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Subsoil Injection of Concentrated Organic Pellets: A New Technique for Subsoil Compaction Mitigation

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Abstract

Subsoil compaction is a growing environmental concern in mining, forestry, agriculture, and other industrial operations. Heavy traffic and activities such as topsoil removal, admixing, and soil reconstruction result in persistent (and often permanent) subsoil compaction problems. Compaction in the subsoil impedes root growth, aeration, water infiltration, and availability of nutrients. So far there was no technology for mitigation of this problem in a sustainable manner. The main objectives of this research were to develop techniques for mechanical ripping and simultaneous injection of organic pellets, and to quantify the benefits of this technique in terms of improvement in soil quality and productivity.

Introduction

Soil structure is a single most important soil property that determines aeration, rooting depth, water storage, and activity of soil organisms. Subsoil compaction is a growing environmental concern because of increase in use of heavy machineries and various practices that result in soil structural deterioration during construction and reclamation. The problem becomes more serious in clay and Solonetzic soils and when construction and reclamation is practiced while the soil is wet and susceptible to compaction.

Past research shows that subsoil compaction leads to a very persistent and often permanent loss in soil productivity, which is often reflected in yield reductions (Hakansson, 1994). Excessive subsoil compaction impedes root growth and therefore limits the depth of soil explored by roots. It significantly reduces aeration, water infiltration, and availability of nutrients (Unger and Kaspar, 1994). Ishaq et al. (2001) reported a 12–35% reduction in N uptake in wheat and a 23% reduction in sorghum. Decreased crop yields may be a result of lower soil N availability under compacted conditions. Impaired root growth, reduced soil water availability, and change in proportion of macropores have been reported in Motavalli et al., (2003). Subsoil compaction also contributes to increase in rates of denitrification or N_2O production during wet periods (Linn and Doran, 1984; Torbert and Wood, 1992).

Subsoiling is one of the most common methods used to alleviate soil compaction. It disrupts compacted soil profiles and allows roots to proliferate downward to obtain adequate soil moisture (Raper, 2005). It breaks up dense soil layers, improves water infiltration and movement, enhances root growth and development, and increases crop production (DõÂaz-Zorita, 2000). Other studies, however, published data that contradict the benefits stated and stressed a recompaction problem (Larney and Fortune, 1986; Munkholma et al., 2005). The argument by the later group is that mechanically loosened subsoil is prone to recompaction as a recently tilled soil has a substantially lower strength.

Techniques that permanently improve soil physical quality, such as organic matter incorporation can be coupled with subsoiling operations if the benefits, feasibility, and cost justify the practice. Research to date has proven that organic materials reduce the compressibility of a soil by increasing resistance to deformation, elasticity of the soil, and biological activities (Soane, 1990). In addition, application of organic sources of nitrogen will overcome the negative crop growth effects of soil compaction. In general, it improves soil physical, chemical and biological properties in the zone of incorporation and reduces compressibility of a soil by increasing resistance to deformation. The technique can also significantly contribute towards carbon sequestration and air quality.

Paragon Soil and Environmental Consulting Inc. (Paragon) has developed and tested a technique that couples deep subsoiling with organic pellet injection. The technique initiates the following sets of processes that sustainably mitigate subsoil compaction and improve productivity on marginal lands. The subsoiling operation breaks the compacted subsoil layer. The deep injection of organic pellets forces plant roots to penetrate deeper in search of nutrients and moisture. The macropores created by the roots and the organic matter from the root biomass will permanently alleviate the compaction problem.

After rigorous testing of the subsoiling and pellet injection technique through bench scale and greenhouse experiments, Paragon, in collaboration with several research partners have launched field scale trials of the technology in fall of 2008. The main objective of this article is to evaluate the benefits of the subsoiling and pellet injection technique based on field data on soil structure, nutrient status, and crop productivity.

Research Methods

The study sites are located within 180 km radius of the city of Edmonton, AB, Canada. Data from seven sites, W09, K09, TCPL-1, TCPL-2, TCPL-3, TCPL-4 and Field-2 are discussed in this article. The sites W09, K09, and Field-2 are grain farm sites located northeast of Edmonton (53°59' 2" Latitude and 111°54' 41" Longitude) on Black Chernozemic soils with a sandy loam texture. The sites TCPL-1, TCPL-2, and TCPL-3 are pipeline disturbed sites located south of Edmonton (52°32' 3" Latitude and 113°1' 31" Longitude) on Black Chernozemic (TCPL-1, TCPL-2) and Brown Solodized soils (TCPL-3). TCPL-4 is also a pipeline site located southeast of Edmonton (52°26' 36" Latitude and 112°16' 28" Longitude). Soil texture at the TCPL-1, TCPL-2, TCPL-3, and TCPL-4 sites is respectively, Loam, Sandy loam to Loam, Sandy loam, and Clay loam. The texture at the newly established TCPL-6 and TCPL-7 was dominantly Loam; whereas, at TCPL-8 soil it is Sandy Loam.

This article focuses on 2009 growing season results conducted on farmland and pipeline rights of ways with attention to improvements in soil physical and chemical quality as well as crop productivity. Treatments tested were undisturbed control (UC), compacted control (C), subsoiling alone (SS), and subsoiling with pellet injection (SP). Paratill type subsoiler shanks mounted on especially designed and pellet delivery and injector system (Patent Pending) were used for ripping the subsoil layer and simultaneous injection of pellets. A 60 cm spacing of shanks and 30 to 40 cm depth of subsoiling were used in our study.

To alleviate subsoil compaction problems and also meet optimal N requirements, the pellets were applied at 20 Mg ha^{-1}. This rate was based on initial calibration results from the bench scale and green house tests. The pellets were produced by EarthRenew from organic wastes such as manure, municipal biosolids, and green wastes, through a drying process where temperatures reach far higher than what composting or other drying processes could achieve. This 'flash' vaporization instantly breaks down and destroys pathogens, weed seeds, and chemicals including pesticide and herbicide residues. The pellets have an average density of 0.60 Mg m^{-3} and nutrient contents of 1.6, 1.1, and 1.4% of nitrogen, phosphorus, and potassium, respectively, on a dry weight basis. Extractable metals and microbial content are within environmentally acceptable ranges, and meet the category-A compost standard of the Canadian Council of Ministers of the Environment (CCME).

The field data reported in here was collected in the early fall of 2009. These include subsoil bulk density, volumetric water content, composite samples for soil nutrient analysis, crop yield, and soil permeability. Soil chemical analyses (available nutrients, organic carbon, and total nitrogen) were performed for both topsoil and subsoil horizons, whereas soil physical analyses focused on the subsoil layer. All soil chemical analysis was performed at the Boycott laboratory (Boycott Testing Group, Edmonton, AB). The Air-permeameter test was conducted at three new sites that are within 50 km radius from TCPL-1 through TCPL-6 sites. Site average volumetric water content during the permeameter test was 12, 10, and 6%, respectively at TCPL-6, TCPL-7, and TCPL-8 sites.

Results and Discussion

Tables 1 shows bulk density and volumetric water content at the upper subsoil (~30-40 cm depth from the surface) of the studied sites four to five months after subsoiling and pellet injection. The SP treatment has significantly lowered ($P<0.05$) subsoil bulk density at both K09 and W09 sites, and significantly increased ($P<0.05$) volumetric water content at the W09 site Table 1). Relative to the C treatment, the SP has lowered subsoil bulk density by 18% and 11% at the W09 and K09 sites, respectively. The effect of the SS treatment was not apparent at both the K09 and W09 sites where both bulk density and volumetric water content was not different from the C treatment.

Table 1 Subsoil bulk density and volumetric water content of the three treatments at the K09 and W09 sites (five months after subsoiling and pellet injection).

	K09	**W09**
	----------------BD (Mg m^{-3})--------------	
C (n=6)	1.80 (0.08)[†]a[‡]	1.76 (0.07)a
SS (n=6)	1.89 (0.12)a	1.77 (0.08)ab
SP (n=6)	**1.59** (0.15)b	**1.44** (0.16)b
	---------------- θ (cm^3 cm^{-3})-------------	
C (n=4)	0.16	0.15 (0.04)a
SS (n=6)	0.17	0.10 (0.03)a
SP (n=6)	0.16	**0.22** (0.04)b

[†] 95% Confidence interval; [‡] Values in a column followed by the same letter are not significantly different ($\alpha = 0.05$). A one-way ANOVA with Holm-sidak multiple comparisons was used for statistical tests. C = Control; SS = Subsoiling; and SP = Subsoiling + pellets.

Bulk density and volumetric water content data of the TCPL-1, TCPL-2, TCPL-3, and TCPL-4 sites are shown in Tables 2. Significant (at $P<0.05$) effect of the subsoiling and pellet injection treatments were observed in TCPL-1 and TCPL-4 sites. At the TCPL-1 site, the SP treatment showed a significant improvement in subsoil bulk density, whereas SS treatment increased volumetric water content. At the TCPL-4 site, both SP and SS treatments showed a significant improvement in subsoil bulk density; however, none of the treatments significantly affected volumetric water content of the subsoil layer at this site. TCPL-1 and TCPL-4 sites have finer soil textures (Loam and Clay loam, respectively) than TCPL-3. Hence, the observed treatment effect in these sites could be attributed to soil textural differences; more specifically, finer textured soils that are prone to compaction have benefited more from the subsoiling and pellet injection practice.

Table 2 Subsoil bulk density and volumetric water content of the four treatments at the TCPL-1 through TCPL-4 sites (four months after subsoiling and pellet injection).

	TCPL-1	**TCPL-2**	**TCPL-3**	**TCPL-4**
	------------------------------ BD ($\mathrm{Mg\ m^{-3}}$) ---------------------			
C (n=3)	1.66 (0.2)[†]a[‡]	1.45	1.62	1.61 (0.11)a
SS (n=3)	1.64 (0.0)a	1.33	1.70	**1.39** (0.07)b
SP (n=3)	**1.35** (0.1)b	1.20	1.44	**1.37** (0.05)b
UC (n=3)	1.51 (0.1)ab	1.15	1.56	**1.25** (0.03)b
	------------------------------ θ ($\mathrm{cm^3\ cm^{-3}}$) --------------------------			
C (n=3)	0.22 (0.0)a	0.23	0.29	0.30
SS (n=3)	**0.50** (0.0)b	0.26	0.26	0.32
SP (n=3)	0.29 (0.1)ab	0.42	0.26	0.45
UC (n=3)	0.37 (0.2)ab	0.24	0.27	0.24

[†] 95% Confidence interval; [‡] Values in a column followed by the same letter are not significantly different ($\alpha = 0.05$). A one-way ANOVA with Holm-sidak multiple comparisons was used for statistical tests. C = Control; SS = Subsoiling; and SP = Subsoiling + pellets; and UC=undisturbed adjacent land.

Soil bulk density and water content (at sampling) distribution across the subsoiling and pellet injection line is shown in Figure 1. At the injection depth, the distribution of bulk density is such that it is the lowest at the injection points and then increases linearly on the either side. Soil water content, however, did not show any systematic distribution across the injection line (dotted lines in Figure 1). The results are expected as the ripping force of the shank as well as organic matter accumulation was the highest along the injection line and then decreases laterally away from this line. It appears, however, that it is too early to see the benefits in terms of improving soil water storage, which is expected because of a slight loss of stored soil moisture to evapotranspiration during the subsoiling operation. This pattern is expected to change in near future as the furrow is closed and the soil becomes more stable.

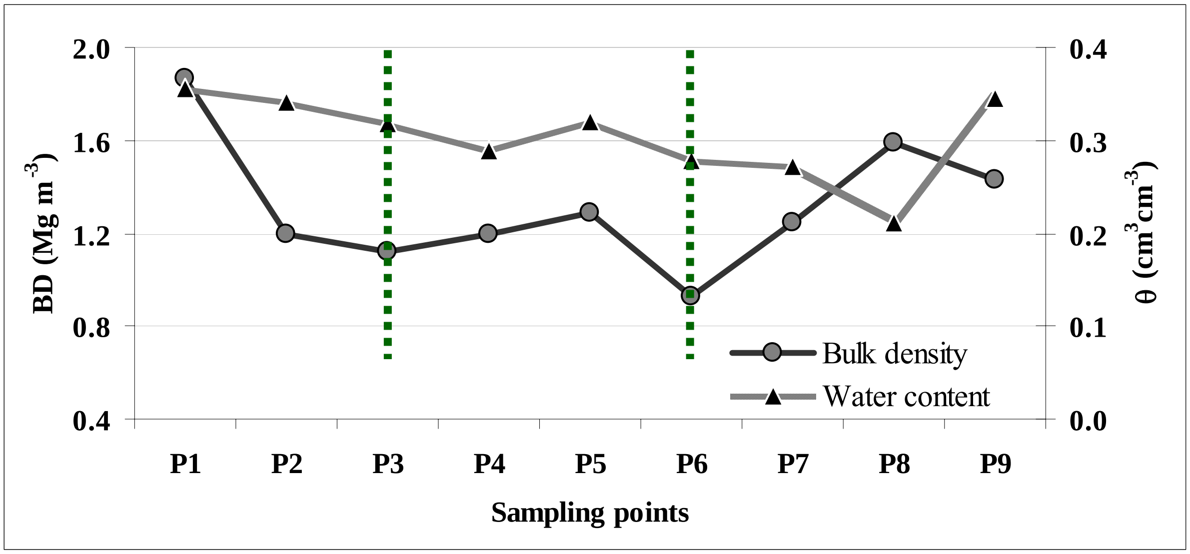

Figure 1 Variation in subsoil bulk density and volumetric water content across the subsoiling and pellet injection lines at the TCPL-4 site. The dotted lines denote pellet injection lines; and '**P1 …P9**' are pointes where samples for bulk density and water content measurement were collected.

Available nutrients (NPK in mg Kg^{-1} of soil), organic carbon and total nitrogen data of W09 and K09 sites are shown in Table 3. At both sites, the treatments did not affect soil nutrient levels in topsoil (except for available K in the K09 site, where SS treatment showed a significantly high available K). The lack of statistically significant treatment effect in the topsoil is to be expected because the treatment, specially the pellet injection targets the deeper (subsoil) layer.

The SP treatment showed a consistently and significantly ($P<0.05$) high nutrient levels in the subsoil horizon of the W09 and K09 sites. Only available K at both sites and available K in the K09 site were not significantly increased by this treatment. The highest increase over the control was observed for available K (390%) in the W09 site, followed by available P (>235%) in the same site. In the W09 site, organic carbon and total nitrogen have increased respectively by 81% and 75%. Similarly, in the K09 site, organic carbon and total nitrogen have increased by 33% and 28%, respectively. Comparing the two farm sites, W09 appears to have benefited more from the treatments because of the initially lower OC and total N contents.

Table 3 Soil nutrient status of the four treatments at the W09 and K09 sites (five months after subsoiling and pellet injection)

	Available N (mg Kg^{-1})	Available P(mg Kg^{-1})	Available K(mg Kg^{-1})	OC (%)	N (%)
W09 Site			Topsoil (0-20 cm)		
C (n=3)	7.3	58.7	279	1.68	0.16
SS (n=3)	3.7	47.7	165	1.31	0.12
SP (n=3)	6.7	52.7	275	1.52	0.14
			Subsoil (20-40 cm)		

C (n=3)	<2.0	28.0a[†]	87a	0.37a	0.04a
SS (n=3)	<2.0	22.3a	106a	0.47a	0.04a
SP (n=3)	<2.0	**94.0**b	**427**b	**0.67**b	**0.07**b
K09 Site			Topsoil (0-20 cm)		
C (n=3)	3.3	23.0	189a	2.54	0.23
SS (n=3)	3.3	30.3	**236**b	2.36	0.22
SP (n=3)	4.7	29.3	175a	2.19	0.21
			Subsoil (20-40 cm)		
C (n=3)	2.3	10.0a	110	1.47a	0.14a
SS (n=3)	2.0	9.3a	124	1.36a	0.13a
SP (n=3)	3.7	**14.3**b	101	**1.96**b	**0.18**b

[†] Values in a column followed by the same letter are not significantly different (α = 0.05). A one-way ANOVA with Holm-sidak multiple comparisons was used for statistical tests. C = Control; SS = Subsoiling; and SP = Subsoiling + pellets.

Available nutrients (N, P, and K in mg Kg^{-1} of soil), organic carbon and total nitrogen data of TCPL sites are shown in Table 4. In the topsoil, the SS and SP treatments did not show any significant effect on both available and total nutrient pools at all TCPL sites. On the other hand, the C treatment, which was sampled mostly from the highly compacted zones (closet to the pipeline centerline), has a slightly higher nutrient content than the SS and SP treatments and the undisturbed adjacent land (Table 4). It appears that organic amendments added in the past to encourage crop growth have masked effects from the treatments. Owing to the high degree of subsoil compaction, this nutrient, however, was not reflected in the vegetation performance or soil productivity.

The SP treatment showed significant ($P<0.05$) effect in the subsoil of TCPL-2 (for organic carbon and total nitrogen) and in TCPL-4 (for all nutrients but nitrate N). The SS treatment also showed significant ($P<0.05$) effect in the subsoil of TCPL-4 for all nutrients levels. Relative to the C, the SP treatment increased OC and total N in the subsoil of TCPL-2 by 39 and 50% and in the subsoil TCPL-4 by 67 and 33%, respectively. Similarly, the SS treatment increased OC and total N in the subsoil of TCPL-4 by 31 and 33%, respectively.

Table 4 Soil nutrient status of the four treatments at the TCPL-1 through TCPL-4 sites (four months after subsoiling and pellet injection)

	Available N (mg Kg^{-1})	Available P(mg Kg^{-1})	Available K(mg Kg^{-1})	OC (%)	N (%)
TCPL-1			Topsoil (0-20 cm)		
C (n=3)	1.9a[†]	11.0	486a	4.6	0.6
SS (n=3)	3.7a	11.3	441a	6.0	0.6
SP (n=3)	2.7a	9.0	**574**b	4.4	0.7
UC (n=3)	**4.7**b	8.3	454a	5.5	0.7
			Subsoil (20-40 cm)		
C (n=3)	2.3	9.3	440	3.4	0.4

SS (n=3)	4.3	9.0	428	2.2	0.3
SP (n=3)	2.9	7.7	506	3.5	0.5
UC (n=3)	3.3	6.0	373	2.5	0.3
TCPL-2			Topsoil (0-20 cm)		
C (n=3)	**5.3**b	6.3	569	**5.3**b	0.6
SS (n=3)	4.7a	5.6	468	3.0a	0.3
SP (n=3)	2.9a	7.7	568	4.2a	0.5
UC (n=3)	2.6a	5.6	440	3.0a	0.4
			Subsoil (20-40 cm)		
C (n=3)	3.6b	7.0	559	3.3a	0.4
SS (n=3)	3.7b	4.9	458	2.1a	0.2
SP (n=3)	**5.7**b	5.9	523	**4.6**b	**0.6**b
UC (n=3)	2.2b	4.8	361	1.7a	0.2
TCPL-3			Top soil (0-20 cm)		
C (n=3)	2.0	8.3	203a	1.90	0.23
SS (n=3)	**4.3**b	8.7	259ab	2.56	0.26
SP (n=3)	2.0	8.3	229ab	1.82	0.20
UC (n=3)	2.0	9.0	326b	2.27	0.26
			Subsoil (20-40 cm)		
C (n=3)	2.3	9.7	204a	1.59	0.20
SS (n=3)	3.0	6.3	228ab	1.50	0.16
SP (n=3)	2.7	7.3	234ab	1.51	0.17
UC (n=3)	2.0	5.7	**275**b	1.28	0.15
TCPL-4			Topsoil (0-20 cm)		
C (n=3)	2.3	27.0	336ab	2.15a	0.18
SS (n=3)	3.7	28.7	**410**b	1.50ab	0.16
SP (n=3)	3.0	24.3	251a	**1.97**b	0.19
UC (n=3)	2.0	13.3	326ab	1.66ab	0.17
			Subsoil (20-40 cm)		
C (n=3)	2.7a	14.7a	269a	0.85a	0.09a
SS (n=3)	**4.0**b	**20.0**b	**460**b	**1.12**b	**0.12**b
SP (n=3)	3.0ab	**19.7**b	**345**b	**1.42**b	**0.12**b
UC (n=3)	2.0a	**21.3**b	**391**b	**1.46**b	**0.15**b

†Values in a column followed by the same letter are not significantly different (α = 0.05). A one-way ANOVA with Holm-sidak multiple comparisons was used for statistical tests. C = Control; SS = Subsoiling; and SP = Subsoiling + pellets; and UC=undisturbed adjacent land.

First season barley yield from three sites planted in spring of 2009 are presented in Figure 2. In the two of the three sites, the SP treatment significantly increased yield over the C. The percentage increase in barley yield was 38 and 84%, respectively in the W09 and Field-2 sites. The SS treatment showed higher yield over the C only in one of the sites (Field-2) and slightly lower than C in W09 site. It should also be noted that the observed increase in yield was achieved only after few months of subsoiling and pellet injection.

These benefits are expected to increase over next seasons as more nutrients become available, and soil structure is improved.

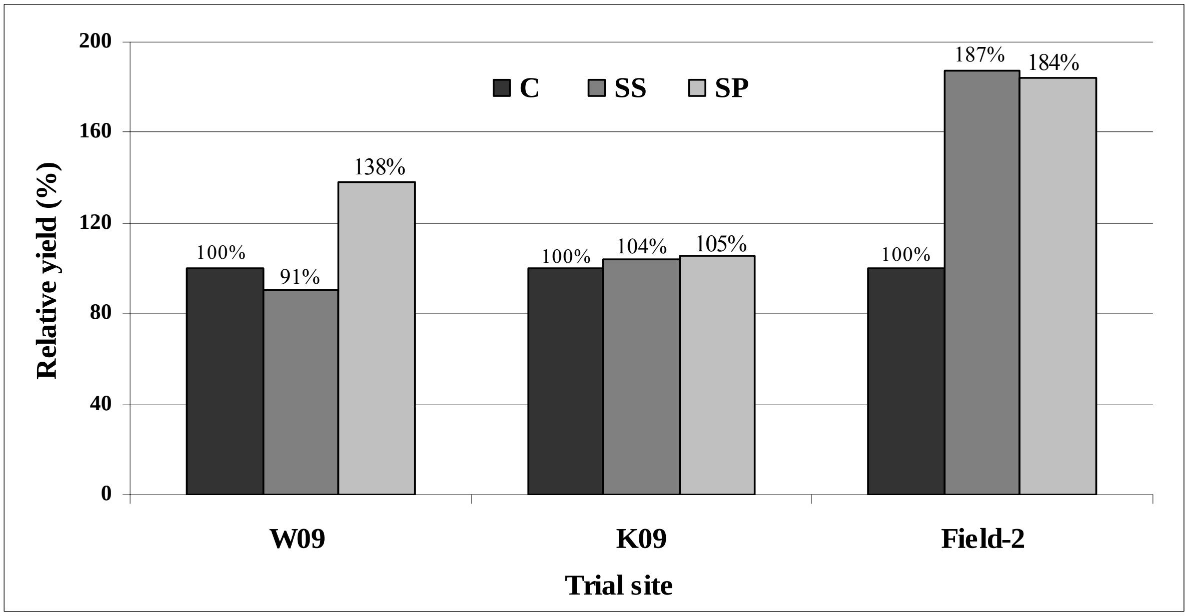

Figure 2 First season barley yield at the W09, K09, and Field-2 sites. Data is presented in percent relative to the C treatment. Values are means of three replicates (n=3). C = Control; SS = Subsoiling; and SP = Subsoiling + pellets.

Soil permeability rate, measured using an air-permeameter method is shown in Figure 3. The SP treatment resulted in higher permeability than the C at all sites, and than the UC treatment at two of the sites studied. Relative to C, SP treatment increased soil permeability rate by 32, 17.7, and 2.5 mm/hr, respectively in TCPL-8, TCPL-6, and TCPL-7 sites. The highest increase in permeability was observed in the site with sandy loam texture.

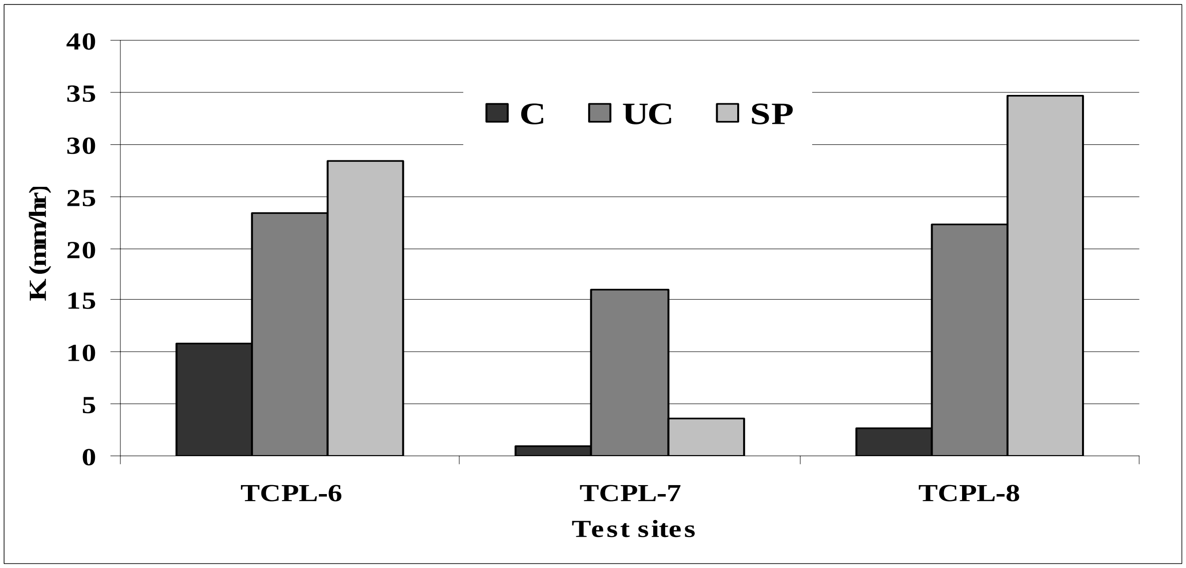

Figure 3 Soil permeability rates measured at three new TCPL sites (within 50 km radius to the TCPL-1 through TCPL-4 sites) using a recently developed Air-permeameter system. Site average volumetric water content during the permeameter test was 12, 10, and 6%, respectively at TCPL-6, TCPL-7, and TCPL-8 sites. Soil texture at the TCPL-6 and TCPL-7 was dominantly Loam; whereas, at TCPL-8 soil texture is Sandy Loam. C = Control; UC=undisturbed adjacent land; SP = Subsoiling + pellet injection.

Summary

A technique has been developed for coupling subsoiling with organic pellet injection (SP) and evaluated against a compacted control (C), subsoiling alone (SS), and undisturbed adjacent land (UC). Replicated tests were conducted in pipeline and agricultural sites to determine the effects of this technique on soil structure (bulk density, water content, and permeability), total and available nutrients, and plant growth. The result shows that after five months of treatment applications, the SP treatment has significantly reduced subsoil bulk density in four sites. Subsoil bulk density and organic matter accumulation was the highest along the subsoiling and injection line and decreases laterally away from this line. Preliminary results (not replicated) also showed that the SP treatment increased soil permeability rates over control treatment.

In the topsoil layer, the subsoiling and pellet injection practice did not affect soil nutrient pool and availability. The data show that nutrient pool and availability distribution in topsoil was slightly affected only by amendments added in the past to encourage crop growth. In the subsoil layer, however, the SP treatment has significantly increased organic carbon and total nitrogen in four of the six sites sampled. Based on the average values for the four sites (two agricultural and two pipeline right-of-ways), SP resulted in more than 46% increase in both organic carbon and total nitrogen content. A consistent and significant increase in plant available nutrients (nitrate-N, available P, and available K) was observed only in one of the six sites studied. The SP treatment also resulted in a significant improvement in barley yield in two of three agricultural sites for which yield data was evaluated. Yield increase as high as 84% was recorded in one of these sites. The SS treatment has also increased yield in one of the three sites.

Close examination of the result also showed that maximum benefit in bulk density (up to 23% reduction) and nutrient content was observed for sites with finer soil texture and lowest initial nutrient content. It is also worth noting that the benefits observed in here will increase considerably in the near future as more nutrients become available and plant roots develop both laterally and vertically into the subsoil.

Acknowledgement

Sustainable Development Technology Canada, Prairie Agricultural Machinery Institute Saskatchewan; EarthRenew Corporation; University of Saskatchewan; Canadian Natural Resources Ltd.; and TransCanada Pipelines Ltd..

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