1258–1265.
McLeod, J.G., Campbell, C.A., Gan, Y., Dyck, F.B., Vera, C.L., 1996. Seeding depth, rate and row spacing for winter wheat grown on stubble and chemical fallow in the semiarid prairies. Can. J. Plant Sci. 76, 207–214.
Papendick, R.I., 2004. Farming with the Wind II: Wind Erosion and Air Quality Control on the Columbia Plateau and Columbia Basin. Special Report by the Columbia Plateau PM_{10} Project. Washington Agric. Exp. Stn. Rpt. XB 1042, Pullman, WA.
Papendick, R.I., Lindstrom, M.J., Cochran, V.L., 1973. Soil mulch effects on seedbed temperature and water during fallow in eastern Washington. Soil Sci. Soc. Am. Proc. 37, 307–314.
Schillinger, W.F., Papendick, R.I., 2008. Then and now: 125 years of dryland wheat farming in the Inland Pacific Northwest. Agron. J. 100, S166–S182.
Sharratt, B., Wendling, L., Feng, G.L., 2010. Windblown dust affected by tillage intensity during summer fallow. Aeolian Res. 2, 129–134.
Tompkins, D.K., Fowler, D.B., Wright, A.T., 1991a. Water use by no-tillage wheat influence of seed rate and row spacing. Agron. J. 83, 766–769.
Tompkins, D.K., Hultgreen, G.E., Wright, A.T., Fowler, D.B., 1991b. Seed rate and row spacing of no-till winter wheat. Agron. J. 83, 684–689.
Thorne, M.E., Young, F.L., Yenish, J.P., 2007. Cropping systems alter weed seed banks in Pacific Northwest semi-arid wheat region. Crop Prot. 26, 1121–1134.
Vander Vorst, P.B., Wicks, G.A., Burnside, O.C., 1983. Weed control in a winter wheat corn-ecofarming rotation. Agron. J. 75, 507–511.
Williams, J.D., 2004. Effects of long-term winter wheat, summer fallow residue and nutrient management on field hydrology for a silt loam in north-central Oregon. Soil Till. Res. 75, 109–119.
Wuest, S.B., 2010. Tillage depth and timing effects on soil water profiles in two semiarid soils. Soil Sci. Soc. Am. J. 74, 1701–1711.
Xie, H.S., Rourke, D.R.S., Hargrave, A.P., 1998. Effect of row spacing and seed/fertilizer placement on agronomic performance of wheat and canola in zero tillage systems. Can. J. Plant Sci. 78, 389–394.
Young, F.L., Thorne, M.E., 2004. Weed-spiecies dynamics and management in no-till and reduced-till fallow cropping systems for the semi-arid agricultural region of the Pacific Northwest, USA. Crop Prot. 23, 1097–1110.