COVER CROP EFFECTS ON INFILTRATION, SOIL TEMPERATURE, AND SOIL MOISTURE DISTRIBUTION IN THE CANADIAN PRAIRIES

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ABSTRACT. *Excess root zone soil moisture resulting from annual precipitation in excess of crop water requirements negatively affects crop yields. A field study was conducted in the 2005 and 2006 seasons on sandy loam soils to investigate the influence of berseem clover (*Trifolium alexandrium *L.) cover crop in oats (*Avena sativa *L.) on soil temperature, infiltration, and soil moisture redistribution within the growing season and during the fall to spring seasons. A 4-year crop rotation experiment to investigate farming with fewer chemicals was used to grow oats in a no-till cultivation system with and without the cover crop. The total and unfrozen water contents were measured in the field using neutron moisture meter and time domain reflectometry, respectively, at 0.2-m intervals from the surface to 1.8-m deep, plus a 0.1-m measurement depth. The cover crop significantly reduced soil moisture during the growing season resulting in significantly lower biomass yields (6146 kg ha^{-1} combined biomass for oats and berseem clover, vs. 7327 kg ha^{-1} for oats alone). By mid-August 2005, the cover crop treatment had 34.6% lower water content (0.17 vs. 0.26 m^3 m^{-3}) within the 0.0- to 0.7-m root zone depth compared to the non-cover crop. During the fall, the soil profile in the cover crop treatment was 3 °C warmer, thus delaying soil freezing and leading to a shallower depth of the frozen soil layer (0.4 vs. 0.6 m) in March 2006. During the spring, the cover crop treatment warmed and thawed earlier enabling more snow melt infiltration and deep percolation. Areas experiencing excess soil moisture could use annual cover crops as a means for reducing excess soil moisture during the summer growing season and avoiding accumulation of soil moisture during the fall, winter and spring seasons.*

Keywords. *TDR, Soil moisture, Soil freezing, Cover crop, Infiltration, Soil temperature.*

The quantity and distribution of soil moisture in seasonally frozen soils such as in the Prairies in Canada plays a significant role in ensuring optimum crop yield from agricultural lands. Among the primary factors contributing to crop failure, and hence low yield, is the presence of excess soil moisture within the root zone for an extended period of time during the growing season (Cavers and Heard, 2001). Conservation practices involving cover crops have long been used as a means of reducing the excess soil moisture during the growing season by improving soil physical properties, and increasing the plant water uptake (Dabney, 1998; Bargar et al., 1999; Boquet et al., 2004). The use of cover crops combined with no-till conservation practice have also been reported to prevent soil erosion and nutrient leaching, increase organic carbon, modify soil temperature, increase water holding capacity, improve soil trafficability, and reduce machine compaction (Unger and Vigil, 1998; Dabney et al., 2001; Boquet et al., 2004). However, little has been reported on the influence of the cover crop on the redistribution of soil moisture within the soil profile during the fall and early winter and its effect on the response of the soil to thawing during the following spring season. In addition, the existence of soil moisture in both frozen and unfrozen states during the fall through spring seasons provides a challenge in predicting the soil's response to previous farm management practices (Flerchinger et al., 2000).

Annual cover crops such as berseem clover (*Trifolium alexandrium* L.) planted in spring influence the availability and redistribution of soil moisture within the growing season, during the winter, and in the following spring. Previous studies on the effect of cover crops during winter have mainly focused on the winter cover crops grown during the fall after the harvest of summer crops (Raper et al., 2000; Dabney et al., 2001; Joyce et al., 2002). The effect of the within-season cover crop on the soil's response to freeze-up and melt-down in the fall, winter, and spring seasons as reported in the present study is sparse in the literature. Joyce et al. (2002) investigated the influence of a common vetch (*Vicia sativa* L.) winter cover crop on the availability of soil moisture for the subsequent growing season. They concluded that the winter cover crop could potentially improve water storage for the next crop if the cover crop is destroyed early, thereby reducing water loss by evapotranspiration. The use of continuous cropping instead of fallow before winter wheat has also been reported to cause soil moisture depletion and

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low yield of winter wheat (*Triticum aestivum* L.) (Nielsen et al., 2002).

Excess soil moisture affects several processes in the soil, which in turn, influences the crop yield potential. Cavers and Heard (2001) studied processes affected by excess soil moisture and found that the problems associated with excess moisture are poor aeration, reduced root respiration, changes in the soil redox potential, and production of phytotoxic compounds within the root zone. When the excess moisture occurs during the middle of the growing season (i.e., during the time of flowering and seed set), the negative effect on crop yield is even more magnified.

The excess soil moisture problem is especially important in parts of the Canadian prairies, such as that of southern Manitoba, which includes the study site, the Ian N. Morrison Research Farm (formerly Carman Research Station) of the University of Manitoba (Carman, Manitoba), that receive excess precipitation in the form of both rainfall and snowmelt. Average annual precipitation of the Carman area is 588.8 mm (Environment Canada, 2007). The average seasonal crop moisture requirement for the crops grown in this area (estimated as total evapotranspiration) ranges from 250 to 350 mm (Entz et al., 2002). The extent of crop failure due to excess soil moisture within the growing season depends on soil type, plant species, stage of plant growth, temperature, and day length (Cavers and Heard, 2001; Osborne et al., 2003a). Cavers and Heard (2001) found that water logging over five days during the flowering stage of peas (*Astragalus nuttallianus* DC) reduced the yield to 25% compared to the control (non-flooded), while two days of water logging had insignificant effect on yield.

Currently, surface drainage (i.e., field ditches and drains) is the most widely used technique to reduce excess soil moisture in the area around Carman, Manitoba. With this drainage technique, the potential for pollution from agricultural chemicals and sediments discharged along with the drained water from agricultural fields is also a major concern. Therefore, to minimize the loading, long-term experiments have been conducted from year 2000 at the Ian N. Morrison Research Farm on a site managed with no-till cultivation to investigate how various crop rotation options can best be adopted in "farming with fewer chemicals (FFC)" (Schoofs et al., 2004). Berseem clover, an annual legume, has also been included as a cover crop in the 4-year rotation to determine its suitability under Manitoba's soil and environmental conditions. However, the influence of the cover crop management practice on the availability and distribution of soil moisture has not been fully investigated. The effect of the presence of cover crops on the freezing and thawing characteristics of the soil during the fall, and its impact on soil moisture redistribution during the following spring snowmelt also needs further investigation.

The use of cover crops, such as in an intercropping system, provides a protective cover that reduces runoff, erosion, and nutrient losses, thereby facilitating more infiltration (Bargar et al., 1999). In the case of excess soil moisture, cover crops work with the main crop to uptake more water from within the root zone. Osborne et al. (2003b) found that the addition of a cover crop assists in reducing the excess moisture that could otherwise negatively affect the main crop yield potentials. The same study reported that no-till cultivation delayed soil warming in the spring and resulted in excess soil moisture during the spring growing season. They further noted that the use of cover crops with a no-till system helped to reduce the excess soil moisture.

Considering the agronomic advantages of cover crops, Boquet et al. (2004) reported that compared to conventional tillage with a cover crop, the no-till cover crops led to lower yield if no nitrogen fertilizer was used. Higher yields were obtained when N-fertilizer was added. However, the no-till cover crop needed more fertilizer to attain the optimum yield than conventional tillage with cover crop. The main problems with the use of cover crops are: 1) excessive consumption of water that could otherwise be available for the subsequent growing season if it were drier; 2) competition of crop nutrients with the main crop resulting in decreased crop yield if less fertilizer is applied; 3) additional costs of seed, planting, and chemicals; and 4) water deficit at the time of the subsequent planting time (Unger and Vigil, 1998; Dabney et al., 2001; Sainju and Singh, 2001; Boquet et al., 2004).

Soil moisture status during the spring and summer season can be attributed to the soil conditions during the fall before soil freezing. The freeze-thaw processes and the presence of a crop cover on the ground prior to soil freezing affects infiltration, soil temperature, and soil water movement (Kane and Chacho, 1990; Zuzel and Pikul, 1987; Spaans and Baker, 1995). Therefore, the objectives of this study were to: 1) determine the influence of an annual berseem clover cover crop in oats on infiltration, soil temperature, and soil moisture redistribution during the fall through spring; 2) determine the influence of within season berseem clover cover crop on the crop performance and yield; and 3) determine the potential of berseem clover cover crop and native prairie grass to reduce excess soil moisture within the growing season, and to reduce the accumulation of total soil moisture in the root zone during the fall through spring.

Materials and Methods

Site Description

A field study was conducted from May 2005 to April 2006 at the University of Manitoba Ian N. Morrison Research Farm (Carman, Manitoba) located 90 km west of Winnipeg, Manitoba (49° 30' N, 98° 02' W, 262 m elevation). The Carman region is at the eastern edge of the Canadian prairies and experiences seasonal soil freezing and thawing during the fall, winter, and spring seasons, with the frost-free season ranging from 119 to 126 days. The frost-free season starts from 15 May to 26 September (Nadler, 2007). The area receives average annual precipitation of 588.8 mm per year (15 years average from 1991-2005), of which 477.5 mm is rain and 111.3 mm is in the form of snow (Environment Canada, 2007). The annual precipitation for year 2005 was 637.4 mm, and the annual mean temperature for the same year (2005) was 4.1°C (figs. 1 and 2; Nadler, 2007). The monthly mean temperatures over the area (15 years average) ranges from -16.2°C in January to +19.1°C in July; the 15-year mean annual temperature was 3.4°C (fig. 2). Topography of the area is relatively flat with ground slopes ranging from 0.0% to 0.5%. The surface texture of the soil at the experimental site was classified as a well drained Hibson, with a texture class of very fine sandy loam from the sub group Orthic Black Chernozem (Mills and Haluschak, 1993) or Mollisol (very fine sandy loam) in the USDA Soil

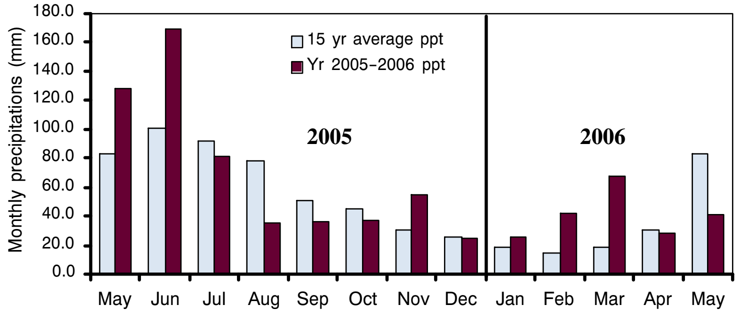

Figure 1. Monthly precipitations (ppt) from May 2005 to May 2006 and 15-year mean monthly precipitations (1991-2005) for Carman, Manitoba.

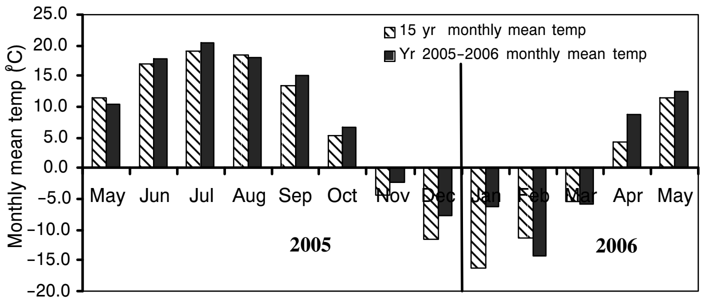

Figure 2. Monthly mean temperature from May 2005 to May 2006 and 15-year average monthly temperature (1991-2005) for Carman, Manitoba.

Taxonomy. The soil particle size distributions were 76% sand, 8% silt, 16% clay, and 4% organic matter in the top 0.16 m. The average depth to the clay layer was 0.70 m. The bottom layers from 0.7 to 1.2 m had 4% sand, 44% silt, and 52% clay. Detailed soil survey carried out by the Canada-Manitoba Soil Survey Unit (Mills and Haluschak, 1993) indicated uniform soil profiles within the selected site, with the depth to clay layer on an area 500 by 800 m across the experimental plots being between 0.70 and 0.75 m (Mills and Haluschak, 1993).

The very fine sandy loam soils in the study area are generally well drained with water table within 1 m during the spring and early summer, and dropping to 1.5 to 2.0 m during the fall and winter (Mills and Haluschak, 1993). The soils at the selected site had a field capacity (FC) ranging from 0.22 to 0.25 m^3 m^{-3}, and a permanent wilting point (PWP) of 0.064 to 0.082 m^3 m^{-3} (Mills and Haluschak, 1993). The bottom layers from 0.7 to 1.2 m had 0.30 m^3 m^{-3} FC, and 0.13 m^3 m^{-3} PWP. The available water (% volume) ranged between 15% and 17% on the top 0.0- to 0.7-m soil layers, and 21% between 0.7- and 1.2-m depth. The average saturated hydraulic conductivity of the top soil layers was 29 mm per day (Mills and Haluschak, 1993).

Experimental Design

The experimental site selected was within a long-term no-till, 4-year crop rotation trial for investigating the concept of farming with fewer chemicals (FFC). The FFC trial, which started in year 2000, examines the growing of crops under no-till cultivation and the absence of in-crop pesticides application during the growing season (Schoofs et al., 2004). The trial rotation includes wheat (*Triticum spp.*), canola (*Brassica napus*), oats (*Avena sativa* L.), linola /flax (*Linum usitatissimum*), and alfalfa (*Medicago sativa* L.) with native prairie, and continuous fallow for comparison. Of these, only four treatments consisting of oats alone, oats with berseem clover, native prairie grasses, and continuous fallow plots (fig. 3) were instrumented for detailed soil moisture and temperature measurements. The total soil moisture and soil temperature monitoring was carried out in one individual plot for each of the four treatments (plots 46, 48, 18, and 52 for oats with berseem clover, oats alone, native prairie grass, and fallow, respectively (fig. 3). Within each of these four plots one replicate of neutron access tube, one replicate of soil temperature probes, and three replicates of TDR probes were installed. Therefore, for the total soil moisture measured by NMM and soil temperature, one measurement value was taken per depth for each treatment and each time of data collection. For the unfrozen water content measured by TDR, three measurement values per depth were taken for each treatment and each time. The continuous fallow and native prairie grasses were included in the study as two opposite extremes of continual bare-ground and vegetated conditions, respectively.

Nason (2007) investigated the water use efficiency of various cropping systems in experimental plots within the same study area during the growing season in 2005 and 2006. Mean differences between treatments as low as 0.02 m^3 m^{-3} were found to be significantly different (α = 0.05) based on NMM soil moisture data obtained from plots located in three different blocks for each treatment. This is an indication of the uniformity of the soil profile within the long term experimental plots. The maximum length of the TDR coaxial cable that will allow us to make accurate soil moisture measurements was found to be 40 m (Kahimba et al., 2007). This limitation in length and the inaccessibility to the entire experimental area during the winter prevented the installation of TDR miniprobes in all individual plots.

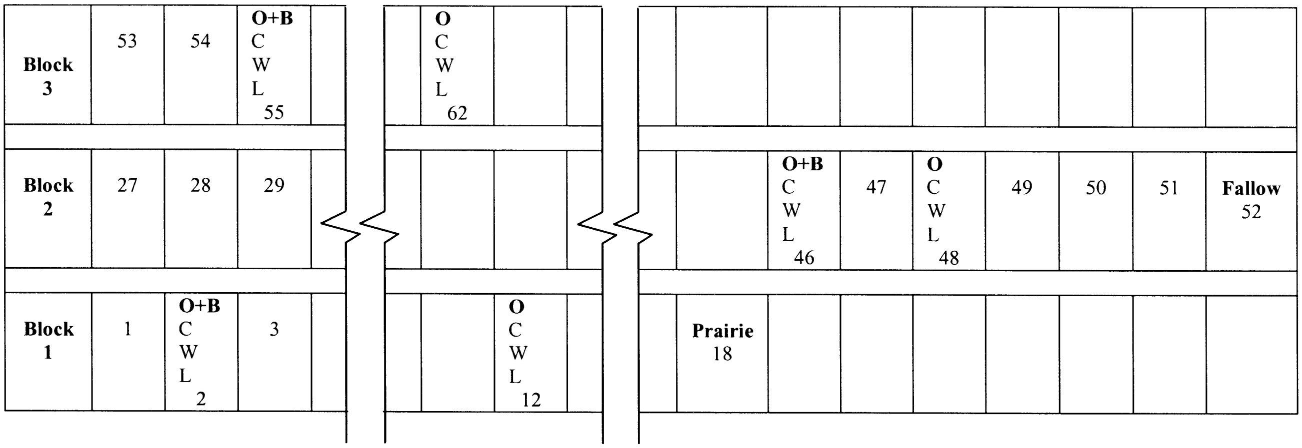

Figure 3. Field layout showing three blocks each with oats with berseem clover (O+B) and oats alone (O) in the 2005 growing season. Numbers at the bottom are plot numbers. The C, W, and L are respectively canola, wheat and linola (flax) in the 4-year rotation along with O+B or O.

For the crop performance data that were collected during the summer growing season, a randomized complete block design was used with three replicate blocks of the oats with berseem clover cover crop (plots 2, 46, and 55) and the oats alone (plots 12, 48, and 62) treatments (fig. 3). No yield measurements were taken on the fallow and native prairie grass treatments, hence one plot was used for the soil moisture and soil temperature measurements on the fallow (plot 52) and prairie (plot 18), as stated earlier. To minimize measurement variations due to soil heterogeneity and management practices for the cover crop and non-cover crop treatments, the plots were selected within the same block (plot 46 and 48) that were fairly close (6-m gap). The crop planting date was the same and the two treatments received the same farm management practices. The repetition of total soil moisture and soil temperature monitoring at the same depth over several days within the year also assisted to confirm the soil moisture and soil temperature trends over time.

Field Installations

Time domain reflectometry (TDR) cable tester (Tektronix model 1502B, Tektronix Inc., Beaverton, Oreg.) and TDR miniprobes with probe rods 35 mm long and 1.6 mm diameter (three-wire configuration) were used for measuring the unfrozen water content. The measurement precision for the down-sized TDR probe lengths ranging from 25 to 75 mm is 0.035 to 0.015 m^3 m^{-3}, respectively (Kelly et al., 1995; Persson and Haridy, 2003). Sri Ranjan and Domytrak (1997) using a wave-form noise reduction algorithm in a study to determine the effective volume of 50-mm miniprobes, reported a precision of 0.01 m^3 m^{-3}. To minimize the effect of soil variability and plot disturbance due to access during the winter months, three replications of the TDR probes were installed within each treatment. The TDR miniprobes were installed in the field at depths of 0.1, 0.2, 0.4, 0.6, and 0.8 m from the ground surface for each of the three replicates in a treatment. The probes were attached to RG58-50 Ω coaxial cables that were brought above the ground surface for connection to the TDR. The installation of the miniprobes was done at a 30° angle to the vertical to avoid preferential water flow through the installation holes. One replicate of thermocouples for recording soil temperature were installed along with the TDR probes at the same depths. A combination of profile soil temperature and the TDR unfrozen soil moisture measurements assisted in determining the soil freezing depth during the fall to spring seasons. The advantage of TDR miniprobes (35-mm) compared to commercial probes (>150 mm long) is that they can be used to accurately measure soil water content at depth intervals of 100 mm or less. The applications and effectiveness of downsized TDR miniprobes are described in Sri Ranjan and Domytrak (1997), Persson and Haridy (2003), and Kahimba and Sri Ranjan (2007).

Aluminium access tubes (50 mm diameter) were installed, one tube in each treatment, to a depth of 2.0 m from the ground surface for use with the neutron moisture meter (NMM, Troxler model 4302, Troxler Electronic Laboratories, Inc., Research Triangle Park, N.C.). One NMM access tube was installed for each treatment close to the center of the three TDR replicates on plots 18, 46, 48, and 52 (fig. 3). The NMM was used to measure the total water content along the vertical soil profile at 0.2-m intervals from 0.2 m to a depth of 1.8 m. Prior to data collection, the NMM was calibrated in the field by taking both NMM data and volumetric water content data obtained from core samples using the gravimetric method and the bulk density. A calibration equation was established (eq. 1) that was used for the interpretation of the NMM field data.

$$Y(\%) = \frac{CR}{0.022} - \frac{22.3}{2.2} \tag{1}$$

where

Y = total volumetric water content (%)

CR = count ratio.

The measurement precision of the NMM for measuring volumetric water content is ±0.01 m^3 m^{-3} (Evett and Steiner, 1995). Due to its high precision and extensive references in the literature, the NMM has been used as a standard measurement technique to compare with other methods of water content measurement (Evett, 2003). In this experiment, one replicate of NMM measurement was used as the standard for each treatment, along with the three replicates of the TDR measurements that were also installed in each treatment.

Field Data Collection and Analysis

One of the challenges in studying soil moisture availability and redistribution during the fall and winter seasons is the ability to quantify the soil water in the frozen and unfrozen states. As the soil transforms from the unfrozen to frozen state, physical measurement of the depth of freezing front and the available unfrozen and frozen water content requires the combination of soil moisture measuring methods that can partition total moisture into the frozen and unfrozen states. In this study, the total soil water content was measured using the NMM because this method is only influenced by the presence of hydrogen atoms irrespective of its state. The TDR was used to measure the unfrozen (liquid) water content because this method measures the dielectric constant of water in the liquid state (Topp et al., 1980; Seyfried, 2004). A combination of the two methods allowed partitioning of the total water content into the frozen and unfrozen components. The detailed procedures on the principles of NMM measurements are described in Evett (2000).

Both the TDR and NMM measurements and the soil temperature within the soil profile were taken on the same day within one hour of each other to allow comparison of the two methods. The measurements were taken once every month from August 2005 to April 2006. The Topp model (Topp et al., 1980) used to relate the dielectric constant with the volumetric water content is as follows:

$$\theta_v = -5.3\cdot 10^{-2} + 2.92\cdot 10^{-2}\varepsilon_b - 5.5\cdot 10^{-4}\varepsilon_b{}^2 + 4.3\cdot 10^{-6}\varepsilon_b{}^3 \qquad (2)$$

where

θ_v = volumetric water content ($m^3\ m^{-3}$),

ε_b = the composite dielectric constant of the medium corrected for the temperature.

As the soil started to freeze, and throughout the winter, the two methods of soil water content measurements were used simultaneously to track the depth of the freezing front, and the partition of frozen and unfrozen water within the soil profile. Details on the combination of TDR and NMM methods to determine the soil freezing and thawing patterns are given in Kahimba and Sri Ranjan (2007). Soil temperature was measured using a digital thermocouple thermometer with a precision of ±0.1°C at the same depths as the TDR soil water content measurements. Analysis was performed to determine the influence of the crop cover on soil temperature and soil moisture redistribution, as well as the soil freezing-thawing response during the fall through spring seasons for different ground cover conditions.

In year 2005, the maximum daily air temperature at the Carman meteorological station started below zero (-0.2°C) on 14 November, and by 30 November it was -8.7°C (Nadler, 2007). This was an indication that the fall freeze-up started in late November. During the spring, the soil started to thaw between 4 and 9 April 2006 (Nadler, 2007). The 2005-2006 was a wetter season compared to the 15-year average as recorded at the Carman met station. During the growing season from May to August 2005, the total precipitation was 414.2 mm compared to the 15-year average of 354.1 mm in the same period (Environment Canada, 2007; fig. 1). During the fall to spring season from November 2005 to April 2006 the total precipitation (rain and/or snow) was 241.8 mm compared to a 15-year average of 138.7 mm (fig. 1). The snow depth was measured using a meter rule at the end of the winter on 24 February 2006. Three measurements of the snow depth were taken at three difference locations surrounding the neutron access tube within each treatment.

Measurements of the crop performance (above ground biomass) in the cover-crop and non-cover crop treatments were taken during the growing season from May to October 2005. The oats were seeded on 12 May 2005 and harvested on 8 August 2005. The berseem clover in the cover crop treatment was also seeded on 12 May 2005, and continued to grow after the main crop had already been harvested in August 2005 (Nason, 2007). The oats yield measurements were taken at the end of the growing season in August 2005. During the harvest, a strip of 1.0 × 2.0 m (2.0 m^2 area) was harvested close to the centre of the plots and used for the yield measurements. The yield was taken by averaging data from three replicates, each having the same 4-year rotational strategy and receiving the same crop management practice. After harvest of the rest of the main crops, 200 mm of oats stubbles were left along with the berseem clover cover crops. The cover crops continued to grow (table 1) till late November when the fields were covered with snow and the soil started to freeze.

Statistical Analysis

The soil moisture and soil temperature data within the soil profile were compared for different treatments and different times of the year. The general linear model (GLM) procedure of the SAS statistical analysis software (SAS Inc., 1988) was used to determine the variation of total soil moisture in the root zone to a depth of 0.8 m, with a null hypothesis that there was no difference between the crop-covered and the non crop-covered treatments at $\alpha = 0.05$. The Least Significant Difference (LSD) multiple comparisons test with $\alpha = 0.05$ was used to determine the means that had no significant difference at similar depths. The means procedure of the SAS was also used to compare the total and the unfrozen water content, and to determine the differences in the soil temperature along the soil profile as a function of time.

Table 1. Oats biomass and yield for the treatments with and without a berseem clover cover crop in the 2005 growing season at the Ian N. Morrison Research Farm (Carman, Manitoba).

	Above Ground Biomass Yield (kg ha^{-1})				
	Crop Specific Biomass			Total Biomass	
Date	Oats Alone	Oats In Cover Crop	Berseem Clover Cover Crop	Oats Alone	Oats Plus Berseem Clover
26 May	12 a[a]	13 a	0	12	13
17 June	959 a	975 a	77	959	1052
12 July	5949 a	5304 a	66	5949	5370
5 Aug	7327 a	6080 b	66	7327	6146
6 Sept	0	0	241	0	241
30 Sept	0	0	399	0	399
25 Oct	0	0	640	0	640

[a] Means followed by the same letter on each date are not significantly different ($\alpha = 0.05$).

Results and Discussion

Influence of Berseem Clover Cover Crop on the Main Crop Performance and Yield

While cover crops help to reduce excess soil moisture during the growing season, the competition with the main crop in terms of nutrient and water availability at later stages of the growing season may affect the performance and hence, the yield of the main crop. A paired two sample test for means analysis was performed to assess the growth performance of oats on two treatments of oats alone and oats with berseem clover cover at different stages of plant growth. Considering the growth performance for the two management systems (table 1), both treatments had no significant difference in biomass yield at early stages of the growth from May to July 2005 when the cover crop had not yet fully established. However, towards the end of the season on 5 August 2005, the biomass yield in oats alone (7327 kg ha^{-1}) was significantly higher ($\alpha = 0.05$) compared to the combined biomass of oats and berseem clover yield (6146 kg ha^{-1}). The competition for soil moisture between the cover crop and the main crop at the later stages of the plant growth did not give a significant difference ($\alpha = 0.05$) in the oats yield (1844 kg ha^{-1} for oats alone and 1671 kg ha^{-1} for oats with berseem clover). Results on low yields of the main crop due to moisture competition with the cover crops were also obtained by Reddy (2001). Although cover crops could be helpful in reducing the excess soil moisture, the cover crop can lead to soil moisture competition at later stages of plant growth when the precipitation becomes low in August and September (fig. 1). Hence, for farm management systems involving both no-till and a berseem clover cover crop, consideration has to be given on the soil moisture competition between the main crop and the cover crop, which may affect the performance of the main crop if there is less soil moisture available at the later stages in the growing season.

Influence of the Cover Crop within the Growing Season on Soil Moisture Distribution

During the growing season, the cover crop helped to reduce excess soil moisture that could otherwise cause stress to the main crop, especially at the early stages of the plant growth. However, during the later stages of plant growth when both the main crop and the cover crop need a lot of soil moisture, the cover crop may cause a soil moisture deficit to the main crop leading to lower crop yields. During the maturity stage in August 2005, the total volumetric water content within the root zone (0.0- to 0.7-m depth) was 34.6% lower in the cover crop treatment (0.17 m^3 m^{-3}) compared to the oats alone treatment (0.27 m^3 m^{-3}) (table 2). The unfrozen (TDR) water content at each depth from 0.2 to 0.8 m in the oats with berseem clover cover crop treatment was also significantly lower ($\alpha = 0.05$) compared to the water content in the oats alone treatment on 16 August 2005 (table 3).

As the soil began to freeze in late November 2005, the oats alone and oats with berseem clover treatments accumulated soil moisture due to fall snowmelt infiltration from early

Table 2. Reduction of root zone water content in oats with a berseem clover cover crop compared to oats alone during the growing season on 16 August 2005.

Soil Depth (m)	Root Zone Water Content on 16 August 2005[a] Oats Alone[b] (m^3 m^{-3})	Oats + Berseem[b] (m^3 m^{-3})	Reduction[c] (%)
0.10	0.23	0.15	34.8
0.20	0.25	0.17	32.0
0.40	0.31	0.19	38.7
0.60	0.27	0.18	33.3
Total[d]	0.26	0.17	34.6

[a] Water content measurements taken using time domain reflectometry (TDR) method

[b] TDR measurements at each depth on each treatment are averages of three replicates

[c] The percentage reduction is relative to the oats alone as the denominator

[d] Total unfrozen soil water content in the depth from 0.05 m to 0.7 m.

Table 3. Unfrozen (TDR) water content in the 0.0- to 0.8-m soil profile for the four cropping systems from August 2005 to April 2006.

Soil Depth (m)	Management System	Unfrozen Soil Water Content (measured by TDR) (m^3 m^{-3})[a] 16 Aug 2005	07 Sept 2005	11 Oct 2005	24 Nov 2005	21 Dec 2005	30 Jan 2006	29 Mar 2006	04 Apr 2006
0.2	Oats + Berseem clover	0.17 a[b]	0.25 a	0.32 a	0.24 a	0.0 a	0.0 a	0.0 a	0.0 a
	Oats alone	0.25 b	0.26 a	0.31 a	0.19 b	0.0 a	0.0 a	0.0 a	0.0 a
	Continuous fallow	0.31 c	0.30 b	0.33 a	0.25 a	0.0 a	0.0 a	0.0 a	0.0 a
	Native prairie grasses	0.17 a	0.26 a	0.32 a	0.24 a	0.17 b	0.15 b	0.14 b	0.327 b
0.4	Oats + Berseem clover	0.19 a	0.18 a	0.34 a	0.25 a	0.08 b	0.08 b	0.0 a	0.0 a
	Oats alone	0.31 c	0.29 b	0.37 b	0.26 a	0.0 a	0.0 a	0.0 a	0.0 a
	Continuous fallow	0.34 d	0.24 c	0.31 a	0.25 a	0.0 a	0.0 a	0.0 a	0.0 a
	Native prairie grasses	0.24 b	0.23 c	0.37 b	0.29 b	0.22 c	0.28 c	0.29 b	0.36 b
0.6	Oats + Berseem clover	0.18 a	0.33 c	0.32 a	0.27 a	0.09 b	0.14 b	0.1 b	0.12 b
	Oats alone	0.27 b	0.28 b	0.35 ab	0.30 b	0.08 b	0.14 b	0.0 a	0.0 a
	Continuous fallow	0.34 c	0.31 bc	0.38 bc	0.32 b	0.0 a	0.0 a	0.0 a	0.0 a
	Native prairie grasses	0.25 b	0.21 a	0.39 c	0.27 a	0.30 c	0.28 c	0.30 c	0.31 c
0.8	Oats + Berseem clover	0.26 a	0.32 c	0.37 a	0.31 a	0.18 b	0.16 b	0.11 c	0.17 c
	Oats alone	0.29 bc	0.29 b	0.37 a	0.35 b	0.21 c	0.20 c	0.07 b	0.07 b
	Continuous fallow	0.32 c	0.31 bc	0.37 a	0.35 b	0.09 a	0.04 a	0.0 a	0.0 a
	Native prairie grasses	0.28 ab	0.25 a	0.43 b	0.36 b	0.34 d	0.37 d	0.33 d	0.34 d

[a] Data were taken as average of three replicate TDR measurements.

[b] Means followed by a different letter in the same column at the same soil depth are significantly different ($\alpha = 0.05$).

Table 4. Comparison of accumulation of total soil water content in the root zone for oats with a berseem clover cover crop and oats alone from the fall in November 2005 to spring in April 2006.

Date	Soil Depth (m)	Total Water Content Measured by NMM[a] Oats Alone (m^3 m^{-3})	Oats + Berseem (m^3 m^{-3})	Reduction[b] (%)
24 Nov 2005	0.20	0.30	0.25	16.7
	0.40	0.30	0.21	30.0
	0.60	0.31	0.25	19.4
	0.80	0.37	0.31	16.2
	Total[c]	0.32	0.26	18.8
13 Dec 2005	0.20	0.38	0.34	10.5
	0.40	0.26	0.20	23.1
	0.60	0.27	0.19	29.6
	0.80	0.31	0.25	19.4
	Total	0.31	0.25	19.4
21 Dec 2005	0.20	0.39	0.34	12.8
	0.40	0.29	0.22	24.1
	0.60	0.26	0.19	26.9
	0.80	0.29	0.22	24.1
	Total	0.31	0.24	22.6
30 Jan 2006	0.20	0.38	0.34	10.5
	0.40	0.29	0.22	24.1
	0.60	0.24	0.20	16.7
	0.80	0.28	0.22	21.4
	Total	0.30	0.25	16.7
29 Mar 2006	0.20	0.39	0.34	12.8
	0.40	0.40	0.35	12.5
	0.60	0.31	0.26	16.1
	0.80	0.22	0.13	40.9
	Total	0.33	0.27	18.2
04 Apr 2006	0.20	0.39	0.39	0.0
	0.40	0.41	0.40	3.5
	0.60	0.34	0.32	5.1
	0.80	0.32	0.30	5.5
	Total	0.37	0.35	5.4

[a] For each treatment, one measurement value was taken using NMM on each date and at each soil depth.
[b] The percentage reduction is relative to the oats alone as the denominator.
[c] Total soil water content in the depth from 0.1 to 0.9 m.

snowfall (table 4). By 21 December, the average total water content in the top 0.8 m was 0.24 m^3 m^{-3} for the cover crop treatment and 0.31 m^3 m^{-3} for the treatment without a cover crop (table 4). The cover crop treatment had 21% lower total soil water content compared to the non-cover crop treatment. This was largely due to the greater reduction of the soil moisture in the root zone by the remaining cover crop vegetation that continued to grow after the harvest of the main crop and consumed the remaining available soil moisture in the root zone before the fall freeze-up.

Variation of Water Content within the Root Zone from Fall through Spring

The quantity and distribution of soil water content from the summer 2005 through spring 2006 of four cropping systems were compared. In the first treatment, oats were grown with annual berseem clover as the cover crop, while in the second treatment, oats alone were grown. The other two treatments were vegetative extremes of a continuous bare fallow and a native prairie grass treatment that was covered with vegetation throughout the season. In the 2005-2006 seasons, the snow started to accumulate in late November 2005.

During spring of 2006 the maximum daily air temperatures started to be above zero (0.8°C) on 24 March, and the minimum temperature was above zero (0.9°C) on 9 April (Environment Canada, 2007; Nadler, 2007). The spring snowmelt started on 30 March 2006. Towards the end of the winter on 24 February 2005 there was no significant difference in snow depth (α = 0.05) between the oats with berseem clover cover crop treatment (0.31 m) and the oats alone (0.29 m). This was partly because by the beginning of the snow accumulation in late November 2005, the oats stubble remaining in the plots were similar in height (200 mm) to berseem clover. However, the native prairie grass treatment had a significantly deeper layer of snow pack (0.68 m) compared to the fallow treatment (0.21 m). The native prairie grass accumulated more snow pack since it had dense grass stands of about 0.7 m by November 2005 that helped to trap snow throughout the winter. The insulation in the native prairie grass caused the treatment to continue having unfrozen water contents throughout the fall through spring seasons (table 3).

Table 4 presents the total soil water content within the root zone at 0.2-m intervals from 0.2- to 0.8-m depths for two treatments shown as a function of time from the fall (November 2005) through spring (April 2006). The soil water content at each depth in the 0.1- to 0.9-m depth was consistently lower in oats with berseem clover cover crop treatment compared to oats alone during the fall and winter from November 2005 to March 2006 (table 4). This is attributed to more consumption of the soil moisture by both the oats main crop and the berseem clover cover crop during the growing season. During the winter, by March 2006, there was a 18% lower accumulation of total water within the top 0.8 m in the oats with berseem clover cover crop treatment compared to the treatment containing oats alone (table 4). In both treatments, the soil started to freeze in late November 2005, and by January 2006 the top 0.2 m had completely frozen (table 3; fig. 4 b2, b3) limiting any further infiltration from the surface. However, as the winter progressed between January and March 2006 there was an increase in total soil water content in the layers 0.4 to 0.6 m (table 4; fig. 4 a2 and a3). At the end of winter in March 2006, the total water content at 0.8 m-depth was the lowest (table 4; fig. 4 a3), indicating upward migration of water towards the freeze-front from the partly frozen soil layers below (fig. 4). In general, compared to the treatments that had less vegetation (oats only) or did not have vegetation (fallow), the treatments with more vegetation (native prairie grasses and oats with berseem clover) had lower soil water contents during the summer and accumulated less total water content during the winter (tables 3, 4, and 5; fig. 4). The presence of vegetation (such as the residual cover crop) after the summer harvest period, contributed to the reduction of soil moisture for the oats with berseem clover compared to oats alone at each depth in the root zone between the fall (24 Nov 2005) and the following spring (29 March 2006) (table 4). This reduction is expected to lower the soil moisture available at the beginning of the next growing season. Reduced soil moisture at the beginning of the next growing season due to previous cover crop was also observed by Nielsen et al.

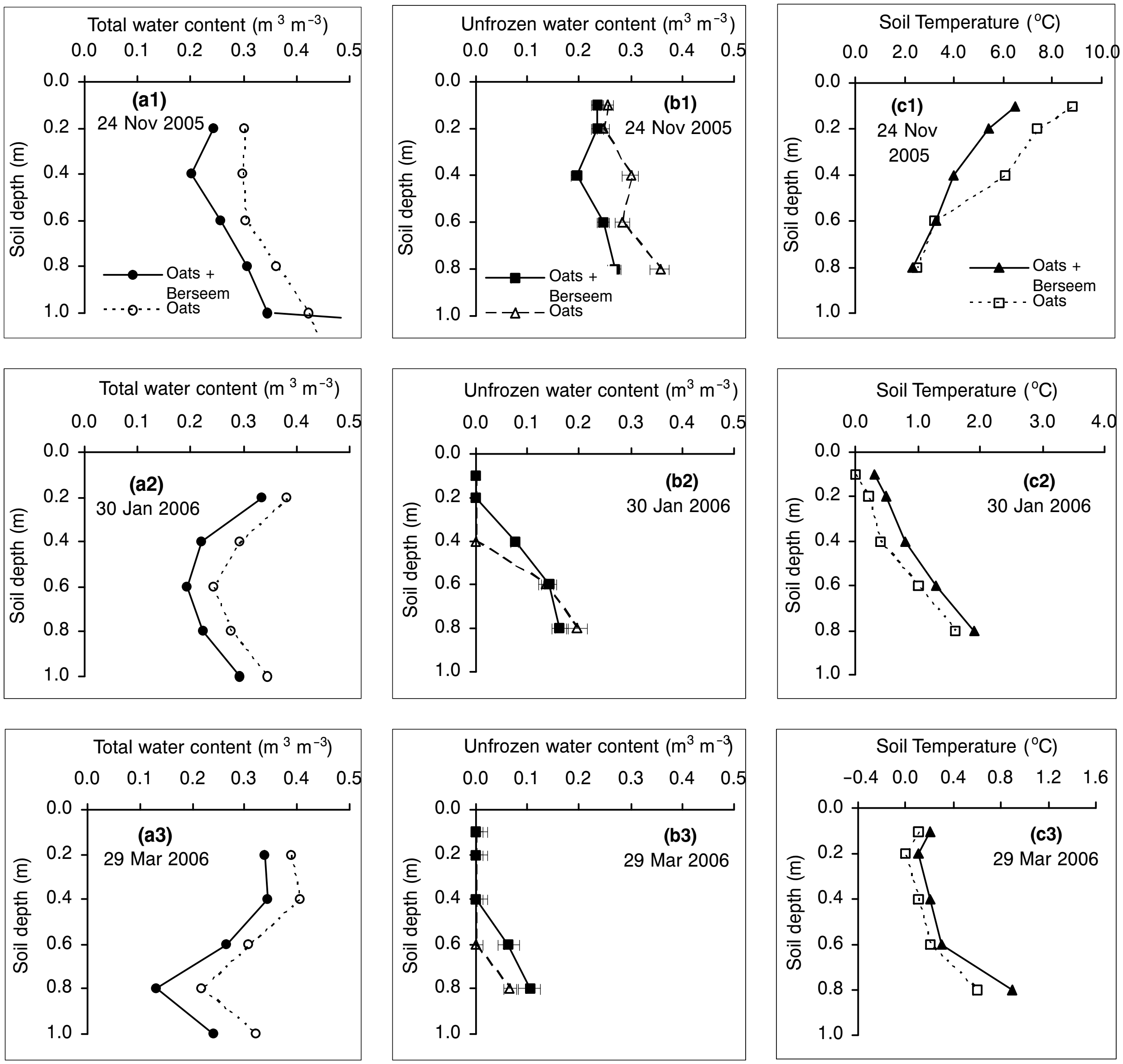

Figure 4. (a) Total water content (measured with NMM), (b) unfrozen water content (measured with TDR), and (c) soil temperature variation for the oats with berseem clover cover crop and oats alone treatments during the fall of 2005 (1), and winter (2) and spring (3, 4) of 2006. Error bars for TDR measurements indicates standard errors of three replicate measurements for each soil depth.

(2002) who studied the influence of a winter wheat cover crop on soil moisture availability.

The total water content, unfrozen water content and soil temperature as a function of depth for the treatments with and without a berseem clover cover crop from the fall 2005 through spring of 2006 are shown in figure 4. Compared to the treatment that had a cover crop, the treatment containing oats alone had consistently higher total soil moisture within the 0.0- to 0.8-m soil depth throughout the fall, winter and spring (fig. 4 a1-a4). However, as the snow started to melt in early April, the top layers of the oats with berseem clover cover crop treatment started to thaw earlier (fig. 4 b4), and allowed snowmelt infiltration into the top layers (0.0 to 0.6 m) causing its total water content to temporarily increase and be approximately equal to the treatment with no cover crop. This was signified by the presence of unfrozen water in the top 0.2 m as measured by TDR, on the treatment with a berseem clover cover crop (fig. 4 b4). The treatment containing oats alone had greater depths of frozen soil layer throughout the winter and early spring as determined by TDR (fig. 4b). Results of lower soil moisture during spring due to the presence of cover crops have also been reported by Sainju and Singh (2001). The presence of the cover crop provided insulation at the ground surface causing a delay in fall freeze-up that led to a shallower depth of the frozen soil layer.

Soil Moisture Partitioning and Determination of the Depth of Freezing Front

A combination of two soil moisture measurement techniques helped to partition the total soil moisture into frozen and unfrozen states and track the depth of the freezing front (fig. 5). The depth to which the TDR measured zero or close to zero unfrozen soil water content was an indication of the depth of the soil profile in which the soil moisture had

Table 5. Comparison of accumulation of total soil water content in the root zone depth for the fallow and native prairie grass treatments from the winter in December 2005 to spring in April 2006.

Date	Soil Depth (m)	Total Water Content Measured by NMM[a]		
		Fallow (m^3 m^{-3})	Prairie Grass (m^3 m^{-3})	Reduction[b] (%)
13 Dec 2005	0.20	0.42	0.29	31.0
	0.40	0.36	0.24	33.0
	0.60	0.27	0.27	0.0
	0.80	0.31	0.33	-6.5
	Total[c]	0.34	0.28	17.6
21 Dec 2005	0.20	0.42	0.28	33.3
	0.40	0.40	0.23	42.5
	0.60	0.26	0.26	0.0
	0.80	0.28	0.33	-17.9
	Total	0.34	0.28	17.6
30 Jan 2006	0.20	0.42	0.26	38.1
	0.40	0.41	0.23	43.9
	0.60	0.26	0.25	3.8
	0.80	0.26	0.32	-23.1
	Total	0.34	0.27	20.6
29 Mar 2006	0.20	0.43	0.25	41.9
	0.40	0.41	0.20	51.2
	0.60	0.41	0.23	43.9
	0.80	0.22	0.31	-40.9
	Total	0.37	0.25	32.4
04 Apr 2006	0.20	0.44	0.43	2.3
	0.40	0.43	0.42	2.3
	0.60	0.42	0.43	-2.4
	0.80	0.23	0.42	-82.6
	Total	0.38	0.43	-13.2

[a] For each treatment, one measurement value was taken using NMM on each date and at each soil depth.
[b] The percentage reduction is relative to the fallow as the denominator.
[c] Total soil water content in the depth from 0.1 to 0.9 m.

completely frozen or partly frozen at temperatures very close to zero. Considering the treatments with and without berseem clover during fall freeze-up, by 21 December 2005 the non-cover crop treatment had frozen to a depth of 0.4 m while the cover crop treatment had frozen only to a depth of 0.2 m (fig. 5). During the spring (04 April 2006), the freezing front had advanced to 0.6- and 0.4-m depths for the non-cover crop treatment and cover crop treatment, respectively (fig. 5). Hence, the presence of a cover crop during the previous season delayed soil freezing during the winter and led to a shallower depth of the frozen soil layer. For both the cover crop and non-cover crop treatments, deeper layers were partly frozen with unfrozen water content increasing with depth and approaching the amount of total water content at 0.8 m-depth. Compared to using one soil moisture measurement technique, the two techniques, TDR and NMM, combined together gave a better indication of how the freezing front was advancing downwards with time as the winter progressed.

Soil Moisture Redistribution during the Winter and Spring

From January 2006 to March 2006, the total soil moisture decreased with time at the 0.6- and 0.8-m depth, and increased with time at the 0.2- and 0.4-m depth (fig. 4 a2 and a3). This data indicates that as the soil continued to freeze and the freezing front advanced downwards, the unfrozen soil moisture from the soil layers below the freezing front migrated upwards towards the freezing front. Partly saturated frozen soils act like dry soil, pulling unfrozen water upwards from the lower layers because the water above the freezing front is already immobilized due to freeze-up. The 29 March was a date just before the start of spring snow melt, while April 4 was a date five days after the start of spring snow melt. The meltdown started on 30 March as explained earlier. Therefore, compared to the soil moisture status when the soil started to freeze in the fall, the soil layers below the freezing front had a net decrease in water content at the end of winter, while the soils above the freezing front had a net increase. As a result, the non-cover crop treatment with higher soil water content during the fall led to greater accumulation of total soil water at the end of the winter season.

Compared to the non-cover crop treatment of oats alone, the cover crop treatment warmed and thawed earlier, with soil profile temperatures being 0.1°C to 0.3°C warmer during the spring (fig. 4 c3 and c4). By 04 April 2006, compared to the non-cover crop treatment, the cover crop treatment had 5.5%, 13.1%, and 10.1% lower total soil water contents at 0.8-, 1.0-, and 1.2-m depths, respectively (fig. 6). The cover crop treatment being drier will require less solar heat to warm up compared to the wetter non-cover crop treatment due to the lower heat capacity of drier soil compared to the wetter soil. The cover crop treatment also had 8.8%, 12.9%, and 11.4% higher total soil water contents at 1.4-, 1.6-, and 1.8-m depths, respectively (fig. 6). This was an indication that the cover crop treatment allowed more infiltration of the melt water into the soil profile and percolation away from the root zone. In their study on winter wheat cover crop, Joyce et al. (2002) also reported increased infiltration on the cover crop plots compared to the continuous fallow.

Based on a precision of 0.2% for the temperature measurement, the non-cover crop treatment had 2.3°C, 2.0°C, and 2.1°C higher soil temperature at 0.1-, 0.2-, and 0.4-m depths of the soil profile during the fall (22 November 2005) compared to the cover crop treatment (fig. 4 c1). By mid-winter (30 January 2006), the non-cover crop treatment had 0.3°C, 0.3°C, and 0.4°C lower soil temperature at 0.1-, 0.2-, and 0.4-m depths compared to the cover crop treatment (fig. 4 c2). However the temperatures had a smaller difference (0.0°C - 0.2°C) for the cover crop and non-cover crop treatments during late winter and spring (fig. 4 c3 and c4). On average, the cover crop treatment was consistently cooler during the fall in November 2005 and warmer during the winter (fig 4c). During the winter and early spring it was warmer by 0.1°C to 0.4°C to a depth of 0.8 m. By 4 April 2006, the soil profile in the drier cover crop treatment was slightly warmer (fig. 4 c4) causing the top 0.2 m to start thawing earlier than in the non-cover crop treatment (fig. 4 b4).

Variation of Total Soil Water Content with Time within the same Treatment

Variations of the total soil water content with time for each individual treatment were also assessed for the depths up to 1.8 m from September 2005 to April 2006 (fig. 6). The native prairie treatment maintained a lower total water content than the fallow within the top 1.0 m of the profile during early spring on 29 March 2006 (table 5; fig. 6a and 6b). This was

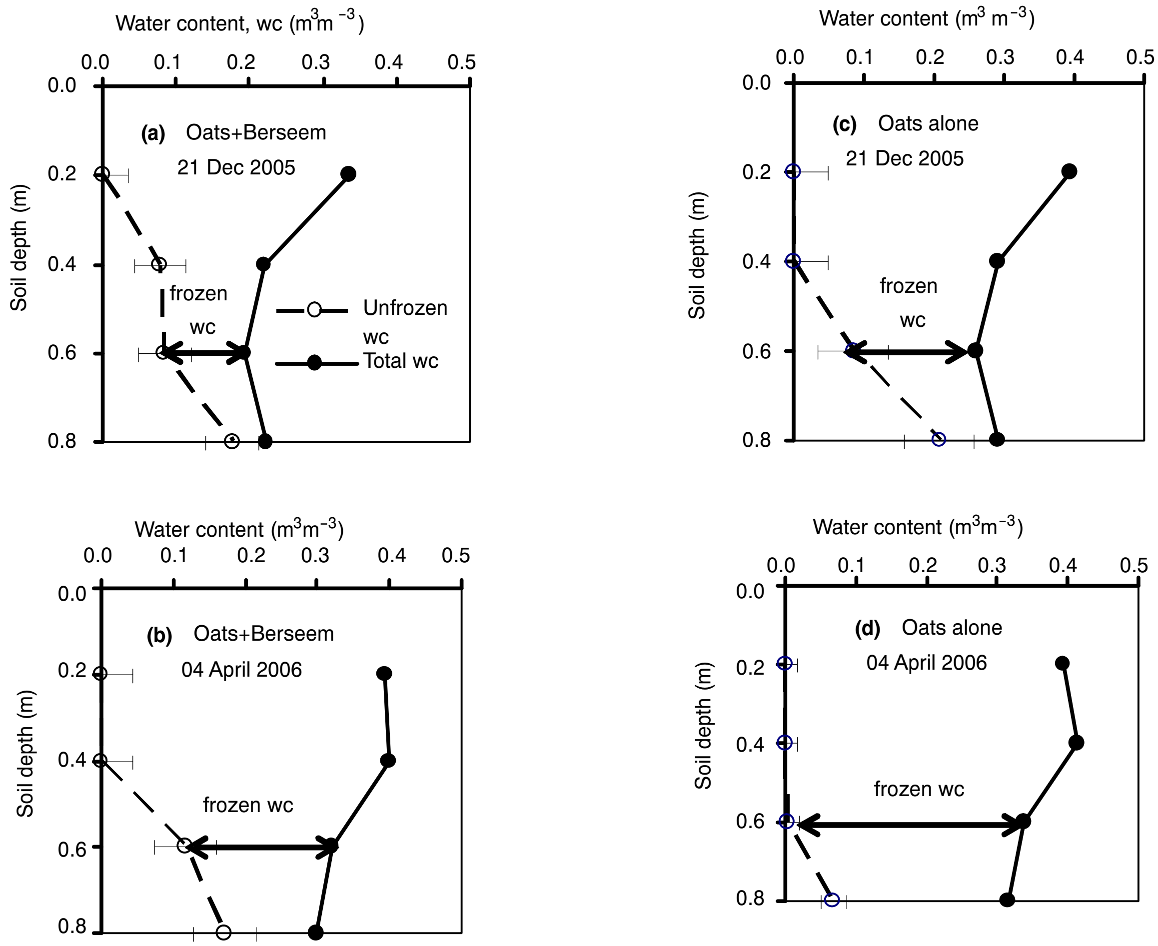

Figure 5. Partitioning of total water content into frozen and unfrozen phases for the oats with berseem clover cover crop and oats alone treatments during fall freeze-up in December 2005 (a and c), and spring in April 2006 (b and d). The difference between the two curves represents the amount of soil moisture in the frozen state. Error bars indicate standard errors of measurement for three TDR replicates.

the time just before the start of spring snow melt. The soil temperatures in the native prairie grass treatment were still above zero by 21 December 2005 even when the temperatures in the fallow had dropped below -3.0°C in the top 0.4-m depth (fig. 7a). The presence of prairie grass residues before the first snowfall (October 2005) helped to trap more snow and insulate the soil, preventing it from early freezing. During spring, the prairie treatment was 1.0°C warmer than the fallow (fig. 7b). The total water content in the 0.1 to 0.9 m increased from 0.25 m^3 m^{-3} on 29 March to 0.43 m^3 m^{-3} on 04 April (72% increase) in the prairie grass treatment after the start of spring snow melt (table 5; fig. 6a). The increased total water content was due to infiltration that was enhanced by the prairie grass residues trapping more snow (fig. 6a). In the continuous fallow, on the other hand, soil moisture in the 0.1- to 0.9-m depth increased by 12% (0.34 to 0.38 m^3 m^{-3}) from the fall on 13 December 2005 to the spring on 29 March 2006 (table 5; fig. 6b). There was 3% change in the soil moisture for the 0.1- to 0.9-m layers during the spring snowmelt (0.37 m^3 m^{-3}on 29 March and 0.38 m^3 m^{-3}on 04 April) (table 5). This was an indication that since the fallow had frozen to a greater depth during the winter, and had lower soil temperatures; thawing was delayed in the top layers, preventing infiltration of the initial spring snowmelt in early April 2006. For the oats with berseem clover, a trend similar to that of the native prairie was also observed during spring (fig. 4) where an increase in the total water content was observed. The presence of vegetation before fall freeze-up helped trap snow and kept the soil warm enough to permit increased snowmelt infiltration in early spring. As the melt water deep percolated to the lower layers, the drier upper layers also warmed up.

The frozen soil layers in the non-cover crop and the fallow treatments held more total water content and prevented deep percolation away from the root zone (fig. 6b and 6d). The frozen soil layers also caused soil moisture to migrate from above and below the freezing layers towards the freezing front causing the root zone to have increasing total soil water content. The layers below the freezing front experienced a decrease in water content due to upward moisture migration as the winter progressed (fig. 6b and 6d). The infiltration and deep percolation that was occurring during the winter within the soil profile of native prairie and the cover crop treatments helped to reduce excess moisture within the root zone during the spring snowmelt infiltration (fig. 6a and 6c).

In summary, the presence of a crop cover or perennial vegetation resulted in relatively warmer soil profile temperatures (fig. 4c), shallower depth of frozen soil layers (fig. 4b), and reduced upward migration of soil moisture from unfrozen or partly frozen soil layers below. Hence, the

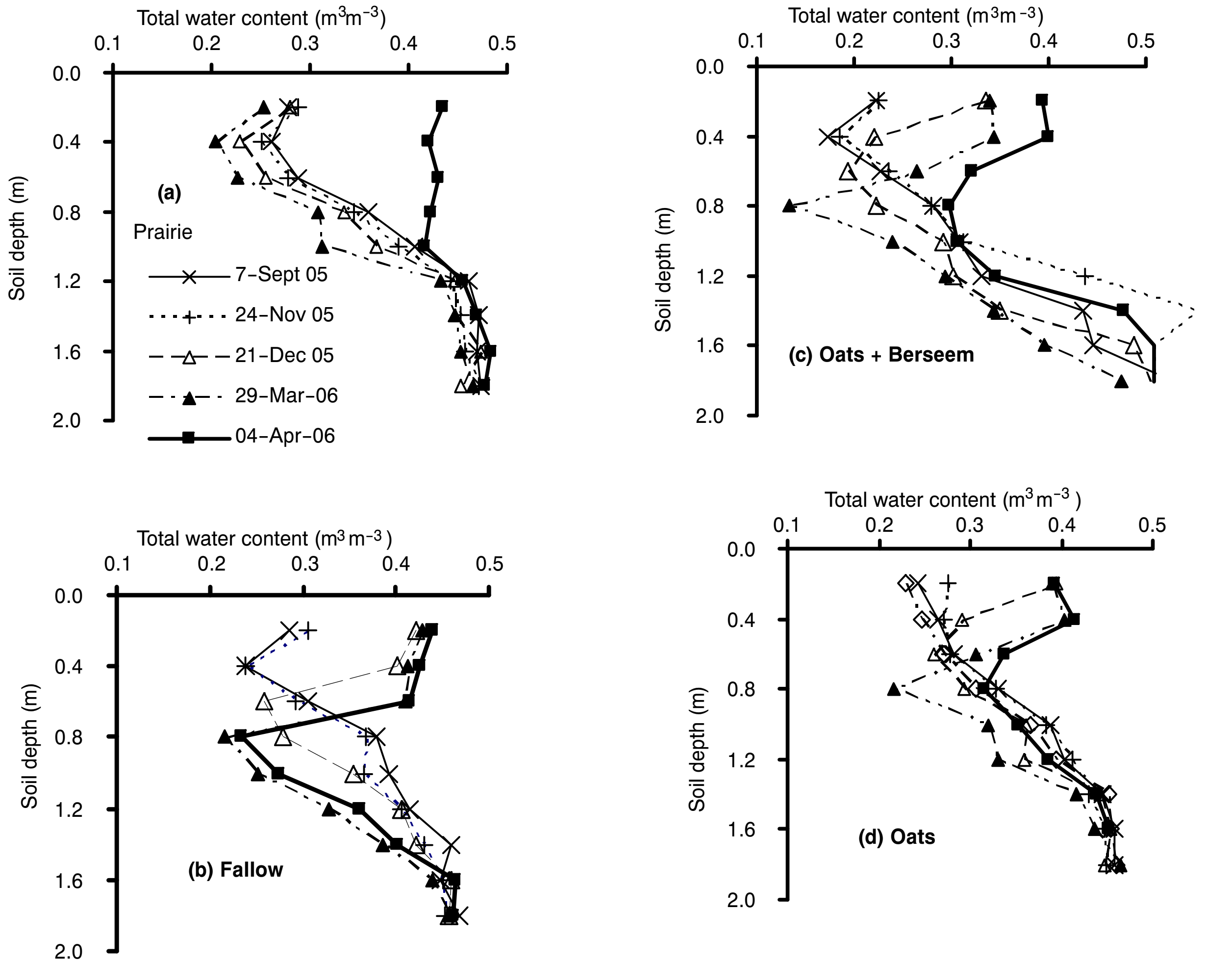

Figure 6. Variation in total water content with depth within each treatment for: (a) native prairie grass (b) continuous fallow (c) oats with berseem clover and (d) oats alone from September 2005 to April 2006. One measurement value was taken for each treatment at each depth on each date using NMM.

reduced upward soil moisture migrations led to low accumulation of water within the root zone later in the winter (fig. 4a). This phenomenon is expected to be of great advantage during spring snow melt as the cover-crop treatments (compared to treatments with no cover crops), will be drier and warm up earlier, thereby allowing early farm operations. These treatments will also experience lesser soil moisture than the non-cover crop treatments at the start of the subsequent growing season. However, in drier seasons the cover crops can have a negative impact on water availability for the main crops due to competition with the cover crop. For wetter seasons like the 2006 covered in this study, the cover crops can therefore be used as a means of reducing excess soil moisture in areas receiving surplus precipitation in the form of both rainfall and snow.

Summary and Conclusions

The movement and redistribution of soil moisture within the soil profile for different cropping systems were evaluated from the end of summer 2005 to the spring of 2006. Soil moisture variations at different depths and different seasons were determined. The influence of a berseem clover annual cover crop in oats on soil moisture availability and crop performance within the growing season, and on infiltration, soil moisture redistribution, and soil freezing and thawing from the fall of 2005 to the spring of 2006 were also explored. Comparisons were also made for the native prairie grass treatment against the fallow treatment. Berseem clover as an annual cover crop contributed to the reduction of excess water during the summer growing season due to increased plant water uptake, as compared to the oats alone (i.e. without a cover crop). The total water content in the root zone (0.0- to 0.7-m depth) by 16 August 2005 was 34.6% lower in the treatment with oats and a cover crop (0.17 $m^3\ m^{-3}$) compared to that of the oats alone treatment (0.26 $m^3\ m^{-3}$).

In 2005, the presence of berseem clover cover crop within the same season did not significantly affect the oats yield (1671 kg ha^{-1} for oats with berseem clover cover crop against 1844 kg ha^{-1} for oats alone). However the presence of the cover crop reduced the soil moisture later in the 2005 growing season, resulting in significantly lower (α = 0.05) biomass yields (6146 kg ha^{-1} the combined biomass of oats and berseem clover, vs. 7327 kg ha^{-1} the biomass yield for oats alone). The farm management systems involving both no-till and a berseem clover cover crop have to consider the soil moisture competition between the main crop and the cover crop, which may affect the performance of the main

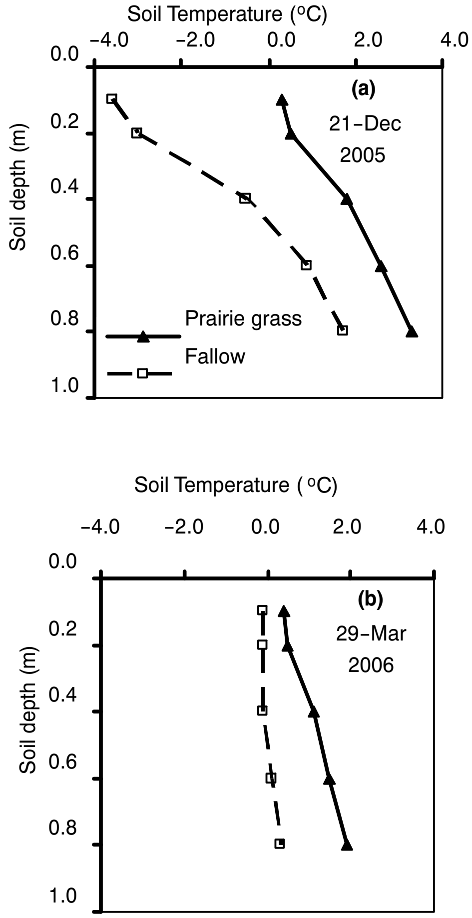

Figure 7. Soil temperature variations with depth for the fallow and native prairie grass treatments during: (a) early winter on 21 December 2005 and (b) early spring on 29 March 2006.

crop if there is less soil moisture available towards the later stages of the growing season.

During the winter, there was an increase in total soil water content for all the treatments in the upper soil layers above the freeze front and a decrease in water content below the freeze front as the winter progressed. Compared to the cover crop treatment, the non-cover crop treatment (oats alone) had consistently higher total water content within the root zone during the winter due to upward soil moisture migration towards the frozen soil layer. By 29 March 2006, the oats with berseem clover cover crop treatment had 18.2% lower total soil water content (0.27 vs. 0.33 $m^3 m^{-3}$ of water) in the 0.1- to 0.9-m soil depth. Soil moisture migrated upwards towards the freezing front. The cover crop treatment, compared to oats alone, had a shallower frozen soil layer (0.4 m against 0.6 m) during the spring. The lower soil moisture in the cover crop treatment enhanced early soil warming during the spring leading to earlier thawing. The relatively drier soils in the cover crop treatment also facilitated more spring snow melt infiltration into deeper layers compared to the non-cover crop treatment, thereby promoting deep percolation away from the root zone. Similar trends were also observed in the comparison of native prairie and the fallow. The native prairie grass had higher above ground standing residue (0.68 m) compared to the fallow (0.21 m), and trapped more snow that insulated the ground during the winter. As a result, the native prairie accumulated lesser total soil water content by due to lack of a frozen soil layer, and had on average 1.0°C warmer profile soil temperatures during the spring.

This study suggests that areas experiencing excess soil water in the form of both rainfall and snow could use an annual cover crop such as berseem clover as a means to reduce excess moisture during the growing season. This cover crop could also be used for enhancing spring snowmelt infiltration, deep percolation, and early warming of the soil by having warmer soils during the winter, shallower depths of frozen soil layers, and less frozen water content within the root zone. This in turn, will allow earlier farm operations.

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