Hard red spring wheat (HRSW) (Triticum aestivum L.) is the major wheat class grown in the Northern Great Plains of the United States and generates the highest gross revenue of all commercial crops grown in the state of Montana (USDA-NASS, 2016). Montana accounts for 23.4% of US HRSW production, second only to North Dakota in that regard. Hard red spring wheat is the most frequently planted of all wheat classes grown in Montana and accounts for 54% of the state's total wheat hectares.

Continual breeding and agronomic practice improvements have gradually increased wheat yield in the United States. However, in the Northern Great Plains (i.e., Montana), the average annual yield gain over time has been shown to be small because of the water-limited environments (Graybosch et al., 2014). Given the unpredictability of rainfall timing and amount, producer interest in irrigating HRSW has increased. Irrigated HRSW now accounts for ~8% (i.e., 61,917 ha) of the total irrigated cropland in Montana.

The yield for irrigated HRSW in the northwest region of Montana lags behind the irrigated yields of HRSW in other Montana regions, except the northcentral region (USDA-NASS, 2016). This response may be due to cultivar selection. In the other

Impacts and Limits of Irrigation Water Management on Wheat Yield and Quality

Jessica A. Torrion* and Robert N. Stougaard

ABSTRACT

Greater understanding of the impacts of irrigation timing in hard red spring wheat (Triticum aestivum L.) promotes better irrigation management, which optimizes the positive and minimizes the negative impacts on yield and quality. An experiment was conducted in 2014 to 2015 at Creston, MT. Eight cultivars (subplots) were randomly assigned to six water regimes (main plots). Aside from a rainfed check, irrigation treatments were: (i) replenishment of seasonal crop evapotranspiratory water loss via 32 mm per irrigation event (100ET); (ii) only 21 mm replenishment (66ET) per event to simulate season-long deficit; and three treatments in which 100ET replacement was terminated prior to grain fill completion by scheduling final irrigation at respective stages of: (iii) med-milk (100ET.MM), (iv) early milk (100ET.EM), (v) and anthesis (100ET.FL). The latter three treatments simulated end-of-season deficit irrigation. Irrigation treatment yields were similar, except for the lower 100ET.FL yield, indicating that wheat yield response to irrigation will be optimal in this environment as long as at least one irrigation event is supplied during grain fill. The cultivar yield responses to irrigation were similar. Irrigation increased biomass but had no impact on harvest index. Grain test weight (TWT) improved with irrigation. Falling number varied by cultivar and generally decreased with irrigation, but only significantly in 100ET, 66ET, and 100ET.MM. Irrigation improved yield and TWT, particularly during the hot and dry year. Irrigation can be terminated before completion of grain fill with no impact on yield and quality. Identification of adaptive cultivars with reduced irrigation or changing weather is necessary for improved productivity and grain quality.

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Continual breeding and agronomic practice improvements have gradually increased wheat yield in the United States. However, in the Northern Great Plains (i.e., Montana), the average annual yield gain over time has been shown to be small because of the water-limited environments (Graybosch et al., 2014). Given the unpredictability of rainfall timing and amount, producer interest in irrigating HRSW has increased. Irrigated HRSW now accounts for ~8% (i.e., 61,917 ha) of the total irrigated cropland in Montana.

The yield for irrigated HRSW in the northwest region of Montana lags behind the irrigated yields of HRSW in other Montana regions, except the northcentral region (USDA-NASS, 2016). This response may be due to cultivar selection. In the other
five regions of the state, more diverse HRSW cultivars are grown compared with those in the northwest region. The producer-preferred cultivar in northwestern Montana is the semidwarf cultivar ‘Solano’ (Westbred), despite recent statewide cultivar trials that indicate other cultivars may offer greater yield potential (Heo et al., 2014). However, Solano does offer significant resistance in years when excessive rain results in lodging of taller cultivars.

Although the regional market price of HRSW drives planting decisions by producers, grain quality (i.e., protein content, test weight, and preharvest sprouting [PHS]) also contributes to the price received locally. The PHS is an economic issue in Montana because it reduces baking quality, which subsequently leads to reduced grain prices at the grain elevator. Not-yet-harvested mature seeds on a wheat plant will germinate as a result of a prolonged exposure to wet conditions (Liu et al., 2008). Upon germination, an α-amylase enzyme breaks down starch into sugar (Brijs et al., 2009), the degree of which can be assessed by the falling number (FN) test (Finney, 1985). The degree of exposure of a mature spike to factors causing PHS is dependent on timing of physiological maturity (PM), which is intrinsically cultivar dependent, but also on the degree to which PM is hastened by water stress during grain fill (Talukder et al., 1987; Passioura, 1996; Torrion et al., 2014). The hormonal mechanisms controlling PHS are complex (Walker-Simmons, 1987; Graybosch et al., 2013), so any wheat management practices (including irrigation timing) that can be used to reduce PHS and its negative impact on baking quality are of interest.

No studies have been conducted in Montana evaluating the yield and grain quality of HRSW cultivars in response to seasonal deficit irrigation or termination of irrigation before completion of grain fill. Wheat is responsive to the rainfall or irrigation that increases the availability of transpirable water (Musick and Porter, 1990; Mogensen and Talukder, 1987; Muck et al., 1994). Many crops have been documented to have a linear yield response to water supplied to meet (but not exceed) estimated crop evapotranspiration (ET) demand (Sinclair et al., 1984; English and Talukder, 1987; Musick et al., 1994). Grain filling in wheat is sensitive to water stress, but its impact is limited only to seed size (Hochman, 1982; Kobata et al., 1992). Yield reduction typically occurs because water stress hastens the onset of senescence. This results in the crop not being able to capture season-ending solar radiation for biomass production, and it also shortens the timeframe for the mobilization and translocation of N and assimilate from plant tissues to the grain (Talbert et al., 2001; Uauy et al., 2006; Sadras et al., 2009; Woo et al., 2013; Zhao et al., 2015; Grogan et al., 2016). However, heat stress also affects crop yield when temperature rises above 25°C from tillering to grain set—the most thermosensitive stage in wheat—which reduces spikelet number (Acevedo et al., 2002). Blum (1986) suggested that a cultivar could reduce that impact if it maintains a high carbon balance (photosynthesis) at elevated temperature. In effect, maintaining transpiration-mediated surface canopy cooling can maintain photosynthesis and thereby maintain high yield during periods of elevated temperature (Idso et al., 1982; Reynolds et al., 1994). Cultivars with this characteristic could be considered to be high temperature resilient, particularly in irrigated production scenarios that can sustain yield under varying weather conditions.

Not much is known about the impact of irrigation timing on grain yield and quality of HRSW cultivars adapted to the northwest region of Montana. This information would be useful in determining what irrigation scheduling strategy improves yield and quality, and which HRSW cultivars consistently achieve high yield and quality under a range of water regimes. The specific objectives of this research were (i) to evaluate the impact of irrigation amount and timing on yield and grain quality, and (ii) to determine the degree to which cultivar choice influences
the response of yield and its components to various irrigation application strategies.

**MATERIALS AND METHODS**

This research was conducted in 2014 and 2015 at the Northwestern Agricultural Research Center at Creston, MT (48°11′24″ lat., −114°8′24″ long). Spring canola (*Brassica napus* L.) was the previous crop in both years. The soil type was a Flathead fine sandy loam (coarse-loamy, mixed, Pachic Haploxeroll) (USDA-SCS and MAES, 1959) with 2.5% organic matter and a pH of 6.5. The field was fall plowed and then disked in the spring. Soil samples were collected from 0 to 15-, 15- to 60-, and 60- to 90-cm depth intervals and submitted to a commercial laboratory for soil nutrient analysis. According to the Montana Fertilizer Recommendation Handbook (Jacobson et al., 2005), the NPK fertilizer was broadcast applied and incorporated with a field cultivator. The field each year was then culti-packed to firm the seedbed prior to planting.

Before planting, the wheat seeds were treated with the fungicides with an active ingredient (a.i.) of difenoconazole, mefenoxam, and sedaxane, plus the insecticide (a.i.) thiamethoxam. In 2014, the herbicides were (a.i.) pyrasulfotole, bromoxynil octanoate, bromoxynil heptanoate, and pinoxaden but in 2015 were (a.i.) thiencarbazone-methyl, pyrasulfotole, and bromoxynil. Pesticide control after emergence included the insecticide (a.i.) λ-cyhalothrin applied in each year, plus the fungicide (a.i.) pyraclostrobin applied in 2014 or (a.i.) azoxystrobin in 2015.

The experimental design was a split-plot with four blocks (replicates) and the treatment design was a factorial set of six water regimes (randomly assigned to main plots within each block). The sub-plots were 4.6-m long and seven rows wide with an inter-row spacing of 0.15 m.

Spring wheat cultivars used in this study were chosen based on their adaptation, yield performance in recent cultivar trials, and diversity in maturity (Table 1). All cultivars were semi-dwarf. The HRSW cultivars were planted at a target seeding rate of 222 seeds m⁻² on 23 Apr. 2014 and 22 Apr. 2015 using a double-disc drill set to a depth of 4 cm. The seeding rate was established on a pure-live basis by measuring replicated thousand-kernel weight (TKW) adjusting percentage germination for each cultivar.

The six main plot irrigation treatments were described in Table 2 with their respective irrigation and rainfall events (Fig. 1A and 1B) and actual yearly cumulative ET (Fig. 1C and 1D). A 100ET was included to simulate non-water-stressed conditions. A deficit treatment (66ET, derived as two-thirds of 100ET [21 mm/32 mm 100ET]) was to simulate season-long deficit irrigation. The three termination treatments in which 100ET replacement was terminated prior to the completion of grain fill by applying the final irrigation event at or close to reproductive stages were anthesis (FL), early milk (EM), and medium milk (MM). These three irrigation termination treatments were designed to examine the impact of deficit irrigation during successive phases of the grain-fill period. Finally, a rainfed check was used to assess the impact of severe water stress.

Daily reference grass-based ET (ET₀) was calculated using data collected at the Creston Weather Station (USBR, 2017), which is located 700 m from the field site. Daily ET₀ was estimated by multiplying ET₀ by the wheat crop coefficient (Kc) (Allen et al., 1998). The Kc values appropriate for a given growth stage and percent canopy cover for each of the named phenological stages were as follows: preinitial = 0.2 from emergence to the four-leaf stage, initial = 0.2 to 1.2 from four-leaf to first-awn stages, middle = 1.2 from first-awn to medium-milk stages, and late = 1.2 to 0.3 from medium-milk stage to PM. Daily soil moisture depletion was estimated by subtraction of daily ET₀ and by addition of any daily rainfall or irrigation, starting from 100% field capacity at planting. The rooting depth for the daily soil water depletion calculation was 0 to 60 cm prior to, but 0 to 90 cm after, the attainment of the crop heading growth stage. With regard to runoff or deep percolation, the effective rainfall amount was based on the amount of rain that could be accommodated (stored) in the soil. The storage field capacity for the soil at this field site is 47 mm 30 cm⁻¹ depth. In calculating soil water depletion via the soil water balance approach, it was assumed that any water in the soil that exceeds field capacity will temporarily bring that soil moisture above field capacity moisture content, with the excess water over field capacity draining into lower soil layers during the 24-h period after a rainfall or irrigation event. Granular matrix soil moisture sensors (Watermark) were installed at 30-, 60-, and 90-cm depths to provide in situ soil moisture depletion estimation as a check with the ET-calculated soil water balance method of depletion (Irrmak et al., 2014).

Irrigation was applied using two drip tapes equidistant from each other in each seven-row-wide main plot, within which the eight seven-row subplots were successively arrayed in the same row direction. The drip tapes emitted water at 30-cm intervals. In each of the five irrigation treatments, irrigation

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Originator</th>
<th>Pedigree</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brennan</td>
<td>Syngenta Seeds</td>
<td>Reeder//China Scab #140/N90-0690</td>
<td>Early</td>
</tr>
<tr>
<td>Buck Pronto</td>
<td>Buck Semiillas</td>
<td>Victoria-inta//Junin/Buck-Pucara</td>
<td>Medium-early</td>
</tr>
<tr>
<td>Expresso</td>
<td>Westbred</td>
<td>Express*/YR15 Avocet/Express 6*/Madsen</td>
<td>Medium-early</td>
</tr>
<tr>
<td>McNeal</td>
<td>Montana Agricultural Station</td>
<td>RS 6880/Glenman</td>
<td>Medium-late</td>
</tr>
<tr>
<td>Solano</td>
<td>Westbred</td>
<td>DA993–191/Express</td>
<td>Medium</td>
</tr>
<tr>
<td>Volt</td>
<td>Pflanzenzucht Oberlimburg</td>
<td>Tx75-U1139/Mr/Walter/5/Gallo/Cuckoo//Seipelk/3/Super-X/4/Kavkaz/ Granat//Kentana</td>
<td>Medium-late</td>
</tr>
<tr>
<td>WB-Rockland</td>
<td>Monsanto</td>
<td>Expresso/2*Solano</td>
<td>Medium-early</td>
</tr>
</tbody>
</table>

*Table 1. Descriptions of hard red spring wheat cultivars (CIMMYT, 2017).*
commenced the day after soil water depletion by the crop in the 100ET treatment reached 35% of the soil field capacity. The irrigation application rate was 4.5 mm ha\(^{-1}\) h\(^{-1}\), so it took ~7.1 h to apply ~32 mm water per irrigation event (or 4.6 h for the 21-mm events in the 66ET treatment). All irrigation events in all treatments were synchronous (to avoid confounding) except for the irrigation applications omitted in the medium milk (100ET.MM), early milk (100ET.EM), and flowering (100ET.FL) treatments. Given the fine sandy loam soil of the site with a 0% slope, there was no evidence of surface runoff. We assumed that excess water above field capacity of the soil drained deeper in the soil. Using granular matrix moisture sensor, we were able to determine the number of days during which water from excess rainfall was temporarily held above field capacity. That water was considered as water credit in our soil-water-balance approach because plant root hairs can use some of that temporary water before most of it drains away as the soil water content returns to field capacity.

Phenological development was monitored in each subplot by a twice-weekly staging of 10 contiguous tillers or heads in a random subplot row using the Zadoks staging scale (Zadoks et al., 1974). The PM occurrence was recorded as the date when 50% of the spikes and peduncles were completely yellow. Biomass was collected as soon as possible after PM by collecting aboveground plant material from two randomly assigned, adjacent inner rows at 1-m length each (i.e., a 0.30-m\(^2\) sampling area). The numbers of plants and spikes per plant (SPP) were counted from the collected biomass samples. Ten heads were bagged and threshed to determine seeds per spike (SPS). The biomass was dried in a drying room for at least 48 h or until the dry weight was stable then weighed to determine harvest index (HI) calculated as the ratio of grain yield to total aboveground biomass. Mature plant height was measured from the ground surface to the tip of the spike for several plants and averaged. Lodging was not measured nor observed.

The subplots were combine harvested on 26 Aug. 2014 and 12 Aug. 2015. Total seed weight, seed moisture, TKW (i.e., seed mass), grain test weight (TWT), grain protein, and FN were determined. Seed yields were adjusted to 13% moisture. The TKW was determined by weighing two sets of 500 seeds plot\(^{-1}\) counted by a Seedburo 801 Count-A-Pack counter. Grain protein, moisture, and TWT were determined using a near-infrared technology (Infratec1241 Grain Analyzer) calibrated with local standards. Falling number values (i.e., time it
takes for a stir rod to fall through the suspension of flour and water to the bottom of the viscometer tube) were measured using a FN 1700 (Perten).

For data analyses, SAS version 9.4 (SAS Institute, 2014) PROC GLIMMIX (Little et al., 2006; Wolfinger and O’Connell, 1993) was used because the majority of the trait datasets were not normally distributed based on Shapiro–Wilk Tests of normality. In the model statement, the option DDFM = KENWARDROGER was used to estimate denominator degrees of freedom for the fixed effect error adjustment. Year, irrigation, and cultivar (denoted as Y, I, and C when referring to interactions) were treated as fixed effects, whereas replication was treated as a random effect. In PROC GLIMMIX, the SLICE option was used to interpret the nature of any significant two-way interactions (i.e., Y × I, I × C, and Y × C) when the three-way interaction (Y × I × C) was not significant. The LINES option was used to generate LS MEANS comparisons, which were interpreted using Fisher’s protected LSD test. The SLICEDIFF option was also used to examine the simple effect comparison between main effects for some traits.

**RESULTS**

**Seasonal Weather Differences**

Monthly and seasonal means for ambient mean, maximum, and minimum air temperatures were near normal (i.e., 26-yr average from 1989–2015) in 2014 (Table 3). However, in 2015, the seasonal maximum temperature was 2.4°C greater than normal and 5.9°C greater than the normal June temperature. The highest maximum temperature in June 2015 was 38°C (data not shown).

<table>
<thead>
<tr>
<th>Year</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean temperature (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>6.9</td>
<td>11.8</td>
<td>13.8</td>
<td>19.7</td>
<td>18.3</td>
<td>14.1</td>
</tr>
<tr>
<td>2015</td>
<td>7.1</td>
<td>12.6</td>
<td>18.4</td>
<td>19.1</td>
<td>18.3</td>
<td>15.1</td>
</tr>
<tr>
<td>1989–2015</td>
<td>6.6</td>
<td>11.3</td>
<td>14.7</td>
<td>18.9</td>
<td>18.0</td>
<td>13.9</td>
</tr>
<tr>
<td>Mean minimum temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>13.4</td>
<td>18.8</td>
<td>20.4</td>
<td>28.8</td>
<td>27.2</td>
<td>21.7</td>
</tr>
<tr>
<td>2015</td>
<td>14.6</td>
<td>20.4</td>
<td>27.1</td>
<td>28.2</td>
<td>28.8</td>
<td>23.8</td>
</tr>
<tr>
<td>1989–2015</td>
<td>12.6</td>
<td>17.8</td>
<td>21.2</td>
<td>27.2</td>
<td>26.9</td>
<td>21.4</td>
</tr>
</tbody>
</table>

| Total precipitation (mm) |
| 2014    | 21  | 41  | 154 | 12  | 48  | 275    |
| 2015    | 15  | 16  | 25  | 9   | 4   | 69     |
| 1989–2015 | 38  | 52  | 81  | 29  | 24  | 224    |

Monthly precipitation totals in 2014 were nearly double the June and August norm (Table 3) but were otherwise slightly lower than normal in other months, although total seasonal precipitation was 50 mm more than the seasonal norm of 224 mm. In contrast, precipitation in 2015 was, on average, only 30% of normal in total seasonal amount (69 mm) in all months except August (only 16% of normal). There was a season-long rainfall deficit in 2015, which was exacerbated by the concurrent higher-than-normal temperatures.

Monthly and seasonal ET_o values in 2014 were somewhat lower than normal (but notably half of normal August ET_o), resulting in a total seasonal ET_o of 510 mm, versus the normal 600 mm (Table 3). In 2015, the May, June, and July ET_o values were higher than normal but were near normal in the other 2 mo, although the seasonal ET_o total that year was just 29 mm more than normal. Because of the higher precipitation, near-normal temperatures, and lower ET_c in 2014, less irrigation was needed to replenish ET_c (Fig. 1A). In contrast, more irrigation was needed in the hotter and drier 2015 growing season (Fig. 1B).

Crop ET in 2015 showed a steeper gradient than in 2014 (Fig. 1C and D) because of the accelerated growth of wheat with elevated temperature. The duration between emergence and PM was 95 d in 2014, compared with 80 d in 2015 (Fig. 1C and 1D). Concurrently, the duration between all reproductive growth stages (FL, EM, and MM) was more compressed in 2015, which in turn contributed to a steeper ET_c that year. The respective trend lines that coincided with, or were below, the respective early and later portions of the ET_c curve are the cumulative effective water amounts for each of the five irrigated treatments and the rainfed check.

**Irrigation and Cultivar Main Effects and Interactions**

The irrigation main effect was significant for all traits except HI and grain protein (Table 4). Only five traits (including grain protein) were significant for the Y × I interaction. The HRSW response to the irrigation treatments were consistent between years for the other six traits such as HI, seed mass, SPS, PM, TWT, and FN with no Y × I interaction. Only three traits (i.e., TKW, TWT, and FN) were significant for I × C, suggesting that the response of these traits to irrigation was influenced by cultivar choice. However, for all other traits, the lack of a significant I × C interaction indicated that cultivar choice was irrelevant in the sense that all cultivars responded similarly to irrigation. The Y × I × C interaction was significant only for grain protein (Table 4).

The cultivar main effect was significant for all traits (Table 4), which was not unexpected, given the diversity of the eight cultivars chosen for this study. However, the Y × C interaction was also significant for all traits...
but biomass, HI, and plants per hectare, indicating that for most traits, cultivar differences were not consistent between years. Because our primary interest was an examination of the irrigation treatment means or, when applicable, the Y × I or I × C means, rather than focusing on cultivar means per se or Y × C means, bar charts for the significant cultivar main effect means for biomass and HI and for the significant Y × C means for eight other traits (except grain protein) are given in Supplemental Fig. S1, S2, and S3, respectively. Relative to the Solano—the popular choice of producers in northwest Montana—the cultivar ‘Volt’ was significantly higher yielding in both years (Supplemental Fig. S2) but had lower grain protein and significantly smaller seed size (i.e., TKW). Volt was also somewhat taller (Supplemental Fig. S3), which could make it more prone to lodging than Solano in heavy rain-fall years. Among the cultivars used, cultivar ‘Brennan’ had the lowest seed and biomass yield, the lowest SPS, and the lowest HI. Moreover, Brennan consistently had the earliest occurrence of PM in conjunction with ‘Expresso’. The variations of PM occurrence among the cultivars were 92 ± 3 and 83 ± 2 d in 2014 and 2015, respectively (Supplemental Fig. S3A and S3B).

### Yield and Its Components and Related Traits

Plant density was invariant with irrigation main effect and its interactions with the other sources of variation. Instead, only cultivar main effect was significant for plant density, which was mainly due to the significantly low density of ‘WB-Rockland’, a large-seeded cultivar.

The irrigation main effect was significant for PM, with no differential response observed between years or

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### Table 4. Analysis of variance for the 2-yr randomized complete block (b = 4) experiment with a split-plot arrangement of five irrigated and one rainfed treatment (as main plots) and eight cultivars as subplots. The table shows the sources of variation, the numerator and denominator degrees of freedom (i.e., ndf and ddf), and probability values for the F-tests of each main effect and interactions.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>ndf</th>
<th>ddf</th>
<th>Seed yield Biomass Harvest Index 1000-seed wt. Spikes plant−1 Seeds spike−1 Days to Pm†</th>
<th>Year (Y)</th>
<th>Irrigation (I)</th>
<th>Y × I</th>
<th>Cultivar (C)</th>
<th>Y × C</th>
<th>I × C</th>
<th>Y × I × C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>F, b</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
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<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>30</td>
<td>F, b</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>30</td>
<td>F, b</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
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<tr>
<td></td>
<td>7</td>
<td>245</td>
<td>F, b</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
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</tr>
<tr>
<td></td>
<td>35</td>
<td>245</td>
<td>F, b</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
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<td>&lt;0.0001</td>
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</tr>
</tbody>
</table>

† PM, physiological maturity.

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### Fig. 2. Days from emergence to physiological maturity effects of water regimes. Error bar is the standard error of the difference between water regime treatment means. Same letter assignment indicates the nonsignificance between water regime treatment means at α = 0.05. Treatments include: full-season irrigation of 100% evapotranspiration (100ET), deficit irrigation (66ET), irrigations at applied medium milk (100ET.MM) irrigations at flowering (100ET.FL), and rainfed.
among cultivars (Table 4). In irrigated treatments where ETc replenishment was in deficit amounts (i.e., 66ET and 100ET.EM), or severely deficit (100ET.FL) (Fig. 1C and 1D), a significant hastening of PM of these treatments occurred relative to the 100ET irrigation treatment control (Fig. 2). The hastening of PM in deficit treatments, however, was certainly less than what was observed in the rainfed control. Heading date, on the other hand, was not influenced by irrigation treatments ($P = 0.4181$, data not shown), with an average occurrence of 49 d from emergence.

The $Y \times I$ interaction was significant only for seed yield, biomass, SPP, and height (Table 4, Fig. 3), indicating that the response of these traits to irrigation differed between the near-normal year of 2014 and the hotter and drier year of 2015. For seed yield, all five irrigation treatments generated more yield than the rainfed check. The response was greatest in 2015 and likely contributed to the significance of $Y \times I$. The 100ET.FL treatment (in which the last three irrigation events during grain fill were omitted) resulted in lower yield than all other irrigation treatments in 2015 and a lower yield than all but 66ET treatment in 2014. In the near-normal 2014, irrigation treatment yields were at least 6.5 Mg ha$^{-1}$, but in the hotter and drier 2015, those yields did not exceed 5.0 Mg ha$^{-1}$. This overriding effect of temperature stress was also evident in the resulting biomass, SPP, and height (Fig. 3, Table 4), in which the $Y \times I$ interaction sliced by year

![Graphs showing yield, biomass, spikes per plant, and height for 2014 and 2015](image)

Fig. 3. (A, B) Yield, (C, D) above-ground biomass, (E, F) spikes per plant, and (G, H) height of water regime treatment means for 2014 and 2015. Error bar is the standard error of the difference between water regime treatment means. Same letter assignment indicates the nonsignificance between water regime treatment means at $\alpha = 0.05$. Treatments include: full-season irrigation of 100% evapotranspiration (100ET), deficit irrigation (66ET), final irrigation applied at medium milk (100ET.MM), final irrigation applied at early milk (100ET.EM), final irrigation applied at flowering (100ET.FL), and rainfed.
was highly significant \((P < 0.0001)\) for these traits. The lack of \(Y \times I\) significance for the HI, TKW, or SPS indicated that the response to irrigation was not differentially affected by the contrasting temperature and rainfall difference between years. No \(I \times C\) interaction was detected for any seed yield-related trait except TKW (Fig. 4). The HRSW cultivars responded differently to the six water regimes \((P < 0.0001–0.0056)\) on the basis of the SLICE test of \(I \times C\) on cultivar effect. For instance, TKW of Brennan and Volt responded to 100ET.FL with respective \(P\)-values of 0.0002 and <0.0001 in relation to rainfed but not to other irrigation treatments. In contrast, the TKW of the Expresso in all but one irrigation treatment did not change much from the rainfed treatment, except for the 100ET treatment \((P = 0.0003)\), which produced a greater TKW. The cultivar ‘Buck Pronto’ stood out from all other cultivars with respect to having highest cultivar TKW in each of the six water regimes.

**Grain Quality**

Relative to TWT and FN, the irrigation main effect was significant, but so was the \(I \times C\) interaction (Table 4, Fig. 4), indicating that cultivars did not respond similarly to irrigation relative to these two traits. For TWT, the cultivar response pattern to irrigation main effect was quite heterogeneous. Although irrigation did lead to improvement in the TWT of most cultivars vis-à-vis the rainfed check, this was not the case for Volt, which also happened to be the cultivar with highest TWT in each of the six water regimes. Relative to FN, for which higher values denote less \(\alpha\)-amylase activity (Fig. 4c), irrigation decreased FN in some cultivars (e.g., Brennan), but not in others (e.g., Buck Pronto). Very high FN numbers for ‘McNeal’ were noted, which were greater than those for the other cultivars in each of the six water regimes.

As previously mentioned, a \(Y \times I \times C\) interaction was detected for grain protein (Fig. 5), making it difficult to unravel the complexity of this HRSW grain quality trait with respect to different irrigation strategies, cultivars, and years. For some cultivars, irrigation increased grain protein in 2014 but did not do so, or decreased it, in 2015. Brennan and WB-Rockland produced the highest grain protein in each of the six water regimes, but only Brennan responded to irrigation consistently with increased grain protein relative to the rainfed check. Brennan showed a consistently lowest SPS (Supplemental Fig. S2G and S2H) and TKW (Supplemental Fig. S2C and S2D), which may have lowered carbohydrate deposition to the seed. Biomass accumulation via irrigation (Fig. 3C and 3D), coupled with preanthesis reserves, may have led to an increased N translocation to the grain with the relative early occurrence of PM for Brennan (Supplemental Fig. S3A and S3B).
DISCUSSION
Supplemental irrigation mitigated hastening of PM. Water-stress-induced PM occurrence typically lowers yields in nearly all crops (Brown, 2007; Hossain et al., 2012; Nezhadahmadi et al., 2013; Torrion et al., 2014). Irrigation reduces the shortening of the grain-filling duration, thereby allowing the crop to sustain photosynthetic production of biomass and seed yield near the end of the growing season.

In this study, irrigation increased HRSW yield, although scheduling less irrigation than required for 100% ET replenishment during the entire season (i.e., 66ET) did not lead to significantly lower yields consistent with deficit irrigation studies in wheat and other crops (English and Nakamura, 1989; Turner et al., 1994; Chai et al., 2015). Similarly, zero replenishment of ETc during the parts of the grain-fill period did not lower yields as well, except for the lower-yielding 100ET.FL strategy in which irrigation was terminated soon after grain fill began. Imposing water stress in the grain-fill period increased remobilization efficiency of preanthesis photosynthates (Ma et al., 2014) that aligned with the reported lesser degree of grain yield sensitivity during grain fill than earlier growth stages (Mogensen and Talukder, 1987). Moreover, the rate of accumulation of grain mass as quantified by Gallagher and Biscoe (1978) was nil during the final 15% of grain-fill period, which corresponds to the slowing down of crop yield response when most of the yield potential had already been achieved (Specht et al., 1986). The lack of yield penalty has implications for HRSW producers who have a limited supply of water for irrigation. A season-long deficit 66ET strategy or a season end omission of one or more irrigation events would not substantively reduce yields in normal or dry years such as those encountered in this study and, in essence, improves irrigation efficiency (a.k.a. water productivity) as of similar deficit irrigation studies (Ali et al., 2007; Chai et al., 2015).

This was also true for total aboveground biomass, which must be increased to improve yield, given that HI was not affected by irrigation per se or by any other factor than the choice of cultivar. The SPP yield component is typically set prior to grain fill and would thus be less affected by a 100ET.FL strategy, except of course in years with low rainfall during the pre-grain-fill months (as was the case here in 2015). Irrigation does increase plant height in dry years, as was shown here, but this impact may not be of much consequence in all but excessive rainfall years when the potential for yield-depressing lodging increases, nor for short-statured, inherently lodging-resistant cultivars such as Solano.

This study did document that one could get by without much yield penalty when applying less irrigation water than needed for 100% of the total seasonal ET water loss when using the 66ET, 100ET.MM, and 100ET.EM deficit irrigation strategies. With regard to the latter two strategies, this would be consistent with reports that maximum aboveground biomass and relocation of assimilates to the grain is mostly from preanthesis-accumulated dry matter (Musick and Porter, 1990). However, most producers do not refill the soil water profile to 100% field capacity at each irrigation event (which was done in this study for all but the 66ET treatment, see Fig. 1). In fact, most
producers prefer not to bring the soil profile to 100% field capacity with each irrigation event, because they want to leave “room” in the soil profile to store rainfall coming from unexpected thunderstorms for subsequent use by the crop. For that reason, producers who are interested in reducing unnecessary applications of irrigation water (including amounts negated by such thunderstorms) would be advised to implement a 66ET strategy (i.e., restricting total water applied at each event to just two-thirds of the ET amount), as opposed to a 100ET.EM strategy if the producer does not fill (in full) the soil profile. A caveat is, in that scenario, that a 100ET.EM strategy could theoretically result in encountering more grain fill water stress than was encountered by that strategy in this study.

Wheat is most sensitive to high temperature from tiller to beginning of flower, otherwise referred to as G2 (Acevedo et al., 2002). Day temperatures >30°C cause floret sterility (Saini and Aspinall, 1982). Our findings indicate that the number of SPS was significantly lower in 2015 (P < 0.0001). In the irrigated treatments, yield reduction was associated with floret sterility (via SPS), whereas both the reduction of SPP and floret sterility resulted in a substantially lower yield in the rainfed check than the irrigated treatments. A severe drought, when accompanied by high temperatures, causes great economic losses in water-limited production agriculture (Hossain et al., 2012). Using irrigation to supplement a rainfall deficit was effective in improving HRSW yields relative to rainfed yields, but irrigation per se certainly did not overcome the yield-depressing effect of coincidently higher temperatures in the 2015 drought year. High day temperatures can depress photosynthesis (Acevedo et al., 2002), high night temperatures can result in greater dark respiration (García et al., 2015), and both nearly always reduce crop biomass and yield. Notably, the 2015 rainfed and irrigated yields were a respective 62 and 30% less than the 2014 yields. During a hot and drought year like 2015, irrigation cannot compensate for the damage caused by temperature, especially when it affects the known thermosensitive stage (i.e., active tillering to early flower), although irrigation can mitigate some of the impacts of high air temperature on the canopy maintenance of transpirational cooling during hot and dry periods that can occur in some years. Given the Montana year-to-year temperature variability during summer seasons (NOAA, 2017), temperature in some years during summer months deviates a lot higher than average, which suppresses wheat yield. Having a hotter year like 2015 to evaluate the irrigation treatments was a fortuitous occurrence, relative to the evaluation of HRSW cultivar response to irrigation treatment strategies in this study. Despite the cultivar variation of the maturity shown in the preceding section of this paper, impact due to such variation was avoided by maintaining plant available water >50% in the rootzone until the PM occurrence of the latest-maturing Volt. Maintaining >50% plant available water until PM guarantees a water-stress-free plant (Rosenthal et al., 1987). Because all other irrigation treatments were applied according to the 100ET events, it can only be assumed that impact due to the synchronicity of water application amongst cultivars via deficit irrigation was minimal. Similar response of cultivars to maturity adjustment with irrigation is evident with the insignificant I × C interaction for PM.

Producers choosing cultivars for irrigated fields need information about cultivar response to irrigation. Given the insignificant I × C interaction in yield, a cultivar choice with respect to the response of various irrigation strategies is irrelevant. However, the C significance in yield suggests that cultivar choice contributes to the overall economic yield as long as such cultivar has superior yield relative to other available cultivars and, importantly, meets the wheat quality characteristics required for a high wheat price. In that regard, Volt and Brennan were respectively the highest and lowest yielding cultivars in both years. A sole goal of maximal yield must be balanced with wheat quality considerations, which also affects net economic returns. Although late-season N addition for protein has not been profitable (Chen et al., 2008), it is imperative to find a cultivar that produces high yield without sacrificing quality. Recently (after this research concluded), Montana spring wheat breeder released cultivar ‘Egan’ (Blake et al., 2014), a HRSW with the Gpc-B1 gene for high protein, resistant to orange wheat blossom midge [Sitodiplosis mosellana (Géhin)] having high FN. Its performance with respect to different irrigation strategies is yet to be determined.

Protein is a trait that is highly cultivar dependent but also shows an association with environment (i.e., year) and management (i.e., irrigation) making the interpretation difficult for grain protein response, especially to irrigation treatments. Irrigation affected TWT and FN, which also had an I × C interaction. Test grain weight is an important indicator of flour milling quality wherein higher TWT is preferred. Supplemental irrigation improved TWT of the cultivars except for Brennan, BuckPronto, and WB-Rockland. Overall, the effect of irrigation on TWT followed the impact of water regimes on yield, whereby 100ET, 66ET, 100ET.MM, and 100ET.EM were not different. Thus, if a producer chooses the 100ET.EM method as an end-of-season water-saving strategy, doing so would not be expected to affect yield and TWT negatively. According to Nuttall et al. (2016), TWT is associated with seed size, wherein a bigger seed size tends to have a higher TWT. However, close examination of that claim with specific cultivars in this study showed otherwise. For instance, Volt, which has the smallest seed size among cultivars, showed superior TWT across cultivars.

Irrigation had a negative impact on FN. This was especially evident with Brennan, which showed a decrease in
FN with water applied during later grain fill. In this study, irrigation was delivered using drip tapes without wetting the wheat spikes. Under the common method of irrigation in northwest Montana (i.e., pivot sprinkler), it can only be hypothesized that irrigation using a sprinkler late in the grain-fill stage can advance preharvest α-amylase activity compared with the drip tape method. One can avoid lowering FN by avoiding irrigation at this stage, in addition to the no further yield benefit associated with the late grain-fill irrigation application. Avoiding irrigation application at this stage in wheat lessens spike exposure to contrasting temperature. Water pumped from a deep well for irrigation in northwest Montana is cool water (~12°C in this study). There is evidence on temperature shock, more so on cold than warm temperature shock exposure of wheat spikes, which induces β-amylase activity in developing wheat grain (Farrell and Kettlewell, 2008). Moreover, Montana August day and night temperatures can be extreme. It is noted that FN is also cultivar dependent, and this study showed that cultivars are available that maintain high FN with irrigation, such as ‘McNeal’. Brennan can be considered less adaptive to northwest Montana, not only because of its low yield, but also its vulnerability to depressed FN when irrigation is applied at medium milking stage and near soft dough. Volt, on the other hand, consistently had high biomass, yield, and TWT regardless of irrigation treatment, except protein. Similar cultivar characteristics possess potential for future breeding improvement for protein and improved resistance to lodging.

In conclusion, our results indicate that irrigation can be terminated early without negatively affecting yield or quality. All cultivars responded similarly with irrigation, but Volt stood out in the pool and had superior yield across cultivars and years, although protein can still be improved. Brennan on the other hand consistently had the lowest yield across cultivars and years, plus the most susceptibility to lowered FN with irrigation. An adaptive cultivar in this environment can be defined as one that consistently produces higher yield relative to the other tested cultivars, is resistant to lowering FN with irrigation, and has economically acceptable protein. However, the latter can be elusive because of the uncertainty in the yearly protein premium. For that reason, Volt may not be the only adaptive cultivar, but the rest of the cultivars, except Brennan, may be adaptive as well. Additional information is needed regarding cultivar yield and quality response to irrigation, not only to provide appropriate information to the growers, but also to help in directing breeding efforts to identify greater responsiveness to supplemental irrigation in future cultivars.

**Conflict of Interest**
The authors declare that there is no conflict of interest.

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**Supplemental Material Available**
Supplemental material for this article is available online.

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**References**


