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Fertilizer Effects on Soil Moisture Changes during Crop Growing Seasons of Dryland Agriculture in Northwestern Alberta, Canada

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Abstract

Efficient use of limited soil moisture resources is important for crop production in dryland agriculture in the study area. Understanding the changes in soil moisture during crop growing seasons can improve crop production. The objectives of the current study were to assess the effects of fertilizer application on soil moisture content (SMC) and its depletion patterns during the growing season. Changes in SMC in the 0-10, 10-20, 20-30, and 30-40 cm depths soil were monitored during the 2013-2015 growing seasons under canola (*Brassica napus* L.) and barley (*Hordeum vulgare* L.) crops with 0 and 100% rates of commercial chemical fertilizers. The crops were grown using direct seeding (DS) on a clay loam soil in the southeast Peace Region (legal: NW7-77-20W5; GPS: 55°39′38.43″ N, 117°6′10.64″ W) of Alberta, Canada. Fertilizer application reduced the SMC at all the soil depths during considerable crop growing seasons. Depletion of SMC started earlier in fertilized pots in 2013 and 2014, but not in the drier early season of 2015. Rapid depletion during the early and middle of growing seasons was followed by slower or no soil moisture depletion by crops near the end. The SMC tended to be somewhat lower under 100 than 0% fertilizer by the end of the growing seasons, with few exceptions. The start of SMC depletion and appearance of fertilizer rates effect after seeding was also influenced by the amount of SMC at seeding in spring, i.e. earlier in dry year of 2015 than in other years with higher SMC in spring and more rain. The results demonstrated that applying fertilizer increased soil water use by plants regardless of the crop type or growing season. They also indicated that if more soil moisture was available, the differences between fertilizer treatments might have continued for extended periods, and yields of fertilized crops may have benefitted more.

Keywords: fertilization, soil moisture, canola, barley, dryland agriculture

1. Introduction

The water used by dryland crops produced in the study area comes from rain during the growing season, the stored SMC from rain/snow before seeding, and water depleted from the root zone (stored soil moisture: at seeding—at harvest of the crops). The temporal and spatial changes in the soil moisture during the growing season depend on the amount of rain during the growing season and SMC depletion by crops from different depths in the soil profile. In such areas, rainfall, water shortage, low nutrient availability, and low water-use efficiency (WUE) are the main factors limiting crop growth (Zhang et al., 1998; Li et al., 2001). Wallace (2000) emphasized the need to increase WUE by more effectively using water resources for plant production to meet the challenge for us and future generations to provide a stable and secure food supply and the efficient use of our natural resources of soil, water, and air. The increasing variability in both temperature and precipitation throughout the world raises the question of how to enhance WUE under current cropping systems, and climate change increases the urgency for optimizing the factors to enhance the stability of crop production across a range of climates (Hatfield, 2011).

Lu et al. (1998) highlighted the critical role of fertilization to optimize the use of stored water in the root zone. McKell et al. (1959) stated that fertilizer application reduced soil water compared to no-fertilizer. During three years (2003, 2004, and 2005), Song et al. (2010) observed significant fertilizer (F) effect (30 N + 20 P, kg ha^{-1}) on soil moisture content (SMC) in clay loam Haploborrols. Across the three years, no fertilizer (NF) treatment had total soil water content higher by 1.2% than F treatment within 10-210 cm soil profile in most of the months, and there were significant differences between NF with F for three years within 90 cm profile. Tesfahunegn (2019) reported that SMC in the 0-20 cm depth was significantly lower with most of the fertilizer rates (21 N +

10 P, 41 N + 20 P, and 64 N + 25 P, kg ha^{-1}) than no fertilize at the tillering, stem elongation, booting, grain filling, and harvesting stages of tef (*Eragrostis tef* (Zucc)) crop. The results from the above studies imply that when fertilizer rate increases, there is increased soil water depletion by the plants because more nutrients are available regardless of crop type or variety (Caviglia & Sadras, 2001; Huang et al., 2003; Zhang et al., 2006; Zou et al., 2012; Wang et al., 2013).

Ritchie and Johnson (1990) stated that fertilization significantly influenced soil water content because fertilization stimulates plant growth, affecting plants' use of soil water and its distribution. Other reports have shown that adequate nutrient supply can contribute to increased water and nutrient uptake (more water used) by plants from the soil for producing better crop growth (Salvagiotti et al., 2008, Setiyono et al., 2010). Reports have also stated that long-term N and P fertilization considerably increased crop water use for transpiration, decreasing soil moisture in a soil profile (Caviglia & Sadras, 2001; Huang et al., 2003; Zhang et al., 2006; Wang et al., 2013). Nielsen and Halvorson (1991) stated that generally plant height, above-ground biomass, leaf area index, rooting depth, water use, and grain yield increased with increasing N rate. However, increasing N rate increased rooting volume and lowered water stress under adequate water supply, but increased water stress when the excessive transpiration demand of the resulting larger leaf area and vegetative mass was not fully compensated by the increased rooting volume. They found the corn (*Zea mays* L.) grain yield was linearly correlated with increased cumulative evapotranspiration from N application, but increasing levels of N fertility was detrimental to winter wheat (*Triticum aestivum* L.) yields when water-limiting conditions reduced evapotranspiration rates to less than 62% of potential evapotranspiration. Wallace (2000) concluded the challenge for us and future generations would be to provide a stable and secure food supply and the efficient use of our natural resources, soil, water, and air.

Plant's ability to obtain water and nutrients from the soil has been related to their capacity to develop their root systems. Greater length, surface area, and volume of canola and barley roots with 100 than 0% fertilizer were reported during the early growing season of 2015 under both the minimum tillage and direct seeding systems (Gill, 2021). Gan et al. (2011) suggested that a crop's root system can compensate by increasing or relocating maximal root growth to higher soil moisture regions, thus helping maintain plant growth under dry soil conditions (Rendig & Taylor, 1989). The root length density of crops during the dry season tended to decrease mid-season at shallow soil depths, whereas it continued to increase throughout the growing season at deeper soil depths (Moroke et al., 2005). These changes were parallel to the maximum soil moisture depletion trend from successively deeper layers as the season progressed.

Farmyard manure combined with inorganic fertilizers was shown to play important roles in better water penetration (Hati et al., 2006), and firm and deep establishment of crop roots (Li et al., 2010). Fertilizers and manure helped plants extract water from deeper soil layers and maintain high relative plant water content under soil moisture stress conditions in rain-fed farming (Hati et al., 2006). Such integration is regarded as a fundamental approach to improving efficient water use in crop production (Mohanty et al., 2007). Wang et al., (2013) stated that manure application or increasing the fertilizer application rate could reduce soil water evaporation, make reasonable use of soil water and improve water-use efficiency at different growth stages of maize.

Campbell et al. (1988) observed that the yield increase of spring wheat per unit of moisture use during 1967-1984 tended to be greater for the better-fertilized rotations and that precipitation during the grain-filling period was most important. Increased barley, canola, and wheat yields were observed with fertilizer applications during the 2010-2015 (Gill, 2019).

The preceding literature review demonstrated the effects of additional nutrients on the soil moisture changes and crop growth under several climatic, agronomic, and soil conditions. However, there has been limited research on the effects of fertilizer on SMC and its depletion patterns during the growing seasons under rainfed agriculture conditions prevailing in the study area. We hypothesized that SMC and its depletion pattern during the growing season and residual SMC would be affected by fertilizer rates. Thus, changes in SMC and its depletion pattern were monitored during three growing seasons of canola (*Brassica napus* L.) and barley (*Hordeum vulgare* L.) that received 0 and 100% fertilizer rates.

2. Materials and Methods

Small plot field trials were conducted in the southeast Peace Region of Alberta, Canada (legal: NW7-77-20W5; GPS: 55°39′38.43″ N, 117°6′10.64″ W). The soil at the site is a clay loam Luvisol (Soil Classification Working Group 1998). Initial soil samples had 48 g kg^{-1} organic matter, 6.1 pH (water), and 16.4 cmol (+) kg^{-}CEC at 0-15 cm; and 3.4 g kg^{-1} organic matter, 6.5 pH (water), and 15.0 cmol (+) kg^{-1} CEC at 15-30 cm.

More details on the treatments and experimental layout are available in Gill (2019). Briefly, the four fertilizer rates (0, 60, 100, and 140% of the soil tests-based recommendations) were replicated four times in two adjoining areas (canola and cereal sites) from 2010-2015 (6 years), under DS (direct seeding) and MT (minimum tillage) systems. A canola-cereal rotation (most commonly used by farmers in the area) was used on both sites.

For the present study, the soil moisture data were collected during 2013, 2014, and 2015 from the canola and barley plots that had received 0 and 100% fertilizer rates under the DS system. Soil test-based N, P, K, and S amounts were applied in the 100% fertilizer rate plots (Table 1). Fertilizers were applied at seeding, using combinations of seed row placed 11-52-0, and banded away from seed row 46-0-0, 0-0-60, and 20.5-0-0-24 commercial fertilizers.

Table 1. The amounts of N, P, K, and S applied to the 100% fertilizer canola and barley plots in different years

Nutrient (kg ha^{-1})	Canola			Barley		
	2013	2014	2015	2013	2014	2015
N	130	145	125	95	159	104
P	21.4	21.4	21.4	16.7	24.5	22.3
K	18.2	18.2	18.2	14.0	14.0	28.1
S	45.0	25.0	11.0	18.0	18.0	24.0

Seeding of both crops was on May 15, 2013, May 21, 2014, and May 11, 2015. Due to herbicide damage in 2013, the barley plots were reseeded on June 22. Barley was harvested on October 14, 2013, September 3, 2014, and August 19, 2015. Harvest of canola occurred in September; 14, 2013, 6, 2014, and 28, 2015. Spring soil moisture (SSM) and monthly precipitation during the growing season data were obtained from the weather station at Ballater in Alberta, located 5 km from the site (Table 2).

Table 2. Spring soil moisture (SSM), monthly rain during crop growing seasons, and their 30-yr average (Normal); from the Ballater weather station, Alberta, Canada

	2013	2014	2015	Normal
SSM and monthly precipitation (mm)				
SSM	60.0	60.4	50.0	75.0
May	19.6	21.1	19.4	42.2
June	101.8	58.1	34.4	74.2
July	65.4	30.4	28.6	66.5
August	13.6	2.6	44.5	55.8
Total rain	**200.4**	**112.2**	**126.9**	**237.7**

Soil moisture was measured from the depths of 0-10, 10-20, 20-30, and 30-40 cm, designated as 5, 15, 25, and 35 cm depths for presentation, respectively. The frequency of measuring the SMC was decided considering that plots were not too wet and occurrence of rainy and dry periods during the growing season of crops. A profile probe (PR2-UM-3.0) and a moisture meter (HH2 version 4.0) of the Delta T Devices Ltd, 2008, 130 Low Road, Burwell, Cambridge, CB25 0EJ (www.delta-t.co.uk) were used to measure soil moisture. The profile probe has a sealed polycarbonate rod (~2.5 cm diameter) with paired stainless steel electronic sensors at fixed intervals along its length. When power is applied, each pair of sensors generates a simple analog DC voltage (100MHz) that transmits an electromagnetic field extending about 10 cm in the soil. The moisture meter was used to apply power to the profile probe sensors, measure the output signal voltage returned, and convert it to soil moisture units (volumetric) using a linearization table and soil-specific parameters. The signal's strength is related to the permittivity of soil, predominantly dependent on its water content (permittivities: ≈ 81 for water, ≈ 4 for soil, and ≈ 1 for air, Farad m^{-1}). Specified fiberglass access tubes (2.5 cm diameter) were installed at the start of each growing season to insert the profile probe for readings at different soil depths.

The soil moisture data for the 0 and 100% fertilizer rates are presented in Figures 1-6, with their standard deviations indicated by vertical lines. The differences between the soil moisture data for the 0 and 100% fertilizer rates at different soil depths (5, 15, 25, and 35 cm) were compared using the Paired sample t-test for each soil depth. The standard error (SE) values and significance of the level of differences from the Paired sample t-test are presented in Table 3. The $t_{0.05}$ is used in the discussion to indicate significant differences between the means.

3. Results

3.1 2013 Season

The season started with 75% of the average spring soil moisture (SSM), and 84% of the normal rainfall was received during the growing season (Table 2).

3.1.1 Canola

The fertilizer treatments showed only slight differences in the SMC on the 37 and 44 DAS (days after seeding) at all the depths (5 15, 25, and 35 cm) of soil (Figure 1a). But from 58 DAS onward until the 79 DAS, the SMC for 5 cm depth was significantly lower in the 100 than 0% fertilizer treatment (Table 3). Similarly, the SMC at the 15 cm depth was significantly lower in the 100 than 0% fertilizer treatment on the 58-103 DAS observations, except for 86 DAS. For the 25 cm depth, the SMC was significantly lower with 100 than 0% fertilizer at all observation times on 58-111 DAS, with large differences for the 58-103 DAS observation dates (Figure 1b; Table 3). At the 35 cm soil depth, the SMC was significantly lower under 100 than 0% fertilizer at all observation times from 58 DAS onward. The differences were large for all these observation dates.

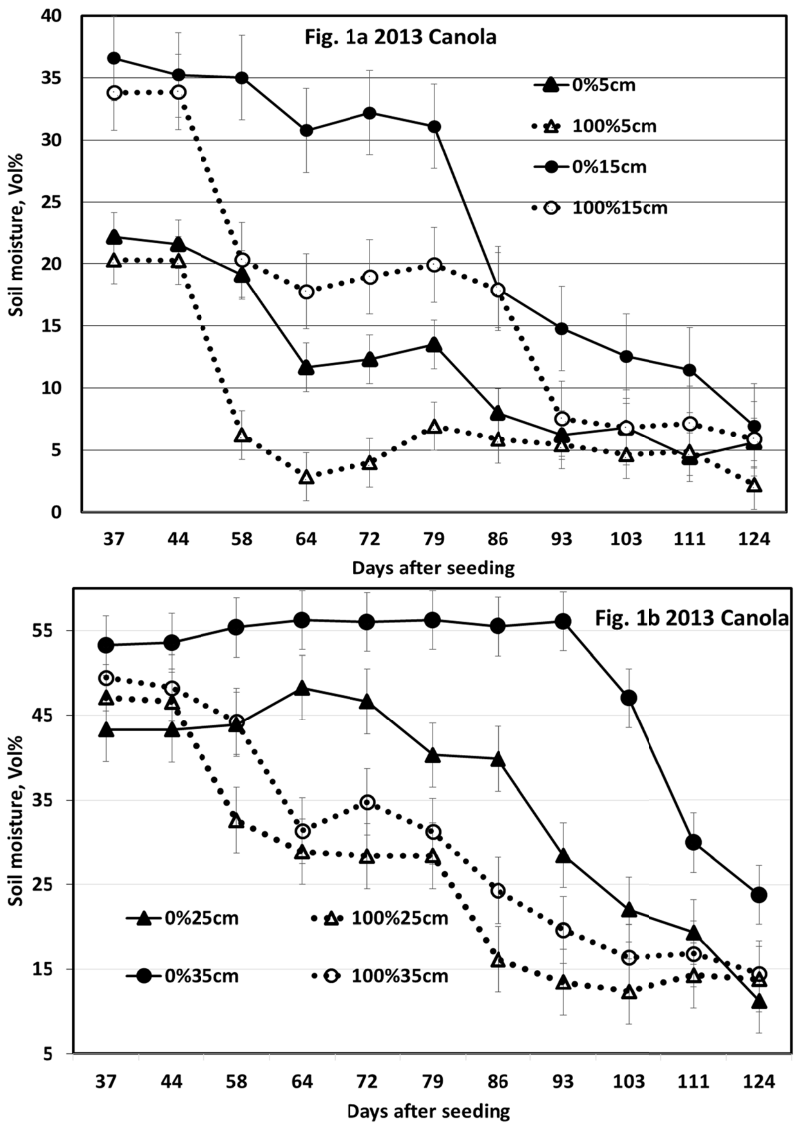

Figure 1. Soil moisture at the 5, 15, 25, and 35 cm depths during the 2013 canola growing season with 0% and 100% fertilizer

Table 3. Standard Errors (SE) of soil moisture content (SMC) differences between the 0% and 100% fertilizer rates based on Paired T-test, at the 5, 15, 25, and 35 cm soil depths under canola and barley at various days after seeding (DAS) in 2013, 2014, and 2015. The 0% fertilizer rate had higher SMC, except in few cases (shown by underlined values). Significant differences between the 0% and 100% fertilizer rates are indicated by ^{T}, *, **, and ***, respectively, for the 0.10, 0.05, 0.01, and 0.001 probability

Canola					**Barley**				
DAS	5	15	25	35	DAS	5	15	25	35
2013									
37	3.75	0.96	<u>1.33</u>^{T}	3.19	-1	2.84*	0.58*	2.47*	133
44	1.05	1.11	<u>0.80</u>	4.31	6	1.34**	1.33	5.95	1.33
58	1.59**	4.70^{T}	4.84^{T}	0.54**	20	2.04*	1.36^{T}	2.15*	1.28
64	0.92**	4.44^{T}	2.72**	0.48**	26	2.57^{T}	<u>3.18</u>	2.69*	0.01***
72	1.89*	179**	4.73*	2.08*	34	2.70	1.54	2.47^{T}	2.30
79	1.32*	1.55**	1.29**	0.24***	41	1.14	0.81**	2.36	0.94
86	0.80^{T}	1.48	4.90*	681*	48	1.09	2.06	1.83	<u>1.48</u>
93	1.01	0.91**	2.65*	4.3**	55	<u>2.26</u>	<u>1.52</u>	0.86	0.43^{T}
103	0.45*	1.32*	0.98*	0.01***	65	<u>1.54</u>	<u>2.00</u>	0.83	3.83
111	0.83	2.91^{T}	1.89^{T}	1.66***	73	1.68	1.89	0.46	2.21*
124	0.03***	0.46	<u>2.77</u>	0.29***	86	<u>1.28</u>	125	ND[a]	1.36
2014									
2	0.86	1.14	2.93	0.82	2	2.32	1.43	2.78	2.50
8	0.16**	0.00	3.42	0.24	8	0.50	1.60	3.07	2.24
16	1.51	<u>2.36</u>	<u>2.42</u>	0.44^{T}	16	1.14	2.43	2.16	1.41
23	4.42	1.67	1.02**	1.87	23	0.45*	1.14*	<u>2.05</u>	2.07*
28	1.49**	<u>3.14</u>	6.52	1.22*	28	0.50*	2.29^{T}	<u>0.47**</u>	1.58*
36	1.32^{T}	1.83	1.47**	<u>0.37***</u>	36	0.03***	4.56	13.62	1.03***
43	0.88	0.91**	2.08*	<u>1.30</u>	43	1.18*	0.08	1.75	1.18**
50	3.43	3.77	0.62***	0.84*	50	3.00	1.19	8.72	2.43
57	3.35	5.73	2.50*	1.77**	57	2.37	1.44	4.80	2.81
62	3.30	4.89	4.91	2.40^{T}	62	0.80	0.79**	5.45	0.98**
71	3.00	5.94	3.38	5.35	71	<u>1.40</u>	0.12***	5.87	0.86*
77	3.42	<u>6.17</u>	<u>2.85</u>	4.93	77	0.07***	0.22***	0.95*	1.46*
86	0.77	<u>1.40</u>	<u>1.62*</u>	1.81*	86	0.27*	0.37**	2.25^{T}	3.67^{T}
92	1.69	<u>4.39</u>	3.57	3.25	92	1.76	0.33**	1.25^{T}	0.33**
2015									
16	1.70	3.98	1.15	<u>2.26</u>	16	<u>3.17</u>	<u>1.27</u>	3.98	3.02
25	2.77	3.30	2.31	<u>0.95</u>	25	1.03	<u>3.57</u>	3.25	2.68
32	2.04	4.62	<u>1.44</u>	0.95	32	2.04	<u>1.39</u>	7.98	2.44
53	3.50	4.40^{T}	9.19	2.46**	53	1.81	3.18	2.32^{T}	3.22^{T}
64	2.05	5.83	3.56*	1.40***	64	1.59	<u>1.14</u>	3.03*	4.51^{T}
72	0.48**	2.96^{T}	0.87**	2.23*	72	0.88	4.60	1.10**	4.54^{T}
95	0.18**	6.87	1.15**	2.62**	95	1.67	0.38**	0.92***	0.95***
102	<u>1.03</u>	2.61	0.77**	2.68^{T}	102	ND	ND	ND	ND

Note. [a] ND refers to No Data.

The SMC at all four depths did not show any change until 44 DAS (Figures 1a and 1b), apparently due to very little water use during the crop-emergence and early growth periods and adequate rain received to cover the water use by the crop under both fertilizer rates (Table 2). Rapid Soil water depletion at 5 cm depth was observed between the 44-58 DAS under 100% fertilizer and between the 58-86 DAS under 0% fertilizer. Rapid SMC depletion from the 15 cm depth started after 44 DAS and after 79 DAS under the 0 and 100% fertilizer rates, respectively. At the 25 cm depth, SMC was gradually depleted between the 44-93 DAS with no change later under the 100% fertilizer, and from 64 DAS until last observation on 124 DAS under the 0% fertilizer rate. The

35 cm depth showed gradual depletion of SMC from 64 DAS until 124 DAS under the 100% fertilizer, while no change in SMC was observed until 93 DAS with relatively faster depletion between 93 and 124 DAS under 0% fertilizer. These observations clearly showed the earlier start of SMC depletion under 100% compared to the 0% fertilizer rate, indicating that fertilizer application advanced SMC depletion time.

As a result of an earlier start to SMC depletion under the 100 than 0% fertilizer rate, the differences in SMC between the two fertilizer rates increased until a certain time and then diminished.

There was very little change in SMC at the 5 cm depth after 58 DAS under 100% fertilizer and after 86 DAS under 0% fertilizer. At the 15, 25, and 35 cm depths, there was very little change in SMC under 100% after 93, 86, and 103 DAS, respectively. The plants could not use water when the SMC reached about 7, 12, and 15% at 15, 25, and 35 cm depths, respectively. Unlike 100% fertilizer, the SMC continued to decline until 124 DAS under 0% fertilizer. These results indicated that delayed start in SMC depletion did not hinder the ability of plants under 0% fertilizer as they continued to use soil water for a more extended period.

3.1.2 Barley

Just a note that barley was reseeded on June 22. For the 5 cm depth, the SMC was significantly less under 100 than 0% fertilizer until 26 DAS, and tended to less (not significantly) on 34, 41, and 48 DAS, with no differences after that (Figure 2a; Table 3). At the 15 cm depth, the SMC was or tended to be less under 100 than 0% fertilizer until 48 DAS and had a similar level under both fertilizer rates at later observation dates. The SMC at 25 cm depth was also less under 100 than 0% fertilizer until 55 DAS with similar levels under both fertilizer rates at later observation dates (Figure 2b; Table 3). The SMC tended to be less under 100 than 0% fertilizer for all the observation dates at 35 cm depth, with significant differences for the 26, 55, and 73 DAS.

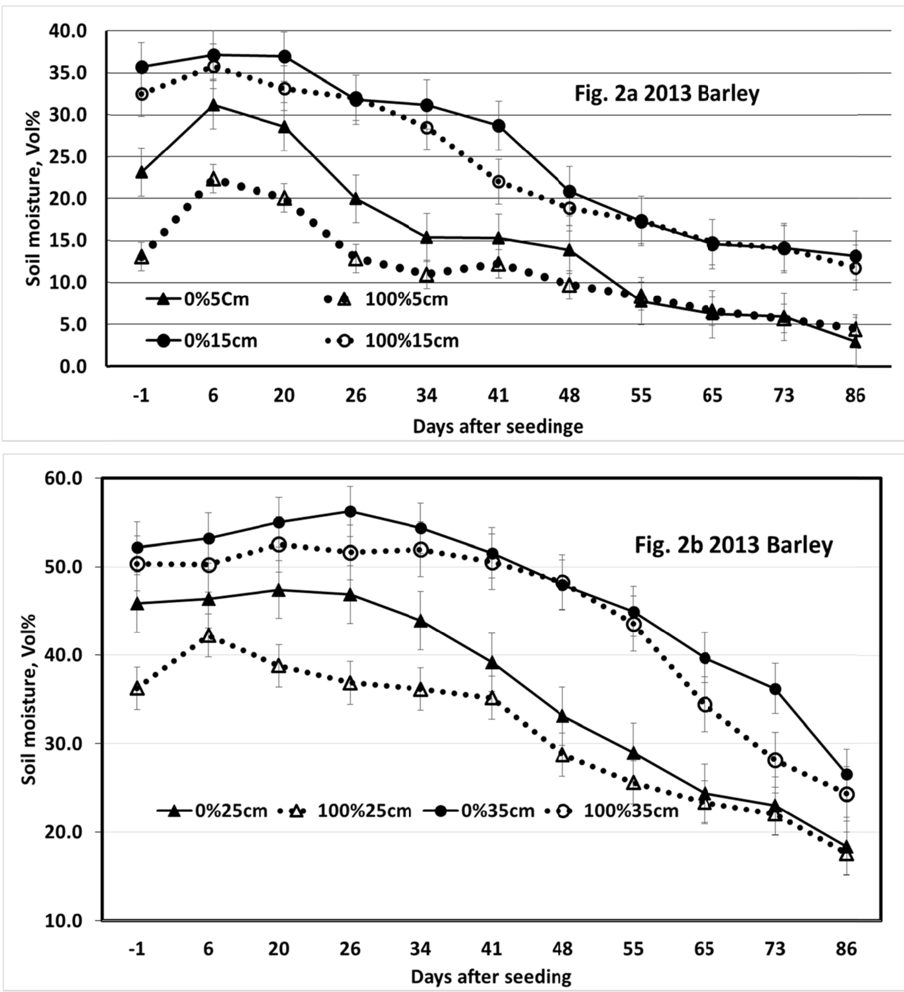

Figure 2. Soil moisture at the 5, 15, 25, and 35 cm depths during the 2013 barley growing season with 0% and 100% fertilizer

The SMC at all four depths increased or did not show any change until six (6) DAS due to rain and very little water use during the crop's emergence period (Table 2; Figures 2a and 2b). Depletion of soil moisture at the 5 and 15 cm depths started after six (6) DAS under both fertilizer rates. The SMC depletion under 100% fertilizer at the 25 and 35 cm depths started after six (6) and 20 DAS, respectively. Under the 0% fertilizer, the start of SMC depletion at the 25 and 35 cm depths was delayed to 26 DAS. Like canola, SMC depletion at the 25 and 35 started earlier under 100% compared to the 0% fertilizer rate.

Very little SMC change occurred at the 5 and 15 depths after 55 DAS. Apparently, plants could not use water from the 5 and 15 cm depths after 55 DAS under both fertilizer rates as a result of the very low SMC (near the 5% SMC at 5 cm and below 15% SMC at 15 cm depth). At the 25 and 35 depths, the SMC declined until 86 DAS under both fertilizer rates. A very similar SMC was observed under both fertilizer rates at 86 DAS, just below 20% at 25 cm depth and near 25% at 35 cm depth. Similar to canola, the barley results showed that a delayed start to SMC depletion did not hinder the ability of plants under 0% fertilizer to continue using soil water for a more extended period.

3.2 2014 Season

The growing season started with 81% of the normal SSM but had only 47% of normal rain during the growing season with lower than the average amounts received each month (Table 2).

3.2.1 Canola

The SMC at 5 cm depth increased until 23 DAS due to rain (Figure 3a, Table 2). However, the increase in SMC was slightly less under 100 than 0% fertilizer, indicating some moisture use by canola under the 100% fertilizer rate. From 23 DAS, a steady decline in SMC was noticed under both fertilizer rates that lasted until 57 DAS under 100% and until 92 DAS under 0% fertilizer, when SMC reached nearly 5% under both fertilizer rates. From 16 to 86 DAS, the SMC was lower under 100 than 0% fertilizer though the differences were not always significant (Table 3). At the 15 cm depth, there was little change in the SMC until 28 DAS under 100% fertilizer and 43 DAS under 0% fertilizer. From 28 to 57 DAS, the SMC was lower under 100 than 0% fertilizer. Then from 62 DAS onward, the SMC level was similar under both fertilizer rates. The SMC at 25 cm depth showed negligible depletion until 36 DAS under 100% and until 43 days under 0% fertilizer (Figure 3b). It was lower under 100 than 0% from 36 DAS until the last observation on 92 DAS, with significant differences on some dates. At the 35 cm depth, SMC increased from 8 to 23 DAS, with negligible changes during the 23-43 DAS and 23-57 DAS under the 100 and 0% fertilizer, respectively. After 43 DAS, the SMC was lower under 100 than 0% fertilizer.

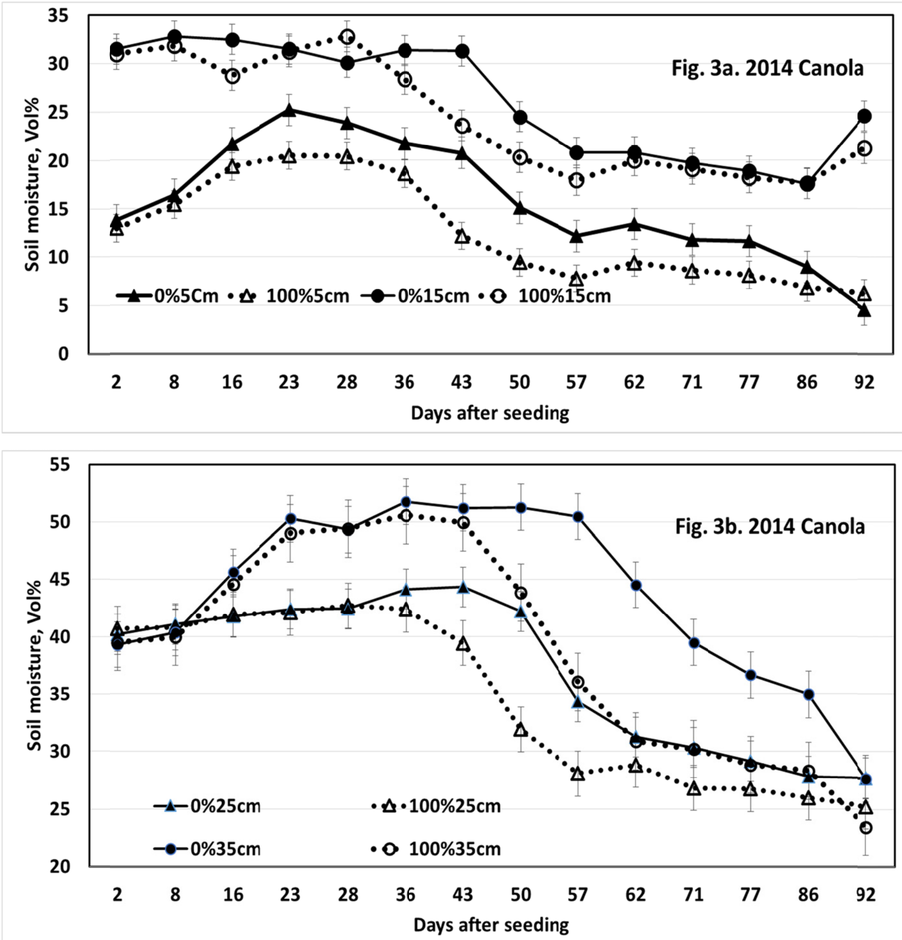

Figure 3. Soil moisture at the 5, 15, 25, and 35 cm depths during the 2014 canola growing season with 0% and 100% fertilizer

Under the 100% fertilizer, depletion in SMC started from 28 DAS at the 5 and 15 cm depths, 36 DAS at 25 cm depth, and 43 DAS at 35 cm depth. The start of SMC depletion under 0% fertilizer was delayed to 43, 50, and 57 DAS at the 15, 25, and 35 depths, respectively, showing earlier start of SMC depletion with 100% compared to the 0% fertilizer rate.

At the end of the growing season (92 DAS), the SMC level appeared similar under both fertilizer rates, indicating canola plants extracted similar amounts of water at both fertilizer rates.

3.2.2 Barley

As a result of rain (Table 2), the SMC at 5 and 15 cm depths increased under both fertilizer rates until 16 DAS (Figure 4a). From 16 to 57 DAS, the SMC at 5 cm depth steadily declined under both fertilizer rates, until the SMC level reached 7-10% and did not decline further. From 23 DAS onward, the SMC at the 5 cm depths was generally lower under the 100 than 0% fertilizer, with significant differences on some dates (Table 3). At the 15 cm, the SMC was lower under 100% than 0% from 23 to 92 DAS, though the differences were not always significant (Table 3). The SMC at 25 depth showed negligible depletion until 28 DAS under both fertilizer rates (Figure 4b). It was lower under 100 than 0% from 36 DAS until the last observation on 92 DAS, with significant differences on some dates (Table 3). At the 35 cm depth, there was little change in SMC until 8 DAS under 100% and until 28 DAS under 0% fertilizer. At all the observation dates (2 to 92 DAS), the SMC was lower under 100 than 0% fertilizer with significant differences from 23 to 92 DAS.

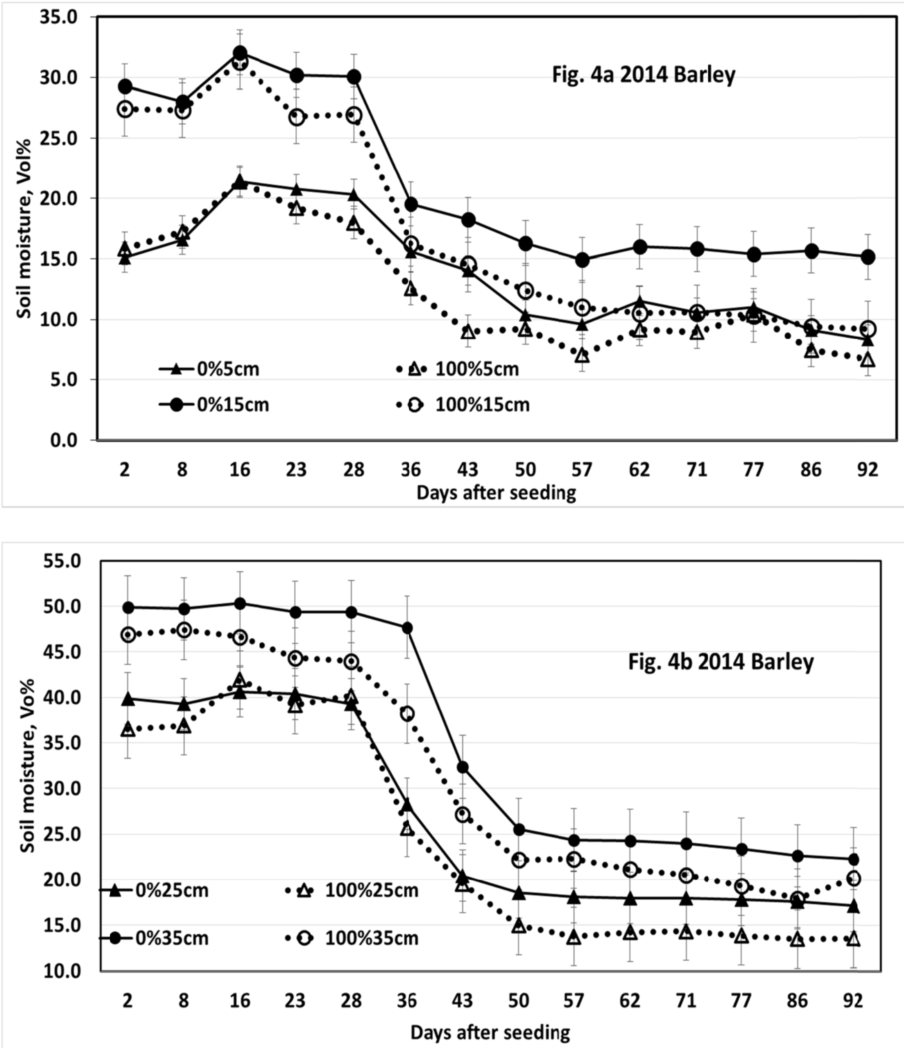

Figure 4. Soil moisture at the 5, 15, 25 and 35 cm depths during the 2014 barley growing season with 0% and 100% fertilizer

Depletion of SMC under the 100% fertilizer started from 16 DAS at the 5 and 15 cm depths, 16 DAS at the 25 cm depth, and 8 DAS at the 35 depth. The start of SMC depletion under 0% was delayed to 28 DAS at the 5, 15, and 25 cm depths and to 36 DAS at 35 depths. Thus there was an earlier start of SMC depletion with 100% compared to 0% fertilizer.

After 57 DAS, there was very little change in the SMC level under both fertilizer rates at all four depths, indicating barley plants were not using much soil water due to either nearing physiological maturity or their inability to extract water due to low SMC. From 57 to 92 DAS, the SMC level was near 10% at 5 cm depth under both fertilizer rates. But for the 15, 25, and 35 depths, the SMC level during the 57 to 92 DAS was about 5% lower under 100 than 0% fertilizer, indicating more water use with fertilizer application.

3.3 2015 Season

Only about 68% of the normal SSM at the start of the season was followed by 53% of normal rain during the growing season (Table 2). Thus drought conditions prevailed during most of the growing season, except for frequent small rain showers that occurred during late July and early Aug. (observation based on daily rain events, daily rain data not reported).

3.3.1 Canola

From 16 DAS until 72 DAS, the SMC at the 5 cm depth was or tended to be lower under the 100 than 0% fertilizer rate with significant differences on some dates (Figure 5a; Table 3). At the 15 cm depth, the SMC at all the observation dates was lower under 100 than 0% fertilizer, with larger differences after 32 DAS. The SMC at 25 and 35 cm depth was similar under both fertilizer treatments until 32 DAS but became significantly lower under the 100 than 0% fertilizer at all the later observation dates (Figure 5b; Table 3).

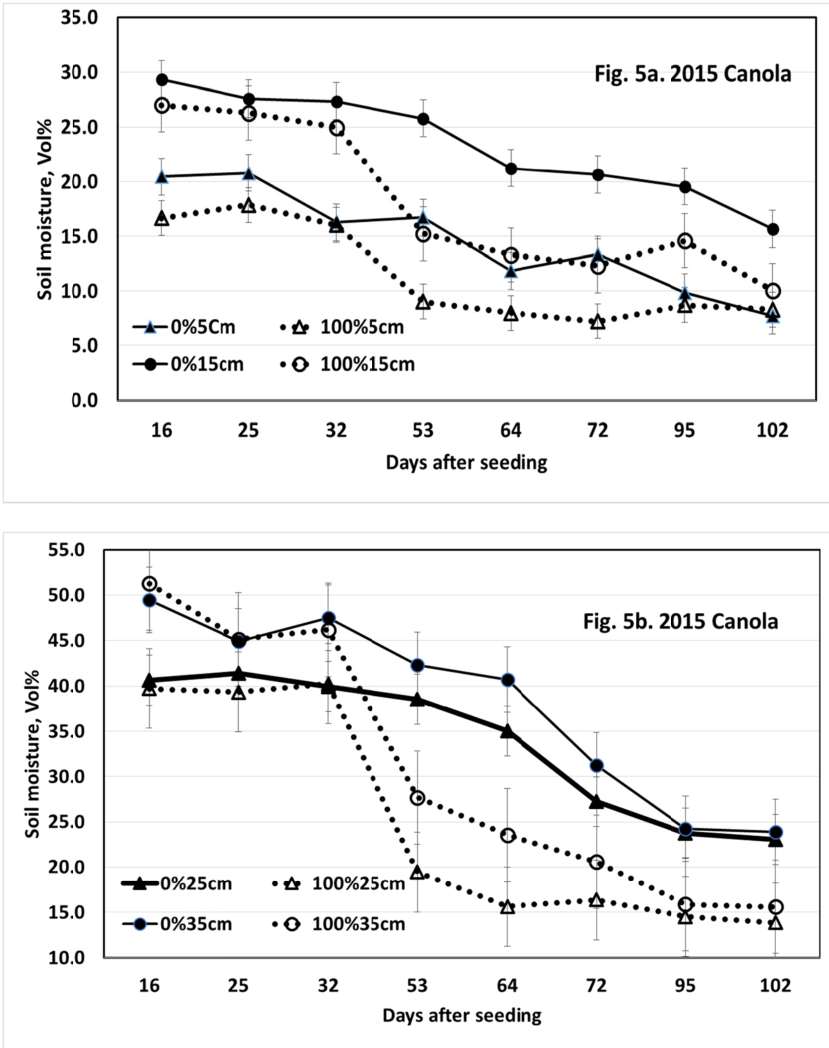

Figure 5. Soil moisture at the 5, 15, 25, and 35 cm depths during the 2015 canola growing season with 0% and 100% fertilizer

At 5 cm depth, SMC depletion started after 25 DAS under both fertilizer rates (Figure 5a). The SMC depletion at 5 cm depth under 100% fertilizer was rapid between 32 and 64 DAS with almost no depletion after that. Under 0% fertilizer, depletion occurred at a slower rate until the last observation on 102 DAS. Depletion of SMC at the 15 cm depths was observed from the 25 DAS under both fertilizer rates, and stopped after 72 DAS under 100% rate while it slowly continued until the last observation on 102 DAS under 0% rate. Under both fertilizer rates, the SMC depletion at the 25 and 35 depths started after 32 DAS and lasted until 95 DAS (Figure 5b). At both 25 and 35 cm depths, faster depletion of SMC under 100% fertilizer was observed from 32 to 53 DAS followed by a relatively slower rate until 95 DAS, but under 0% fertilizer moderate depletion occurred from 32 to 95 DAS. Unlike in 2013 and 2014, the depletion of SMC started at the same time under both fertilizer rates.

At the last observation on 102 DAS, similar SMC was noticed under both fertilizer treatments at the 5 cm depth (near 8%), which was the result of plants being unable to extract additional water. Unlike the 5 cm depth, SMC was lower under 100 than 0% fertilizer at the 15, 25, and 35 cm depths, indicating that fertilized plants were able to use more soil water than unfertilized plants.

3.3.2 Barley

The SMC was very similar under both fertilizer rates until 72 DAS at the 5 cm and 53 DAS at the 15 cm depth, with no consistent differences (Figure 6a, Table 3). After that, it was lower under 100 than 0% fertilizer. But at the 25 and 35 cm depths, lower SMC was observed at all observation dates under 100 than 0% fertilizer, with significant differences from 53 DAS onward (Figure 6b; Table 3).

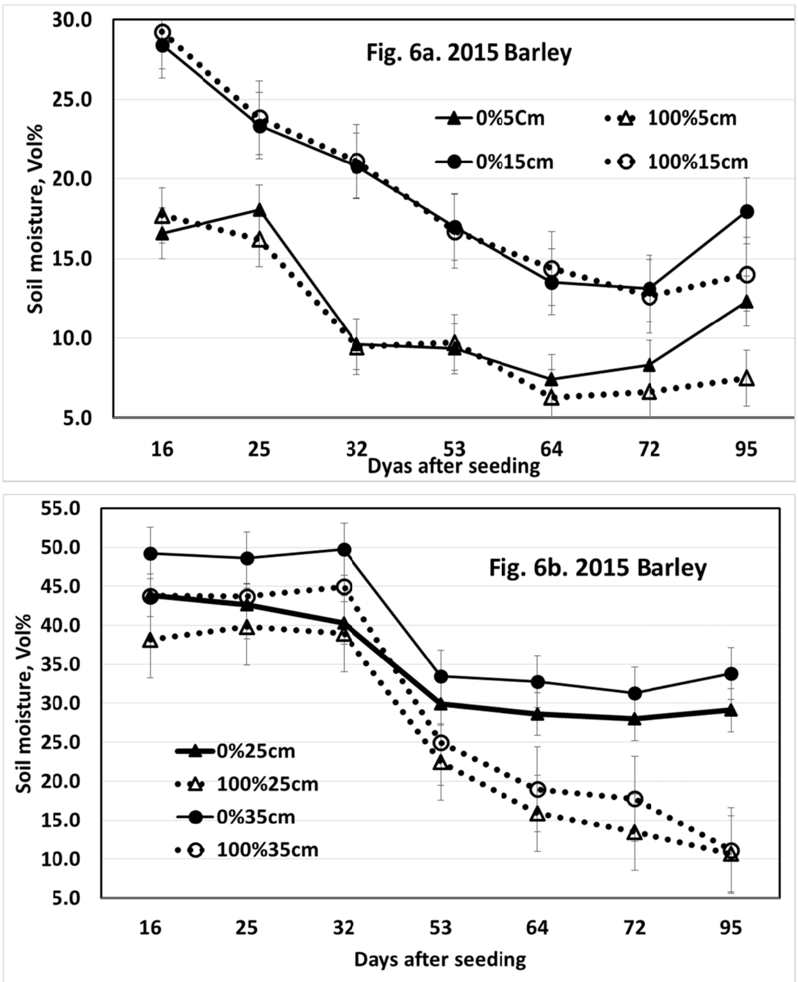

Figure 6. Soil moisture at the 5, 15, 25, and 35 cm depths during the 2015 barley growing season with 0% and 100% fertilizer

Under both fertilizer rates, steady SMC depletion occurred between the 16 to 72 DAS at the 5 cm depth, while depletion of SMC at the 15 cm depth occurred from 25 to 64 DAS. Between 72-95 DAS at 5 cm and 64-95 at 15 cm, a slight increase in the SMC was observed at both depths, probably due to frequent rain during this period. At both the 25 and 35 depths, SMC depletion started after 32 DAS, continued until the last observation of 95 DAS under 100% fertilizer, while it occurred only until 53 DAS under 0% fertilizer.

As a result of continued depletion of SMC at the 25 and 35 cm depths after 53 DAS under 100% fertilizer and no depletion under 0% fertilizer, the differences in SMC under the two fertilizer rates increased between the 53 and 95 DAS. These observations indicated that fertilizer application increased the ability of barley plants to extract soil water, which was contrary to 2013 but similar to the 2014 results.

4. Discussion

Under dryland agriculture practiced in the study area, crops are sown in spring and harvested during the autumn, followed by a cold winter with no crop until next spring. Stored soil moisture plus rain and depletion of soil moisture during the growing season provide water for crops. Rain and snow during winter increase the moisture content of the soil, but with rare exceptions, soil moisture depletion occurs during the growing season. Crop yields suffer in years with less than normal rainfall, especially when SMC is low at the start of the growing season.

Soil moisture depletion occurred under both crops at the 5, 15, 25, and 35 cm depths during 2013, 204, and 2015, which was expected under the dryland conditions prevailing in the study area (Figures 1 to 6). The changes in SMC during and at the end of crop growing seasons, provide information on how fertilizer addition can influence the extent and timing of soil moisture depletion.

During much of the three growing seasons of both crops, SMC at the monitored soil depths was lower with 100 than 0% fertilizer (Figures 1 to 6). However, the duration of these periods of differences between the two fertilizer treatments varied without any consistent trend for the year, crop, or soil depth. For canola, this period lasted for 39-70, 29-86, 49-56, and 49-70 days at the 5, 15, 25, and 35 cm soil depths, respectively. The barley's corresponding values were 23-69, 23-69, 42-76, and 69-87 days. Regarding different years, it lasted for 39-66, 29-70, and 49-70 days for canola in 2013, 2014, and 2015, respectively. The barley's corresponding values were 42-87, 42-69, and 23-76 days. Two reasons were considered responsible for no consistent trend in the duration when SMC was less in 100 than 0% fertilizer. One, there was an almost equal amount of soil water under both fertilizer treatments at seeding time (Figures 1 to 6). Second, there is a progressive reduction in the ability of plants to use water as the soil moisture level decreases because water gets held more tightly by soil particles. So with more water being extracted by plants in 100% fertilizer treatment from the amount present at seeding, it became more challenging for the plants to extract more water when the SMC fell below a certain level. Thus the 0% fertilizer could catch up, eventually resulting in much smaller differences in SMC between the two fertilizer treatments.

Consistent with the lower soil moisture under 100 than 0% fertilizer in the present study, McKell et al. (1959) stated that fertilized plants reduced SMC compared to non-fertilized plants. Tesfahunegn (2019) concluded that the decrease in SMC with increased fertilizer rates was associated with increased crop water demand associated with higher crop yield. Ritchie and Johnson (1990) stated that fertilization stimulates plant growth and thus more soil water use. Other reports have also shown that additional nutrient supply can increase water and nutrient uptake by plants from the soil and produce better crop growth (Salvagiotti et al., 2008; Setiyono et al., 2010). Previous research has also shown that long-term N and P fertilization considerably increase crop water use for transpiration, resulting in decreased SMC (Caviglia & Sadras, 2001; Huang et al., 2003; Zhang et al., 2006; Wang et al., 2013). The implication is that when fertilizer rate increases, there is higher soil water depletion by the plants due to more nutrients available regardless of the type of crop or variety (Caviglia & Sadras, 2001; Huang et al., 2003; Zhang et al., 2006; Zou et al. 2012; Wang et al., 2013).

Soil moisture depletion by both crops in 2013 started earlier under 100 than 0% fertilizer at all the soil depths, except for reseeded barley at 5 cm depth (Figures 1 and 2). Similarly in 2014, an earlier start of soil moisture depletion was noticed with 100 than 0% at all the soil depths for both crops, except canola at the 5 cm depth (Figures 3 and 4). The 2013 and 2014 results showed that more vigorous root growth with fertilizer application resulted in earlier soil moisture use. Gill (2021) observed greater length, surface area, and volume of canola and barley roots with 100% than 0% fertilizer during the early growing season of 2015 under both the minimum tillage and direct seeding systems.

Unlike the 2013 and 2014 results, the 2015 data did not show a fertilizer effect on the start of soil moisture depletion time (Figures 5 and 6). As a result of lower spring soil moisture and less rain in June 2015, relative to 2013 and 2014, soil moisture was depleted from drier soil irrespective of the fertilizer rate (Table 1).

In the study where the soil moisture data were collected, the canopy of both canola and barley usually had lighter colour and delayed development in the 0% compared to 100% fertilizer rate treatments in all years, as shown by using pictures of canola canopy in 2015 (Picture 1, Gill, 2019). Canola plant height also showed significant increase from fertilizer application, while the increase in barley height was not significant (Table 7, Gill, 2019). Even with limited soil moisture in the early growing season of 2015, early season root growth of barley and canola was better under 100 than 0% fertilizer (Gill, 2021). Compared to 0% fertilizer, canola seed yield increase with 100% fertilizer was 2.31 (162%), 2.16 (116%), and 3.02 (202%) Mg ha^{-1} during the 2013, 2014, and 2015 seasons, respectively (Gill, 2019). Corresponding increase for the barley seed yield was 0.96 (21%), 0.77 (15%), 0.61 (25%) Mg ha^{-1}. These results clearly show that same or only somewhat more water extraction with 100 compared to 0% fertilizer resulted in large seed yield increases for both crops. On a loam soil from 1967 to 1984 years, Campbell et al. (1998) reported higher wheat yield per unit of water use from better-fertilized rotations. Srivastava et al. (2020) stated that water use efficiency for corn grain yield was higher for both rainfed

(N60-N100) and irrigated (N75-N125) in comparison with N0 nitrogen level. Oberle and Keeney (1990) observed that for rainfed environments, preplant and early season precipitation amounts were important factors in explaining yield responses and were the factors that caused optimal N rates for maximum corn yield; and N management could cause variation in yield with no differences in amounts of water use. Hatfield et al. (2001) stated that modifying nutrient management practices can increase WUE by 15 to 25%. Results from these studies implies that growth of both plants and roots is improved from early growth period and more seed yield is produced per unit of water used by crops when fertilized relative to no fertilizer. Further, improved water use efficiency of crops with fertilizer application can reduce the carbon footprint per unit of seed production and reduce the environment impact of crop production.

By the end of the growing season, both canola and barley tended to deplete soil moisture to a lower level under 100 than 0% fertilizer, with some exceptions. Thus somewhat less residual SMC may be expected after crops that receive 100 compared to the 0% fertilizer rate. Srivastava et al. (2020) observed cumulative evapotranspiration to be higher for both rainfed (N60-N100) and irrigated maize (N75-N125) in comparison with N0 nitrogen level. Shahadha et al. (2021) found with increasing N rate under high rainfall amounts, the crop transpiration increased whereas the soil evaporation decreased. However, soil water dynamics and crop evapotranspiration were not affected by N application rates under low rainfall amount. Less soil moisture in fertilized crops during the crop growth periods and after harvests may have positive and negative aspects. Positively, more depletion of soil moisture means more rain infiltration, with less water runoff and soil erosion in years with adequate rain. Negatively, if the root zone soil is not fully charged before the start of the next crop, the subsequent crop can suffer from water stress in dry areas.

After rapid depletion of soil moisture during their early and middle periods, crops' slower or no soil moisture depletion could be due to the reduced ability of plants to extract soil water from relatively drier soil. At lower SMC levels, the remaining water is held more tightly by soil particles (higher matric suction), or the crops being near maturity were using less water. Lower SMC at later crop growth stages suggested a lack of available SM for optimum crop growth that probably limited crop yields, especially during the 2014 and 2015 seasons.

Less SM depletion from deeper than from shallower soil depths during the early crop growth period was considered to be the result of evaporation from the surface soil plus initial shallow rooting depth (Figures 1-6). Increased SM depletion from the deeper soil during the later part of the growing seasons indicated greater root growth in the deeper soil and less water available at shallower depths. Earlier reports have shown that the root systems of crops can increase or relocate maximal root growth to regions with more water in the soil profile, thereby maintaining plant growth under dry conditions (Rendig & Taylor, 1989). Moroke et al. (2005) observed that the root length densities of sorghum (*Sorghum bicolor*) and sunflower (*Halianthus annus*) near the soil surface increased rapidly initially and then declined, while they increased throughout the growing season in the deeper soil: and depletion of soil water from the different soil depths corresponded to the root length density. During a dry year, the root length density at shallow soil depths tended to decrease during mid-season but continued to increase throughout the growing season at deeper soil depths (Moroke et al., 2005). Fan et al. (2016) stated that soil water depletion by crops depends not only on the total root system but also on the depth-wise distribution of roots. These statements support our result of more soil moisture depletion from deeper soil depths as the season progressed.

Overall, more soil moisture depletion under 100 than 0% fertilizer during considerable parts of crop growing seasons indicated an improved ability of crops to extract soil water under 100% fertilizer. The smaller differences in SMC near the end of crop growing season under both fertilizer levels indicate that if more soil moisture was available, the differences might have continued for more extended periods. The implication is that yields of the fertilized crops may have benefitted more than the unfertilized crops from additional moisture.

5. Conclusions

Soil moisture at the monitored depths was depleted by canola and barley crops during 2013, 2014, and 2015. The data indicated a relatively lower soil moisture level under 100% when compared to 0% fertilizer during most parts of the growing seasons. This demonstrated an improved ability of fertilized plants to extract soil water. There was generally an early start to soil water depletion when fertilizer was added. With some exceptions for the 5 and 15 cm depths, both crops could deplete soil moisture to a somewhat lower level under 100 than 0% fertilizer by the end of the growing season. Soil moisture availability probably limited crop production, especially during the 2014 and 2015 seasons. Under the area's dryland agriculture conditions, fertilizer application could alter the soil moisture depletion pattern during the growing season and somewhat reduce residual soil moisture at crop harvest. Fertilizer application also improved the water use efficiency by crops. In summary, these findings indicated that fertilizer application might reduce soil moisture availability for subsequent crops, mainly when moisture is limiting during the next growing season, but fertilizer use is recommended due to improved plant and root growth, seed yield and water use efficiency.

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