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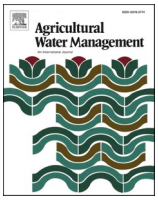

Wheat stubble height effects on soil water capture and retention during long fallow

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ABSTRACT

A 4-yr study was conducted in a dry Mediterranean region of the Inland Pacific Northwest USA (PNW) to measure winter wheat (WW) (*Triticum aestivum* L.) stubble height and orientation effects on overwinter precipitation capture in the soil and subsequent water retention during ensuing dry summer months. The stubble was left standing and undisturbed during the 13-mo fallow periods. Stubble-height treatments were:(i) short (8 cm), (ii) medium (25 cm), and (iii) tall (75 cm). An additional treatment: (iv) mow tall stubble in mid-June, was included in the final two years. Soil water measurements were obtained at the beginning, middle, and end of fallow in 15-cm increments to a depth of 180 cm. Additionally, seed-zone water content was measured at the end of fallow in 2-cm increments to a depth of 26 cm. Near-surface soil temperature was measured from June-August. On average, tall- and medium-height stubble captured 34 and 32 mm ($p = 0.002$) more overwinter precipitation, respectively, than short stubble and these values were particularly pronounced (91 and 79 mm greater than short stubble) during a winter of heavy snow drifting. However, from mid-April until late August, the tall stubble lost an average of 91 mm of soil water compared to 70 and 59 mm in the medium and short stubble treatments ($p < 0.001$). Mowing tall stubble in mid-June before the hot, dry summer did not improved water retention. Continuous soil temperatures at 3, 7, 15, 25, and 40-cm depths measured electronically from June-August were coolest with the short, mowed, medium, and tall stubble, respectively, with frequent significant differences of > 1 °C among treatments. We speculate that soil in the tall treatment was warmest and lost the most over-summer water because all stubble was standing and offered less soil shading than the other treatments. At the end of fallow, medium and tall stubble averaged 14 and 8 mm greater soil water, respectively, than the short treatment ($p = 0.027$). Short stubble was a disadvantage for overwinter precipitation capture but was equal or better than the other treatments for retaining soil water from April to late August; presumably because this treatment had the most residue lying flat on the soil surface for shading. These findings offer opportunity to improve current models for soil water dynamics during fallow by incorporating stubble height. For combined soil water retention and farm management factors, medium-height WW stubble is the best fallow option for farmers in the PNW drylands.

1. Introduction

Stubble management to enhance soil water storage and reduce soil erosion has been studied for many decades. As farm implements and farmers' preferences evolve over time, there is a need for new information on the effects of stubble management options. In the past, moldboard plow or other tillage practices that left soil bare of crop residue were the standard for comparison. No-till production is now common enough to be used as a baseline practice in the United States PNW (Machado et al., 2015) and other Mediterranean-like dryland wheat production regions around the world (Giller et al., 2015).

The climate of the PNW is characterized by cool, moist winters and warm, dry summers with occasional drought cycles. About two-thirds of annual precipitation occurs from October-March with about one-third as snow during this period. One fourth of the annual precipitation occurs during April-June with July-September the driest and warmest months (Karimi et al., 2017). Because of crop adaptation, grain yield stability, and economic advantages, a 2-yr winter wheat-fallow rotation (one crop every two years) has dominated dryland agriculture since the 1890 s on about two million hectares in the low-precipitation zone (350 mm and

Abbreviations: HI, Harvest index; PNW, Inland Pacific Northwest USA; WW, winter wheat.

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less of average annual precipitation) of the PNW (Kirby et al., 2017). On average, precipitation storage efficiency in the soil is 65–70% in the winter of the fallow year, but storage efficiency is reduced to around 30% by the end of fallow (i.e., at time of WW sowing) in late August-early September (McCall and Wanser, 1924; Schillinger, 2016). This stored soil water during fallow allows for timely sowing of WW and reduces the risk of crop failure from drought which enables stable and mostly profitable grain yields (Stöckle et al., 2018).

The question of ideal stubble height is largely focused on the potential to trap drifting snow during winter (Ries and Power, 1981) and likelihood to reduce evaporation during the dry, warm summer. The capacity of tall stubble to trap drifting snow is well established (Black and Siddoway, 1977; Hoefer et al., 1981), but the effect on stored soil water is dependent on weather conditions (Aase and Siddoway, 1980; Black and Bauer, 1990). For example, Campbell et al. (1992) measured only 3 out of 10 years where tall stubble provided greater overwinter soil water storage. These studies were conducted in the Great Plains region of the northern US and southern Canada where snow is the major form of winter precipitation. In regions with milder winters, blowing snow can be infrequent or represent minor amounts of precipitation. In this case, evaporation after rainfall events or in the spring become more important.

The hypothesis that tall stubble can reduce evaporation of stored soil water is complicated to evaluate. Theoretically, the reduction in near-surface wind speed and convection under tall versus short or no residue should reduce evaporation from the soil surface (Aase and Siddoway, 1980). Tall stubble is also generally assumed to shade the soil surface more than short stubble to reflect heat energy (Horton et al., 1996).

Aase and Siddoway (1980) found that tall stubble improved snow capture but could find no direct evidence of less evaporation with standing stubble versus bare soil. In their experiment, no residue was left lying on the soil between rows. Cutforth et al. (2011) measured enhanced wheat grain yields with increasing stubble maintained during the crop year, which they considered an indication of less evaporation and more transpiration with stubble as tall as 45 cm. In contrast, Baumhardt et al. (2002) and Flerchinger et al. (2003) reported that evaporation differences among stubble heights were minor under dry conditions. The quantity of surface soil water is a dominant factor in the amount of evaporation. In some regions summer rainfall is significant, but in Mediterranean regions like the PNW, the final two to three months of the fallow period are dry and warm, and during this period treatments with greater near-surface water will evaporate water faster than drier treatments until surface water contents are equal (Hammel, 1996; Idso et al., 1974).

Flerchinger et al. (2003) reported that standing wheat residue generally warmed soil sooner in the spring compared to flattened residue or bare soil. This contradicts the theory that tall stubble provides shade which reduces solar heating. Bare soils tend to have warmer daytime temperatures, but this begins after the soil surface dries, and does not necessarily result in greater heat flux downward (Flerchinger et al., 2003). Dry surface soil and especially dry residue cover create poor conduction of heat downward, and their high surface temperature creates significant radiation back to the atmosphere and conduction/convection to the air (Cutforth and McConkey, 1997).

Complicating these relatively straightforward concepts on the effects of residue height is the quantity of residue laying horizontal on the soil surface (Swella et al., 2015). In the absence of residue removal, the height of residue left standing is inversely related to the amount of residue lying flat on the soil surface. The tradeoff between standing residue and flattened surface residue is not easily determined and depends on the proportion of time the soil surface is dry (Baumhardt et al., 2002). Flat wheat residue produced the lowest evaporation in several climates, but the differences in evaporation due to residue architecture (tall vs short and amount flat on the soil) were minor; about 8% in dry climates (Flerchinger et al., 2003).

Surface residue provides protection from wind and sun immediately after a precipitation event, and this effect can extend for several weeks compared to bare soil (Wuest and Schillinger, 2011). In climates with low total precipitation and brief events of low intensity rainfall, surface residue needs to be wet through before water reaches the soil surface. Once rainfall infiltrates into the surface soil, the reduction in evaporative loss with surface residue vs bare soil results in a net increase in stored soil water for about a month following the rain event (Wuest and Schillinger, 2011; Swella et al., 2015; Wuest, 2017).

Mediterranean climatic regions have extended dry periods where cropland is sometimes left fallow for a year or longer. There is often wide year-to-year variation in precipitation totals and crop residue produced. Therefore, it is especially important to measure residue factors in combination with soil type and weather patterns through the full fallow cycle over several years (Flerchinger et al., 2003; Ward et al., 2009).

The objective of our study was to determine whether maximizing stubble height would improve fallow water storage in a 2-yr winter wheat-fallow rotation in the drylands of the PNW.

2. Materials and methods

2.1. Overview

A 4-yr field experiment was conducted from 2015 to 2019 on the Derek Schafer farm near Ritzville in east-central Washington (47.077825, - 118.522791). The objective was to assess WW stubble height and orientation on overwinter precipitation capture in the soil and subsequent water retention during the dry summer months of 13-month-long fallow periods. The fallow period began with WW grain harvest in early August and extended until WW planting in late August of the next year. The study was conducted on a separate field each year on the Schafer farm over the 4-yr period. The soil at the experiment site is a Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxeroll) (U.S. classification system), also known as a Haplic Kastanozems (FAO/UNESCO, 1990). Soil is more than 2 m deep with no rocks or restrictive layers and slope at the four sites ranged from 0% to 3%. The four field sites were all located within a 4-km radius.

Collaborating farmer Schafer sowed a different semidwarf soft white winter wheat cultivar each year. These cultivars were Xerpha, ARS-Crescent, Otto, and NW Duet in 2015, 2106, 2017, and 2018, respectively. These cultivars were sown in late August or early September with a custom-built deep-furrow drill with row spacing of 40 cm. Sowing rate each year was 55 kg/ha. Excellent plant stands were achieved every year. Winter wheat grain yield in the fields prior to initiation of each year's experiment was measured by the collaborating farmer with the combine harvester's grain yield monitor as well as a grain elevator weigh scale. These grain yields were 1880, 5310, 5010, and 6080 kg/ha for years one to four, respectively. Harvest index (HI) of semi-dwarf WW averages 0.40 in the PNW (Donaldson et al., 2001) and in other rainfed WW production regions of the US Great Plains and southern Australia (Maeoka et al., 2020). Mature plant height of the WW cultivars sown ranged from 86 to 91 cm. As HI is defined as the percentage of grain in the total above-ground plant biomass, WW straw production in our experiment was approximately 2600, 7400, 7000, and 8500 kg/ha, respectively, over the four years.

A combine harvester equipped with a 11-m-wide Shelbourne Reynolds XCV® (Shelbourne Reynolds, IP31 2AR, Suffolk, England, UK) stripper header cutting platform was used to harvest WW grain from fields every year. The stripper header (Tado et al., 1998) was equipped with a rotating stripping rotor with eight rows of fingers that strip the grain from the wheat spike leaving nearly the entire plant stem standing and attached to the ground. After grain harvest with the stripper header, a combine harvester with a 7-m-wide conventional cutting platform was used to cut stubble to heights of 8 cm and 25 cm with the cut straw distributed across the width of the cutting platform behind the grain combine. Thus, three stubble-height treatments were established: (i)

short (8 cm), (ii) medium (25 cm), and (iii) tall (75 cm). The experiment was expanded in years 3 and 4 to add a fourth treatment of mowing the 75-cm-tall stubble close to the soil surface with a Schulte® rotary mower (Schulte Industries, Englefeld, SK, Canada) in mid-June before the onset of hot and dry weather. The mowed treatment was added to determine if flattening the tall stubble before the hot summer months would facilitate soil water retention. The experimental design was a randomized complete block with four replications. Size of individual plots every year was 7 × 60 m. The treatments are visually presented in Fig. 1.

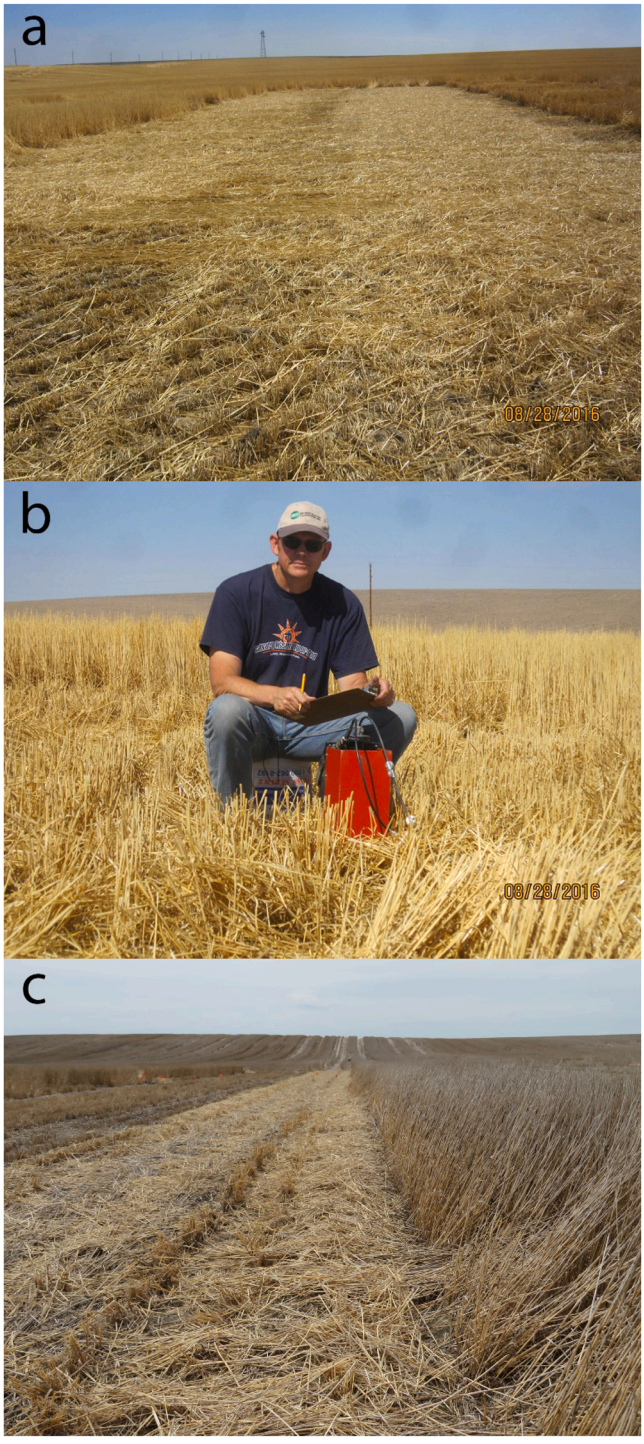

Fig. 1. The stubble height treatments imposed in the experiment were: (a) short (8 cm), (b) medium (25 cm, foreground), and (c) tall (75 cm, right). An additional treatment of mowing tall stubble in mid-June (c, left) was included in 2018 and 2019.

The plots were kept virtually weed free throughout the fallow period by periodic application of glyphosate herbicide as needed. The self-propelled WEED-IT® precision sprayer (WEED-IT Precision Spraying, Hoge Wesselink 8, The Netherlands) had a 36-m-wide boom and was guided by GPS so that wheel traffic was always in the same track to ensure that measurement areas within the plots were not disturbed. Four herbicide applications were required during each 13-mo fallow period.

2.2. Precipitation measurement

Computerized tipping-bucket precipitation recording devices are commonly used to record precipitation at on-farm experimental sites. However, tipping bucket recorders have been documented to underestimate actual precipitation by as much as 40% and/or to stop recording altogether due to various causes (Sypka, 2019; Grossi et al., 2017). Therefore, we report accurate and reliable precipitation data manually recorded from two locations near the field sites (Table 1). Location 1 was the WSU Lind Dryland Research Station situated ≈ 7 km south of the field sites where daily precipitation and other climatic data was officially recorded for the US National Weather Service. Location 2 was ≈ 8 km NE of the field sites in the town of Ritzville where daily precipitation was recorded by the Adams Conservation District.

2.3. Soil water measurement

2.3.1. Total 180-cm profile measurement

Soil water was measured to a depth of 180 cm three times during the 13-mo fallow period. These times were: (i) in early August immediately after WW harvest; (ii) in mid-April, and (iii) at the end of fallow in late August. Volumetric soil water content in the 0- to 30-cm depth was determined from two 15-cm core samples using gravimetric procedures described by Topp and Ferre (2002) using known soil bulk density values. Soil volumetric water content in the 30–180-cm depth was measured in 15-cm increments with an InstroTek® CPN 503 neutron moisture probe (InstroTek, 1 Triangle Drive, Raleigh, NC USA) using methods defined by Hignett and Evett (2002). The neutron probe was calibrated and validated for the Ritzville silt loam soils at the study sites.

2.3.2. Seed zone measurement

Seed-zone volumetric water content was measured just prior to WW sowing in late August 2018 and early September 2019 in 2-cm increments to a depth of 26 cm with an incremental soil sampler designed by Wuest and Schillinger (2008). Adequate seed-zone water for sowing WW is generally located from 10-to 15-cm below the soil surface; this is considered some of the deepest seed placement in the world for sowing wheat (Donaldson, 1996). We designed the incremental sampler to obtain seed-zone volumetric water data to a depth of 26 cm as the water potential below the depth of actual seed placement is important for root hydration during seedling emergence and early growth (Lindstrom et al., 1976).

2.4. Soil temperature measurement

Soil temperature was measured from mid-June to mid-to-late August in two years as this period has the hottest and driest weather conditions during the fallow cycle and immediately precedes sowing of WW. In 2018, Campbell® 616 temperature probes (Campbell Scientific, Logan, Utah USA) were placed at 10 cm in all plots. These probes contain temperature sensors in the electronics housing near where one of the metal wave guides is attached. When placed horizontally, they measure soil temperature at that depth. Readings at hourly intervals were averaged and daily means recorded.

In 2019, soil temperature profiles were measured at 1-cm depth increments to 25 cm, and at 30, 35, and 40 cm depths. As described by Wuest (2013), temperature-sensing thermistors were mounted in a

Table 1
Monthly crop-year (Sept. 1 - Aug. 31) precipitation (mm) at Ritzville and Lind, Washington from 2016 to 2019. The study sites were located about halfway between Ritzville and Lind and, although precipitation was not recorded at the actual sites, precipitation values were likely less than at Ritzville but greater than those from Lind.

Crop year	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Total
	mm												
	Ritzville												
2016	24	12	20	93	56	30	78	12	23	13	16	3	380
2017	9	123	36	35	40	64	71	31	22	8	0	0	439
2018	19	36	57	49	59	27	34	49	26	8	1	2	367
2019	1	20	39	59	54	47	18	23	31	16	3	9	320
4-yr avg.	13	48	38	59	52	42	50	29	26	11	5	4	377
	Lind												
2016	14	13	19	74	48	11	62	24	29	17	9	2	322
2017	8	105	31	18	33	65	56	30	14	15	0	1	376
2018	11	31	53	35	45	24	29	44	34	2	1	1	310
2019	0	14	31	39	37	27	15	23	12	5	4	17	224
4-yr avg.	8	41	33	41	41	32	41	30	22	10	4	5	308

glass-reinforced-plastic shaft that can be installed with very little soil disturbance. Data were measured at 5-min intervals and recorded as hourly averages.

Soil temperature data were examined for trends attributable to treatments. Five-day average temperatures from the early, mid, and late time periods were compared among treatments at the 10-cm depth in 2018 and 3, 7, 15, 25, and 40-cm depths in 2019.

2.5. Statistical analysis

Analysis of variance (ANOVA) was conducted for volumetric water content in the 180-cm soil profile (all four years), seed-zone volumetric water content (2018 and 2019), and soil temperature (2018 and 2019) using a randomized complete block design ANOVA for each year and a split-plot in time ANOVA across years with treatment as the fixed-effect factor and year as the random-effect factor. Tukey's honest significant difference (HSD) test was used to detect statistical differences in treatment means and control the experiment-wise error rate for multiple comparisons. All soil water data ANOVA tests were done at the 5% level of significance whereas soil temperature tests were conducted at both the 5% and 10% level of significance. The Statstix®10 data analysis software (Analytical Software, 2105 Miller Landing Rd, Tallahassee, Florida USA) was used for all ANOVA comparisons.

3. Results

3.1. Precipitation

Over the 4-yr study, fallow-year (Sept. 1 – Aug. 31) precipitation at Lind ranged from 224 to 376 mm and averaged 308 mm. During the same period, fallow-year precipitation at Ritzville ranged from 320 to 439 mm and averaged 377 mm (Table 1). Long-term (100-yr) average annual precipitation at Lind is 244 mm and at Ritzville 292 mm; therefore, only in 2019 was annual precipitation less than normal at Lind and all four years were wetter than normal at Ritzville (Table 1). As the study sites were located essentially equidistance between Lind and Ritzville, precipitation values at the sites were likely greater than those at Lind and less than at Ritzville.

3.2. Water in 180 cm soil profile

3.2.1. Beginning of fallow

At time of grain harvest (i.e., beginning of fallow), WW in the PNW depletes near-surface soil water down to $\leq$ 5% by volume, but plant soil water extraction generally diminishes with depth to $\approx$ 10% by volume at 150 cm soil depth (Schillinger and Young, 2000). Winter wheat extracts water somewhat less efficiently from soil depths $>$ 150 cm. In all four years, most plant-available soil water as defined above was depleted from the soil profile by the time of WW grain harvest as indicated by the baseline start-of-fallow water distribution data shown in solid black circles in Fig. 2. The one exception was at the start of the 2018 fallow year where $\approx$ 50 mm of available water was present from 150 to 180 cm (Table 2, Fig. 2c). This likely occurred because the 2018 study site was located in a basin where soil water storage is frequently greater than other landscape positions. Logically, and as expected, there were never any within-year differences in baseline soil water (Table 2) as these measurements were obtained immediately after the stubble-height treatments were imposed.

3.2.2. Overwinter soil water recharge

Statistically significant differences in overwinter soil water recharge were measured in 3 of 4 years (Table 2). Averaged over the 4 years, there were no differences between the medium and tall treatments and both were significantly greater ($p = 0.002$) than the short stubble (Table 2).

In 2016, the overwinter water gain for the medium treatment was significantly greater than the tall, but not compared to the short treatment (Table 2). Treatment differences were minor among treatments, likely because baseline residue from the preceding WW crop was sparce ($\approx$2600 kg/ha). Soil water content among treatments in April at all measurement increments down to 180 cm were almost identical (solid-colored circles in Fig. 2a).

For the 2017 fallow cycle, dry straw biomass from the preceding WW crop was $\approx$ 7400 kg/ha (nearly 3x greater than the previous year). The 2017 winter was one of high precipitation with much falling as snow and there was extensive snow drifting. There were 77 days of continuous snow cover at Lind that set a 101-yr record for that location (Weaver, 2017). The medium- and tall-stubble treatments were much more effective than the short treatment in trapping drifting snow which was likely the reason the short stubble had 79 and 91 mm less overwinter soil water gain than the medium and tall treatments, respectively ($p < 0.001$) (Table 2). The large differences in overwinter water storage among treatments and the spatial distribution of soil water by depth were consistent among treatments. These data are clearly illustrated in Fig. 2(b).

For the 2018 fallow year, residue produced by the previous WW crop was $\approx$ 7000 kg/ha, only slightly less than residue estimations for the previous year. The winter was relatively mild with only a few days with snow covering the ground. No frozen soil runoff was observed in any fallowed fields in the region. Overwinter water recharge into the soil was high and there were no significant differences in overwinter soil water gain among treatments (Table 2) nor in the spatial water distribution pattern in the soil profile (Fig. 2c).

The approximate WW straw biomass of 8500 kg/ha in 2019 was the greatest for the 4-yr study. In the winter there was ample snow cover

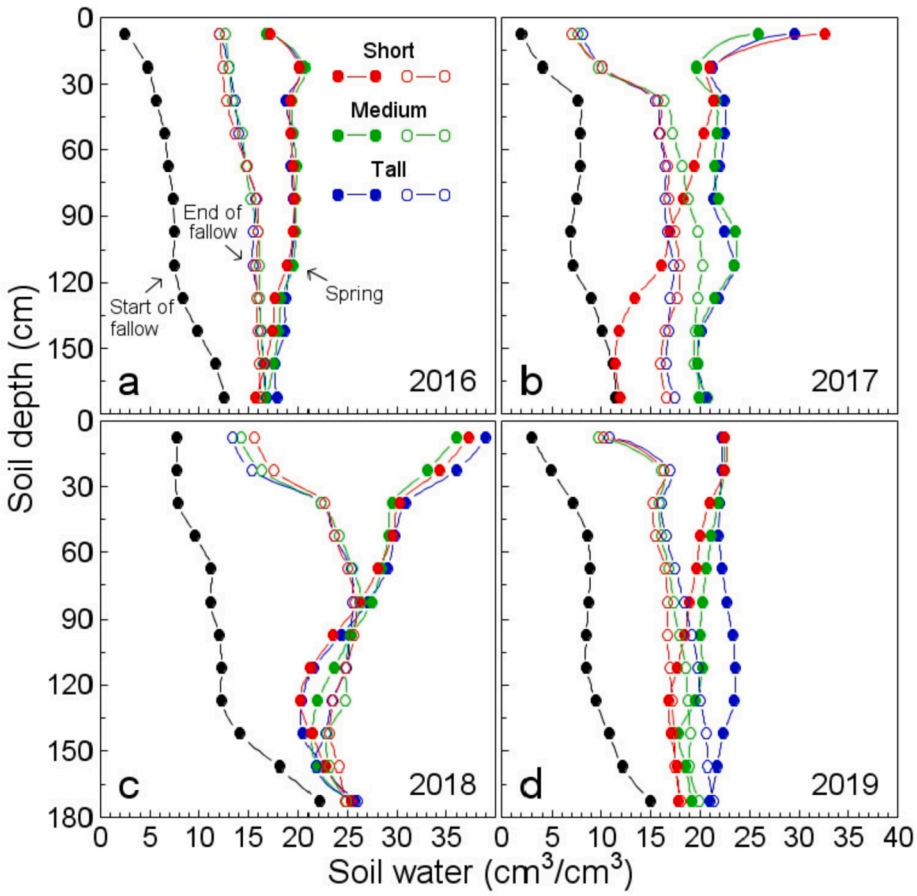

Fig. 2. Distribution of volumetric soil water to a depth of 180 cm measured three times during the 13-month fallow period for four years. Stubble height treatments were: (i) cut short as close to the soil surface as possible; (ii) cut at medium height of 25 cm and; (iii) leave 75 cm tall with the stripper header. Soil water was measured: (i) after grain harvest in August (solid black circle); (ii) in mid-April (colored solid circles) and; (ii) at the end of fallow in late August (hollow circles).

with high winds that gusted to 65 km/h which created substantial snow drifting in February. Soil water content in mid-April was significantly higher ($p < 0.001$) in the tall compared to the medium and short treatments (Table 2) and overwinter soil water gain was tall > medium > short. The enhanced overwinter water gain with tall stubble at soil depths > 60 cm is clearly pronounced in Fig. 2(d). Water at deeper soil depths especially benefits wheat grain yield during the kernel-fill stage of development when available water in upper portions of the profile has been depleted (Sciarresi et al., 2019; Flohr et al., 2020). Precipitation during the 2019 fallow year was the lowest of the four years (Table 1).

Averaged over four years, overwinter soil water gain was the same for medium and tall stubble (Table 2). Overwinter soil water gain in short stubble was reduced by > 30 mm compared to the medium and tall treatments ($p = 0.002$) (Table 2).

3.2.3. *April through August soil water loss*

Statistically significant differences in water loss from mid-April to late August were measured in two years as well as the 4-yr average (Table 2). There were no differences among treatments in 2016 (Table 2), presumably because residue levels were so low due to low WW grain yield during the preceding crop year. Soil profile water distribution at each depth was almost identical among treatments in late August (Fig. 2a).

In 2017, following a winter of heavy snow drifting, highly significant differences of over-summer water loss occurred in the order of tall > medium > short treatments ($p < 0.001$) (Table 2). Overwinter water storage in the short stubble was comparatively low (see Section 3.2.2.), thus there was considerably less water to be lost. Although mid-April water content in the medium and tall stubble were the same, April to August loss for these treatments was 80 and 127 mm, respectively (Table 2). Despite the huge overwinter water storage advantage of tall vs. short stubble, end of fallow water content was the same (Table 2, Fig. 2b). Conversely, the medium treatment had ≥ 25 mm more water retained by late August than the short and tall stubble, which can be clearly visualized in the 50–180-cm depth in Fig. 2(b).

Like the mid-April 2018 water data, there were also no differences among treatments in late August, including from the mowed treatment (as described in Section 2.1 and shown in Fig. 1c) that was imposed for the first time in mid-June (Table 2). There was very little temporal variation in profile water distribution among treatments in mid-April and late-August (Fig. 2c).

In 2019, highly significant differences ($p = 0.005$) in soil profile water were recorded in late August in the order of tall > mowed > medium > short, although the tall stubble was the only treatment significantly different than the short stubble (Table 2). There were no significant late August differences among the tall, medium, and mowed treatments.

Averaged over the four years, there were few differences in late August soil water content among the tall, medium, and short treatments, although the medium stubble was significantly greater than the short stubble ($p = 0.027$) (Table 2). Although the tall and medium stubble stored the most overwinter precipitation, they also lost more water than the short stubble during the summer. There was no water-retention advantage in mowing the tall stubble in mid-June prior to the onset of hot summer temperatures in 2018 and 2019.

Table 2
Total water content (mm) in the 180 cm soil profile during the 13-month fallow period after wheat harvest as affected by stubble height for four years. Stubble height treatments were: (i) short (cut as close to the soil surface as possible); (ii) medium (cut at height of 25 cm); (iii) tall (leave tall with stripper header) and; (iv) mowed (tall stubble mowed in mid-June).

Treatment	Timing in fallow period				
	Beginning (early Aug.)	Spring (mid Apr.)	Overwinter Gain	End (late Aug.)	Apr. to Aug. water loss
	Soil water content (mm)				
			2016		
Short	132	338	206 ab	270	68
Medium	132	345	213 a	276	69
Tall	153	345	192 b	275	70
p-value	0.101	0.392	0.028	0.710	0.961
			2017		
Short	144	327 b	183 b	280 b	47c
Medium	134	396 a	262 a	316 a	80 b
Tall	134	408 a	274 a	281 b	127 a
p-value	0.384	< 0.001	< 0.001	0.022	< 0.001
			2018		
Short	231	488	257	421	67 b
Medium	206	492	286	418	74 ab
Tall	232	498	266	410	88 a
Mowed[a]	232	498	266	414	85 ab
p-value	0.205	0.698	0.454	0.806	0.046
			2019		
Short	154	352 b	198 b	296 b	56
Medium	162	373 b	211 ab	313 ab	60
Tall	167	410 a	243 a	333 a	77
Mowed	167	410 a	243 a	322 ab	88
p-value	0.566	< 0.001	0.033	0.005	0.113
			4-yr avg[b]		
Short	165	376 b	211 b	317 b	59 b
Medium	158	401 a	243 a	331 a	70 b
Tall	171	416 a	245 a	325 ab	91 a
p-value	0.256	< 0.001	0.002	0.027	< 0.001

a Tall stubble mowed in mid-June in 2018 and 2019 only.
b 4-yr. avg does not include the mowed treatment since only two years of data.

3.3. Seed-zone water at time of sowing in late August

During July and August 2018 only minor traces of rain occurred (Table 1). July and August are historically the hottest and the driest months in the PNW (Karimi et al., 2018); thus 2018 is considered "typical". The distribution of seed-zone volumetric soil water in 2-cm increments to a depth of 26 cm among treatments in late August is presented in Fig. 3(a). These data show that the short and the mowed treatments trended highest from the 9- to 17-cm depth. The medium stubble was deficient in water from the 5-cm near surface to 17 cm (Fig. 3a). The tall treatment was especially dry in the lower seed zone increments.

In 2019, considerable, and unusual, rain occurred in July and August (Table 1). These rains negated any differences in seed-zone volumetric soil water among treatments (Fig. 3b).

3.4. Soil temperature from June to August in 2018 and 2019

The 10-cm average daily soil temperatures following the mid-June mowing treatment are shown for 2018 (Fig. 4a) and 2019 (Fig. 4d). When time segments of several days were averaged and compared for 2018, there were no significant differences among treatments. This was due to high variation between replicates in 2018. However, the temperature means trended similarly to 2019, with short and mowed treatments averaging about 1 °C cooler than the medium and tall stubble during the first half of the measurement period (Fig. 4).

Daily maximum (Fig. 4b and e) and minimum (Fig. 4c and f) soil temperatures at 10 cm are presented for 2018 and 2019. The tall stubble produced the greatest maximums and short and mowed the lowest maximums. Apparent treatment effects on the minimum daily temperatures were very small or nonexistent in 2019, making 2-yr trend comparisons at 10 cm difficult.

In 2019, the temperature probes included multiple depths and were driven into the soil with little soil or residue disturbance. There was substantial variability among replicate plots, but when comparing the average temperature over 5-d periods, statistically significant differences were found among the short stubble and the medium and tall stubble at several depths (Fig. 5). In mid-June the short treatment was significantly cooler than the medium and tall treatments at 3, 7, 15, and 40 cm depths. In mid-July, the short treatment was significantly cooler than the medium treatment at 7 cm depth, and cooler than the tall treatment at 7, 15, and 25 cm depth. The differences decreased in magnitude over the summer and were not statistically significant by August.

4. Discussion

4.1. Profile soil water, soil temperature, and seed-zone water

The effectiveness of tall versus short stubble in trapping drifting snow by reducing surface wind velocity has been documented in several studies. For example, McMaster et al. (2000) reported a large reduction in soil surface friction velocity when residue height was increased from 5 to 10 cm, a smaller reduction when residue height increased from 10 to 30 cm, and only a slight reduction when residue height increased from 30 to 50 cm.

Soil temperatures from June to August were coolest at almost all depths in the order of short < mowed < medium ≤ tall (Figs. 4 and 5). Clearly, the tall residue provided lower albedo or shade for the soil surface. Daily maximum temperatures appear to be the major treatment difference. This indicates that more solar radiation is reaching and being absorbed by the soil surface during the hot part of the day, as might be expected when almost all the residue is vertical. The resulting increase in average soil temperature means that the increase in absorbed radiation was not compensated by increased heat loss at night. This logically leads to soil warming at all depths. Our measurements indicated that at least the top 25 cm of soil was affected. Even brief daily periods of direct radiation on consolidated soil might provide energy for increased water flow and evaporation, especially after sundown when the soil is warmer than the air (Pikul et al., 1985).

The decrease in treatment differences over the temperature measurement period (June-August) might be explained by the decrease in soil water content. The gradient in temperature between the 3 and 7 cm depth (Fig. 5) in June is steepest for the tall and medium stubble heights. All treatment gradients become steeper with time, and the four treatment profiles became similar with time. The surface soil water content was not measured repeatedly over time, but we know that it decreased between the April and the end of August measurements (Fig. 2).

While not statistically significant, mowing appears to have influenced soil temperature very quickly after the tall stubble was mowed in mid-June. Before mowing, the plots were presumably identical to the tall stubble. Also note that the influence of treatments on soil temperatures runs deep to a least 40 cm, especially in early summer (Fig. 5).

Cut residue in the short treatment was lying flat on the soil surface where it would have been flattened and compressed by snow and rain during winter. Even if mowing the tall stubble in the mid-June produced equivalent standing stubble height and the same amount of horizontal stubble, much of the mowed residues did not lie flat on the soil surface and was not softened and compressed against the soil surface by the action of rain and snow. Another possible difference between treatments was the amount of bare soil exposed to the impacts of rain and freeze/thaw cycles. This could affect porosity and subsequent heat and water flow (Flerchinger et al., 2003). The barest soil was in the tall stubble, and the least bare soil was in the short stubble.

Water in the seed zone at the end of fallow (i.e., time of WW sowing)

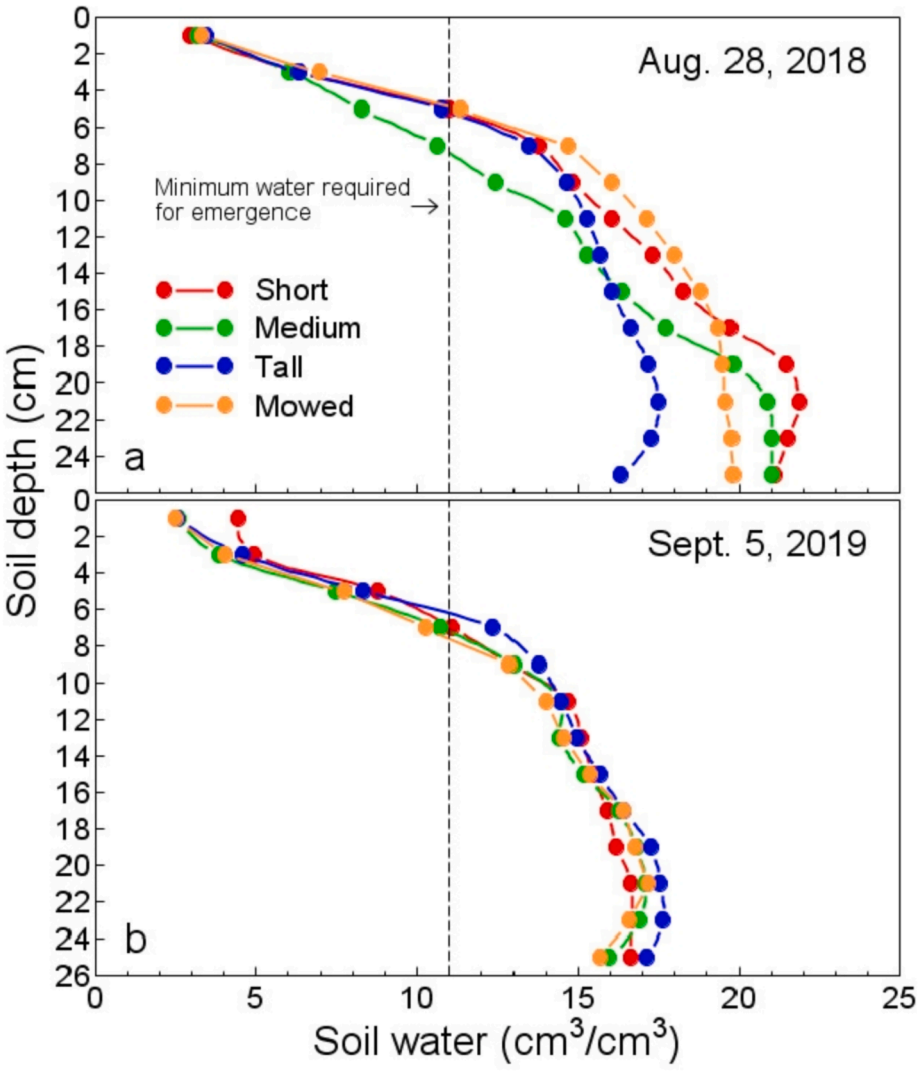

Fig. 3. Seed-zone volumetric water content measured in 2-cm increments to a depth of 26 cm at the end of fallow in 2018 and 2019 as affected by wheat stubble height and mowing. Stubble height treatments were: (i) cut short as close to the soil surface as possible; (ii) cut at medium height of 25 cm; (iii) leave 75 cm tall with the stripper header and; (iv) mow the tall stripper header stubble in mid-June. In August 2018, < 1 mm of rain occurred whereas there was an estimated 13 mm of rain on 11 August 2019.

is critical for stand establishment in the PNW drylands. Farmers use deep-furrow drills to place wheat seed 15 cm or deeper into the soil to reach adequate water for germination and emergence (Donaldson, 1996). Lack of adequate seed-zone water means that farmers need to delay sowing until the onset of fall rains in mid-October or later which results in a 30–40% grain yield decline compared to early-sown WW (Higginbotham et al., 2011). Essentially no rain occurred in July and August 2018; this being the predominant pattern for the PNW.

Based on data collected over several decades, empirical and mechanistic models have been developed in the PNW drylands on available soil water in fallow at the time of planting WW and its relationship with WW grain yield (Stöckle et al., 2003; Schillinger et al., 2008; Karimi et al., 2018). These models show that each additional 1 cm of available soil water at the end of fallow above that needed to achieve plant establishment will result in 176 kg/ha increase in WW grain yield (Schillinger et al., 2008).

4.2. Pros and cons of tall stubble for dryland wheat farmers

Use of a stripper header allows farmers to combine 30–40% greater land area per day compared with a conventional header (Spokas and Steponavicius, 2010) because only wheat spikes pass through the combine harvester (i.e., no straw). For example, with the average WW grain yield of 4570 kg/ha in our 4-yr study, collaborator Derek Schafer with a modern John Deere® S680 (John Deere Co., Moline, IL., USA) combine harvested, on average, 65 ha/day with a 11-m-wide stripper header versus 45 ha/day with a conventional header of the same width. A second important advantage of using a stripper header is a 30–40% reduction in wear to the combine harvester's internal grain separation components due to the huge reduction of volume of material passing through the machine.

There are four negative aspects of using a stripper header versus a conventional header (D. Schafer, personal communication). First, the tall wheat stubble is very difficult to sow through with a deep-furrow drill due to plugging issues. Schafer dealt with the problem by cutting the stubble into smaller pieces using a heavy Summers® Supercoulter vertical tillage implement https://summersmfg.com/tillage/supercoulter for 2–3 operations prior to sowing. In contrast, WW can be direct sown into medium-height stubble (i.e., 25 cm tall) without the need for the coulter implement. Second, the repair/maintenance costs for operating a stripper header are high. The fingers that grab and detach the wheat spikes need to be replaced at a cost of US $7000 after cutting 2000 ha and the labor to replace the fingers requires two people a full 10-hr day to accomplish. Third, collaborator Schafer reported that more wheat spikes fell to the ground in front of the stripper header compared to that with a conventional header. Fourth, the tall stubble causes accelerated wear on the underside of combines, tractors, sprayers, and seed drills by rubbing through wiring harnesses and hydraulic hoses.

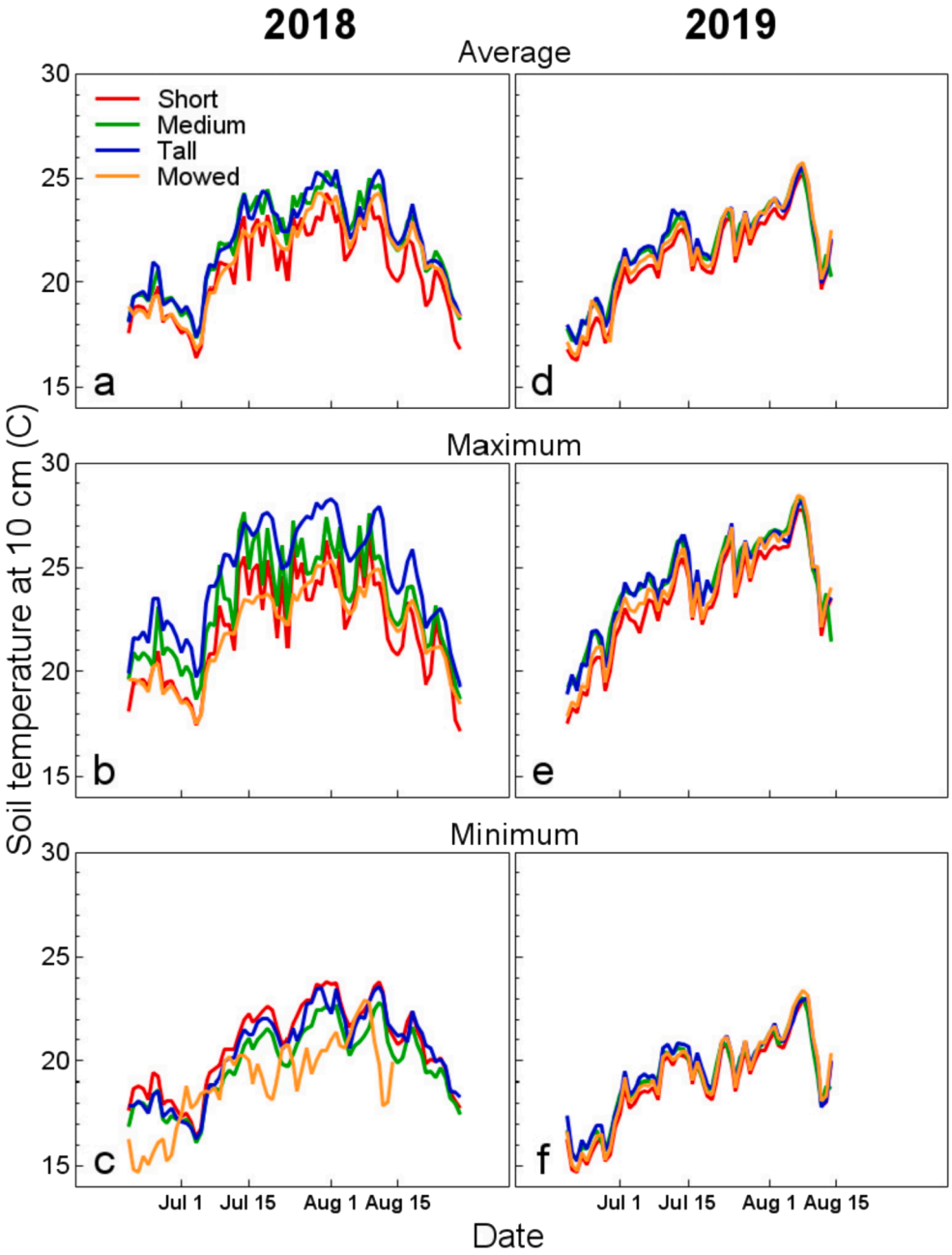

Fig. 4. Daily average (top), maximum (middle), and minimum (bottom) soil temperature at a depth of 10 cm in four stubble management treatments from June to August in 2018 and 2019. A rain of about 13 mm occurred on 11 August 2019.

5. Conclusions

In our study, medium and tall stubble had equal overwinter soil precipitation storage efficiency which exceeded that with short stubble. There was no advantage to mowing the tall stubble in mid-June. During the high evaporative demand of summer, tall stubble lost significantly more soil water than the short and medium treatments. Presumably, this was at least partially due to higher soil temperatures with tall and medium stubble that lacked flat-lying residue along with greater water contents available at the start of the summer season. These novel data on wheat stubble height and orientation offer opportunity to improve empirical and mechanistic models on soil water storage and retention during long fallow periods in Mediterranean climates.

Our data, combined with detailed discussions with farmers in the PNW drylands, suggest that the best stubble cutting height is the medium (25 cm) treatment as it provides the best overall benefit for soil capture of overwinter precipitation and for retention of stored soil water during the dry summer. Medium-height stubble also allows for direct-sowing of WW with deep-furrow drills without undue drill plugging problems.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

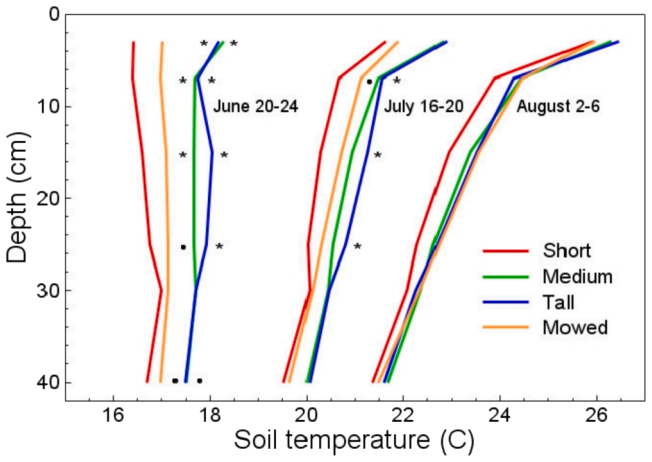

Fig. 5. Soil temperatures at 3, 7, 15, 25, and 40 cm depths averaged within three time periods in June, July, and August of 2019. Significant differences between the short (lowest temperature) treatment and other treatments at each depth are noted by * ($p < 0.05$) and • ($p < 0.10$).

the work reported in this paper.

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