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ARTICLE

Irrigated crop rotation and phosphorus fertilizer-manure addition impacts on soil water repellency of a clay loam soil in southern Alberta

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Abstract: Soil water repellency (SWR) was measured for a 28 yr field study under irrigation on a clay loam Dark Brown soil in southern Alberta. The objectives were to study the effect of legume–cereal crop rotations, feedlot manure, and phosphorus (P) fertilizer application on soil hydrophobicity (SH) and soil water repellency index (RI) under irrigation. Mean SH and RI were similar ($P > 0.05$) for a legume–cereal and cereal rotation and were unaffected by P fertilization. However, P fertilization shifted the RI classification from slight to subcritical. In contrast, SH was significantly greater for manured than nonmanured treatments, while RI was unaffected. Soil organic carbon (SOC) concentration was significantly ($P \leq 0.05$) correlated with SH ($r = 0.74$), but not with RI ($r = -0.17$). This suggested a closer association between the quantity of SOC and quantity of hydrophobic compounds (SH method) compared with the hydrophobic coatings inhibiting infiltration of water (RI method). No significant correlation between SH and RI ($r = -0.09$) suggests that SH is not a good predictor of SWR using the RI method. Overall, manure application increased SH and P fertilization shifted the RI classification from slight to subcritical. In contrast, legume–cereal rotations had no influence on SH and SWR using RI method compared with continuous cereal.

Key words: alfalfa, legume–cereal rotation, cereal rotation, phosphorus fertilizer, manure application, hydrophobicity, soil water repellency.

Résumé : Les auteurs ont mesuré le caractère hydrofuge du sol (CHS) dans le cadre d'une étude de 28 ans sur un loam argileux irrigué de la zone des sols brun foncé, dans le sud de l'Alberta. Le but était de vérifier les effets d'un assolement légumineuses-céréales, du fumier de bovins et de l'application d'un engrais phosphaté (P) sur l'hydrophobicité et l'indice du CHS (RI) d'un sol irrigué. L'hydrophobicité et l'indice RI de l'assolement légumineuses-céréales et de la monoculture de céréales se ressemblaient ($P > 0,05$) et ne sont pas affectés par l'usage de l'engrais P. Cependant, l'engrais a fait passer la classification de l'indice RI de léger à sous-critique. En revanche, l'hydrophobicité était sensiblement plus élevée après l'application de fumier, sans modification de l'indice RI. La concentration de carbone organique dans le sol (COS) présente une corrélation significative ($P \leq 0,05$) avec l'hydrophobicité ($r = 0,74$), mais pas avec l'indice RI ($r = -0,17$). On en déduit que la quantité de COS est plus étroitement associée à la quantité de composés hydrophobes (méthode de l'hydrophobicité) qu'à la présence de revêtements hydrophobes inhibant l'infiltration de l'eau (méthode de l'indice RI). L'absence de corrélation significative entre l'hydrophobicité et l'indice RI ($r = -0,09$) laisse croire que l'hydrophobicité ne permet pas de prévoir correctement le caractère hydrofuge du sol mesuré par la technique de l'indice RI. En général, l'application de fumier accroît l'hydrophobicité tandis que l'usage d'un engrais P fait passer la classification selon l'indice RI de léger à sous-critique. Comparativement à la monoculture des céréales, les assolements légumineuses-céréales n'ont aucune influence sur l'hydrophobicité du sol ni le caractère hydrofuge du sol mesuré d'après l'indice RI. [Traduit par la Rédaction]

Mots-clés : luzerne, assolement légumineuses-céréales, assolement de céréales, engrais phosphaté, application de fumier, hydrophobicité, caractère hydrofuge du sol.

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Introduction

Long-term, legume-based crop rotations, feedlot manure application, and phosphorus (P) fertilizer application to irrigated cropland may increase soil organic carbon (SOC), thereby enhancing soil water repellency (SWR) as reflected by greater soil hydrophobicity (SH) and soil water repellency index (RI). Greater SWR may have positive and negative effects on soil, crops, and the environment (Blanco-Canqui 2011). Slight or subcritical SWR for irrigated cropland may help to alleviate the negative effects on soil physical properties by hydrophobic coatings on soil aggregates protecting soil aggregates from slaking by irrigation water and by protecting SOC from the greater rates of decomposition under irrigation.

Few studies have been conducted on the effect of legume–cereal rotations, feedlot manure application, and P fertilizer application on SWR in the Dark Brown soil zone of Chernozemic soils in western Canada, particularly under irrigated conditions. In southwestern Ontario under dryland, Miller et al. (2020) reported greater SH but similar RI for a 4 yr legume–cereal rotation compared with continuous corn. In a field study with continuous irrigated barley on a Dark Brown soil at Lethbridge, Miller et al. (2017) reported significantly greater water drop penetration times (WDPTs) but similar RI for soils amended with feedlot manure (13–77 $Mg \cdot ha^{-1} \cdot yr^{-1}$ dry wt.) annually for 17 yr compared with unamended and inorganic fertilized treatments. Miller et al. (2021*b*) found significantly greater SH with greater application rates (but no response of RI) in another adjacent study with continuous irrigated barley with feedlot manure applied at increasing rates under dryland (30–120 $Mg \cdot ha^{-1} \cdot yr^{-1}$ wet wt.) and irrigation (60–180 $Mg \cdot ha^{-1} \cdot yr^{-1}$ wet wt.). Long-term fertilization may also increase SOC and soil microbial production of hydrophobic compounds because the greater the crop productivity returns, the more crop residues to the soil (Hallett et al. 2001). However, we are unaware of any studies that have examined the effect of P fertilizer on SWR under irrigation in the Canadian prairies.

The objective of our study was to determine the effects of long-term legume–cereal crop rotations, feedlot manure application, and P fertilizer treatments under irrigation on SWR. We hypothesized that SH and RI might follow: (*i*) legume–cereal > cereal crop rotation; (*ii*) manured > unamended treatments; and (*iii*) P fertilized > nonfertilized treatments.

Materials and Methods

The long-term (since 1910) cropping systems study referred to as "Rotation U" is one of the longest running irrigated rotation experiments in the world (Ellert and Janzen 2008). Originally, the field experiment had been a single 10 yr crop rotation established on 10 plots, with six of every 10 yr under alfalfa (*Medicago sativa* L.). Starting in 1989, the design was a randomized complete block and split-plot design with cropping system on main plots (0.41 ha), fertilizer P-manure on subplots, and three replicates. The study was revised to include three 5 yr cropping systems, each replicated three times on nine of the original main plots. For this work, we used two of the cropping systems: Rotation 1 was similar to the original perennial legume–cereal rotation, with a sequence of alfalfa–alfalfa–alfalfa–wheat–barley (*M. sativa*, *Triticum aestivum* L., and *Hordeum vulgare* L., respectively); and Rotation 2 was an annual cereal rotation with a sequence of silage corn–wheat–silage corn–wheat–barley (*Zea mays* L., *T. aestivum*, and *H. vulgare*, respectively). For the 5 yr rotations, only one phase of each crop sequence was present in any given year since 1989. The perennial legume system relied on biological N fixation, while the annual cereal system received 100 kg fertilizer $N \cdot ha^{-1} \cdot yr^{-1}$. The four fertilizer-manure treatments consisted of 33 kg $P \cdot ha^{-1}$ applied once every 5 yr (P1) or none applied (P0, check); and solid beef cattle (*Bos taurus* L.) manure from an unpaved feedlot applied and incorporated in the fall at 33.5 $Mg \cdot ha^{-1}$ (wet basis) once every 5 yr (M1) or not applied (M0, check). Therefore, the four fertilizer-manure treatments were M0P0, M0P1, M1P0, and M1P1. The fertilizer P was monocalcium phosphate (0-45-0, also known as triple superphosphate) surface broadcast using a drop spreader and incorporated by tillage.

Surface (0–5 cm) soil samples (~2 kg) were collected with a flat spade on 23 October 2017 after 28 yr of the most recently imposed treatments. During the 2017 growing season, all plots were under soft white spring wheat ('AC Andrew'), and the perennial alfalfa had been terminated in October 2016. From each of three replicate plots, soil samples were collected starting at 25 m from one end and at roughly equal distance intervals (45 m) along the plot length (136 m) of each plot and composited for a representative sample. Composite samples were taken from each treatment plot to reduce the effect of high spatial variability on SWR, to obtain a mean SWR for each overall treatment and to obtain a total number of samples that could be analyzed in a reasonable period of time. In the year of sampling, all plots had been uniformly cropped under spring wheat with both grain and residues above cutter-bar height (20–30 cm) removed; in the three years before 2017, crops differed according to the designated crop rotations.

The soils were processed and SOC, total N, C/N ratio, SH, and RI were determined as outlined previously (Miller et al. 2020). Briefly, the SWR was measured on air-dried and sieved (< 2 mm) soil in containers in the laboratory using the RI method (sorptivity of ethanol:water) and Mini Disk Infiltrometer (Decagon Devices, Pullman, WA, USA) with a disk of 4.5 cm diameter and pressure head of −2 cm (Hallett et al. 2001). Scanning electron micrographs of soil material after grinding and <2 mm sieving showed that the majority (80%–90%) of the soil sample was distinct

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Table 1. Influence of 28 yr of crop rotation (RO; main plot) and fertilizer/manure (F/M; split-plot) on soil organic carbon (SOC), total nitrogen (N), soil hydrophobicity (SH), and soil water repellency index (RI).

Treatment[a]	SOC g·kg^{-1}	Total N g·kg^{-1}	SH	RI
Rotation				
Legume–cereal	25.4 ± 1.0a	2.3 ± 0.1a	0.28 ± 0.01a	2.00 ± 0.21a
Cereal	21.4 ± 0.7b	2.0 ± 0.1b	0.23 ± 0.01a	2.45 ± 0.26a
Fertilizer/manure				
P0M0	19.8 ± 0.6c	1.9 ± 0.1c	0.23 ± 0.02b	1.87 ± 0.29a
P0M1	25.7 ± 1.3a	2.4 ± 0.1a	0.27 ± 0.02a	1.89 ± 0.20a
P1M0	22.1 ± 0.8b	2.0 ± 0.1b	0.23 ± 0.01b	2.65 ± 0.42a
P1M1	26.0 ± 1.1a	2.4 ± 0.1a	0.28 ± 0.02a	2.49 ± 0.36a
Estimate[b]	g·kg^{-1}	g·kg^{-1}		
M1 vs M0	4.8***	0.43***	0.05***	−0.07
P1 vs P0	1.3**	0.08*	0.01	0.7
		Prob. > *F*		
RO	0.0007	0.0023	0.1111	0.2581
F/M	<0.0001	<0.0001	0.0014	0.2847
RO × F/M	0.1051	0.3565	0.9531	0.7896

Note: Means ± standard error by column (within crop rotation or manure-fertilizer treatments) not sharing a lowercase letter differ significantly at the $P \le 0.05$ level using a least significant difference test. The asterisks indicate a significant difference between treatments at $P = 0.05$ (*), $P = 0.01$ (**), and $P = 0.001$ (***).

[a]Legume–cereal, alfalfa–alfalfa–alfalfa–wheat–barley; cereal, corn silage–wheat–corn silage–wheat–barley; P0, no phosphorus fertilizer; P1, 48 kg phosphorus·ha^{-1}; M0, no manure; M1, 33.5 kg·ha^{-1}.

[b]Pairwise comparisons between manure and fertilizer treatments were conducted using estimate statements in SAS.

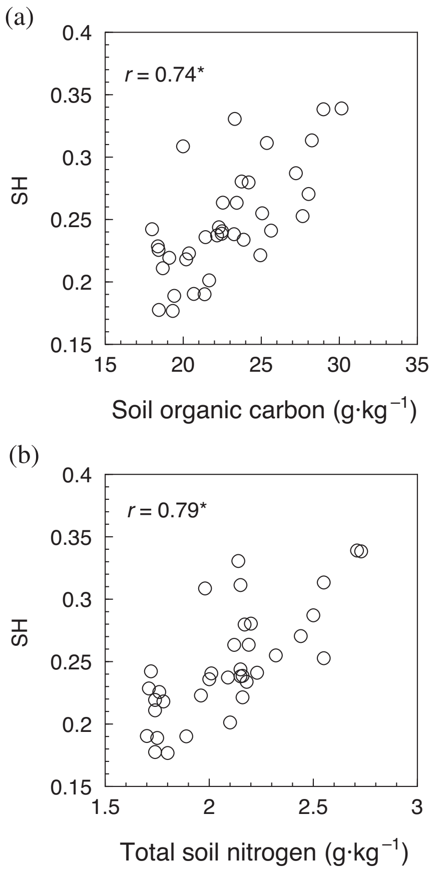
and contained intact soil aggregates about 1 mm in diameter (Miller et al. 2019*a*). The WDPT was determined on air-dried soil by placing three drops of deionized water on the air-dried soil surface and visually recording the time for the water drop to penetrate the soil surface. The WDPTs for all treatments were <1 s and therefore not quantifiable. Since SWR was measured on air-dried (20°C) and not field-moist samples, we measured "potential" rather than "actual" SWR. Dekker and Ritsema (1994) suggested that SWR measurements on oven-dried (60 °C) and field-moist samples were potential and actual SWR, respectively. Fine-ground (<150 μm) soil subsamples were analyzed using Fourier Transform Infrared analysis using a bench-top Bruker 37 instrument (Bruker Optik, Ettlingen, Germany). The Mid-IR spectra were analyzed at two absorption bands: 3020–2800 cm^{-1} bands for the hydrophobic (CH) and 1740–1600 cm^{-1} bands for the hydrophilic (CO) functional groups. The soil hydrophobicity was calculated as the ratio of CH to CO functional groups (Ellerbrock et al. 2005).

A MIXED model analysis (SAS Institute Inc. 2005) was conducted on the dependent variables using a split-plot model. Crop rotation was considered as the main-plot fixed effect, fertilizer/manure treatment as the subplot fixed effect, and replicate as the random effect in the model. Significant differences ($P \le 0.05$) among means were compared using a least significant difference test. The data were first examined using a Proc Univariate procedure to determine if a logarithmic transformation was required. Correlation analysis in SAS was conducted using the CORR procedure and was considered significant at the $P \le 0.05$ level.

Results

The WDPTs <1 s for all treatments indicated no issues with restricted infiltration of free water at zero water potential. Crop rotation and fertilizer manure had a significant ($P \le 0.05$) effect on SOC and total N after 28 yr, and two-way interactions were undetectable (Table 1). Fertilizer/manure treatments significantly affected both SOC and TN. Mean SOC was 19% greater, and total N was 15% greater for the legume–cereal than cereal rotation. Pairwise comparisons showed that SOC was significantly greater for manured (M1) than for nonmanured (M0) treatments when averaged across the two P fertilizer treatments, and for P fertilized (P1) than for nonfertilized (P0) treatments when averaged across the two manured treatments. There was a significant fertilizer/manure treatment effect on SH, where mean values were 17%–22% greater for P0M1 and P1M1 treatments than P0M0 and P1M0 treatments. Mean RI and C/N (data not shown) values were not affected by crop rotation or manure-fertilizer treatments. Mean C/N values were similar for 11.0 (legume–cereal) and

Fig. 1. Correlation between (*a*) soil hydrophobicity (SH) and soil organic carbon (SOC), and (*b*) between SH and total nitrogen.



10.7 (cereal) rotations, and C/N values ranged from 10.4 to 11.1 for the four fertilizer-manure treatments.

There was a positive, significant ($P \leq 0.05$) correlation between SOC and SH (r = 0.74, n = 24) as well as total N and SH (r = 0.79) (Fig. 1). In contrast, there was no significant correlations between SOC and RI (r = −0.17), total N and RI (r = −0.18), SH and RI (r = −0.09), C/N ratio and SH (r = −0.12), and C/N ratio and RI (r = 0.01).

Discussion

Legume–cereal and continuous cereal rotation effects

Mean RI > 1.95 for the two crop rotations suggested subcritical SWR and the presence of hydrophobic coatings. Similar SH and RI for the legume–cereal and cereal rotations did not support our hypothesis that increasing legumes in a crop rotation would enhance SWR. This was despite significantly (19%) greater SOC for legume–cereal than continuous cereal treatments and a significant and positive correlation between SOC and SH. In contrast, there was no correlation between SOC and RI. These results were similar to those comparing perennial grass and annual cropping treatments at Lethbridge (Miller et al. 2021*a*). Similar C/N ratios for the two crop rotations suggested close extents of decomposition, which may have contributed to the indistinguishable SWR. Greater SOC and total N in legume-based crop rotations compared with continuous annual cropping are likely explained by the difference in below-ground plant C inputs between perennial and annual cropping systems. Perennial alfalfa may have also favored reduced decomposition of SOC from reduced tillage under perennials (Kumar et al. 2018).

Our finding that alfalfa in a cereal rotation did not increase SH and RI compared with continuous cereals was consistent with other studies using these two same methods under dryland cropping in southwestern Ontario (Miller et al. 2020) and in Australia (Unkovich et al. 2015). In contrast, McGhie and Posner (1981) reported that greater frequency of legumes in rotation with cereal crop rotations under dryland cropping increased SWR using the WDPT and contact angle methods. The ability of legume-based rotations to enhance SWR under irrigation likely depends on SWR method used, processing of soil, soil type and texture, soil SOC level, irrigation water quality, climatic region, legume species, residue input, tillage, fertilizer, duration of legume in the rotation, and duration of the long-term field experiment. It is also possible that the absence of each phase of the rotations in every year may have been a contributing factor.

Manure and P fertilizer treatment effects

Significantly greater SH for manured than for nonmanured treatments was consistent with our hypothesis that manure application would enhance SWR compared with the unamended control using this method. In contrast, RI was unaffected by manured treatment. Similar C/N ratios among the two manure treatments suggested that extents of decomposition were comparable. Undetectable effects of feedlot manure on RI were consistent with a previous study using feedlot manure in the Dark Brown soil zone of southern Alberta (Miller et al. 2017), suggesting that SH may be a more sensitive indicator of SWR than RI. In contrast, Miller et al. (2017) found significantly greater SWR for manured than for nonmanured soils using the WDPT method, but they applied manure annually at greater rates, whereas it was only applied once every 5 yr in the present study.

Despite significantly greater SOC concentration, SH and RI were similar for P fertilized and nonfertilized treatments and did not support our hypothesis of greater SWR under P fertilization. However, P fertilization shifted the SWR classification from slight (RI = 1.87–1.89) for non-P fertilized to subcritical (RI > 1.95) for P fertilized treatments. Our finding of no P fertilizer effect on RI was generally consistent with studies using N fertilizer under dryland in southern Alberta (Miller et al. 2019) and NPK fertilizer under dryland in southern Ontario for five of six cropping treatments (Miller et al. 2020). In contrast, our finding of no P fertilizer effect on SH was in contrast to other studies that reported significantly greater SH for nitrogen-fertilized than nonfertilized treatments under dryland (Miller et al. 2019*a*, 2020).

Relationships between and among soil properties and SWR variables

The SOC and total N in soil were positively correlated with SH, suggesting that soil hydrophobicity was associated with these two soil properties under irrigation. On a similar soil nearby, Miller et al. (2021*b*) also reported a strong positive correlation between SOC and SH for manured cropland under irrigation. In contrast, no correlation between SOC or total N and RI was found in our study. Miller et al. (2021*b*) reported a significant positive correlation between SOC and RI for manured soils under irrigation on a similar soil. The closer association between SOC and SH than RI is not surprising. The quantity of hydrophobic compounds as indicated by SH generally increases with greater SOC (Capriel 1997; Miller et al. 2019*a*, 2019*b*, 2020, 2021*a*, 2021*b*) and SH generally indicates the quality of SOC (Capriel 1997). In contrast, RI measures SWR by the inhibition effect of hydrophobic coatings on infiltration of water and is useful for determining whether subcritical SWR exists (Smettem et al. 2021). Inconsistent findings have been reported between the quantity of SOC and SWR using conventional methods (Doerr et al. 2000). They proposed that the small amounts of hydrophobic compounds necessary to cause water repellency are not proportional to the actual total amount of organic material present in soil, but rather to the type or organic compounds present. Therefore, inhibition of infiltration by hydrophobic coatings in the RI method may be more related to the type of organic compounds present in the coatings, rather than the total amount of SOC.

No significant correlation between SH and RI suggested that SH may not be a good predictor of SWR using the RI method and was consistent with Miller et al. (2019*a*) for a dryland soil at Lethbridge. In contrast, Miller et al. (2020) reported a significant positive correlation between SH and RI for a dryland soil in southwestern Ontario. Miller et al. (2021*b*) reported a significant negative correlation between SH and RI under dryland and a significant positive correlation under irrigation for manured soils at Lethbridge. Inconsistent findings for SH and RI are likely due to soil type, SOC concentrations, management practices, and other factors. We believe that both SH and RI are useful methods. The SH indicates soil hydrophobicity or the quality of SOC, which is closely associated with SOC concentration, and is generally a more sensitive in detecting management treatment effects. In contrast, RI is not as strongly associated with SOC and is therefore not as sensitive to treatment effects, but it is very useful in classifying whether the soil has slight or subcritical SWR, which SH cannot do.

Conclusions

The long-term (28 yr) study findings suggested that a legume–cereal rotation did not enhance SWR as measured using SH and RI methods. In contrast, feedlot manure application enhanced SH but not RI. Although P fertilizer had no statistical influence on SWR, P fertilizer shifted the SWR classification from slight to subcritical based on RI. Overall, manure application had a greater influence on SWR than legumes in rotation. The SOC concentration was significantly correlated with SH, but not with RI, and there was no correlation between SH and RI. Future irrigated research could study the effect of these treatments on SWR (using various methods) of different soils at other locations, examine the effects of crop phases in the rotation, or examine whether greater frequency of alfalfa phase in the rotation might induce greater SWR.

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