

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

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1 **Abstract**

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

11  
12 **Introduction**

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

19  
20 Past research shows that subsoil compaction leads to a very persistent and often  
21 permanent loss in soil productivity, which is often reflected in yield reductions  
22 (Hakansson, 1994). Excessive subsoil compaction impedes root growth and therefore  
23 limits the depth of soil explored by roots. It significantly reduces aeration, water  
24 infiltration, and availability of nutrients (Unger and Kaspar, 1994). Ishaq et al. (2001)  
25 reported a 12–35% reduction in N uptake in wheat and a 23% reduction in sorghum.  
26 Decreased crop yields may be a result of lower soil N availability under compacted  
27 conditions. Impaired root growth, reduced soil water availability, and change in  
28 proportion of macropores have been reported in Motavalli et al., (2003). Subsoil  
29 compaction also contributes to increase in rates of denitrification or N<sub>2</sub>O production  
30 during wet periods (Linn and Doran, 1984; Torbert and Wood, 1992).

31  
32 Subsoiling is one of the most common methods used to alleviate soil compaction. It  
33 disrupts compacted soil profiles and allows roots to proliferate downward to obtain  
34 adequate soil moisture (Raper, 2005). It breaks up dense soil layers, improves water  
35 infiltration and movement, enhances root growth and development, and increases crop  
36 production (Dóñez-Zorita, 2000). Other studies, however, published data that contradict  
37 the benefits stated and stressed a recompaction problem (Larney and Fortune, 1986;  
38 Munkholma et al., 2005). The argument by the later group is that mechanically loosened  
39 subsoil is prone to recompaction as a recently tilled soil has a substantially lower  
40 strength.

41  
42 Techniques that permanently improve soil physical quality, such as organic matter  
43 incorporation can be coupled with subsoiling operations if the benefits, feasibility, and  
44 cost justify the practice. Research to date has proven that organic materials reduce the  
45 compressibility of a soil by increasing resistance to deformation, elasticity of the soil, and  
46 biological activities (Soane, 1990). In addition, application of organic sources of nitrogen

47 will overcome the negative crop growth effects of soil compaction. In general, it  
48 improves soil physical, chemical and biological properties in the zone of incorporation  
49 and reduces compressibility of a soil by increasing resistance to deformation. The  
50 technique can also significantly contribute towards carbon sequestration and air quality.

51  
52 Paragon Soil and Environmental Consulting Inc. (Paragon) has developed and tested a  
53 technique that couples deep subsoiling with organic pellet injection. The technique  
54 initiates the following sets of processes that sustainably mitigate subsoil compaction and  
55 improve productivity on marginal lands. The subsoiling operation breaks the compacted  
56 subsoil layer. The deep injection of organic pellets forces plant roots to penetrate deeper  
57 in search of nutrients and moisture. The macropores created by the roots and the organic  
58 matter from the root biomass will permanently alleviate the compaction problem.

59  
60 After rigorous testing of the subsoiling and pellet injection technique through bench scale  
61 and greenhouse experiments, Paragon, in collaboration with several research partners  
62 have launched field scale trials of the technology in fall of 2008. The main objective of  
63 this article is to evaluate the benefits of the subsoiling and pellet injection technique  
64 based on field data on soil structure, nutrient status, and crop productivity.

## 65 66 **Research Methods**

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

79  
80 This article focuses on 2009 growing season results conducted on farmland and pipeline  
81 rights of ways with attention to improvements in soil physical and chemical quality as  
82 well as crop productivity. Treatments tested were undisturbed control (UC), compacted  
83 control (C), subsoiling alone (SS), and subsoiling with pellet injection (SP). Paratill type  
84 subsoiler shanks mounted on especially designed and pellet delivery and injector system  
85 (Patent Pending) were used for ripping the subsoil layer and simultaneous injection of  
86 pellets. A 60 cm spacing of shanks and 30 to 40 cm depth of subsoiling were used in our  
87 study.

88  
89 To alleviate subsoil compaction problems and also meet optimal N requirements, the  
90 pellets were applied at 20 Mg ha<sup>-1</sup>. This rate was based on initial calibration results from  
91 the bench scale and green house tests. The pellets were produced by EarthRenew from  
92 organic wastes such as manure, municipal biosolids, and green wastes, through a drying

93 process where temperatures reach far higher than what composting or other drying  
 94 processes could achieve. This ‘flash’ vaporization instantly breaks down and destroys  
 95 pathogens, weed seeds, and chemicals including pesticide and herbicide residues. The  
 96 pellets have an average density of 0.60 Mg m<sup>-3</sup> and nutrient contents of 1.6, 1.1, and 1.4%  
 97 of nitrogen, phosphorus, and potassium, respectively, on a dry weight basis. Extractable  
 98 metals and microbial content are within environmentally acceptable ranges, and meet the  
 99 category-A compost standard of the Canadian Council of Ministers of the Environment  
 100 (CCME).

101  
 102 The field data reported in here was collected in the early fall of 2009. These include  
 103 subsoil bulk density, volumetric water content, composite samples for soil nutrient  
 104 analysis, crop yield, and soil permeability. Soil chemical analyses (available nutrients,  
 105 organic carbon, and total nitrogen) were performed for both topsoil and subsoil horizons,  
 106 whereas soil physical analyses focused on the subsoil layer. All soil chemical analysis  
 107 was performed at the Boycott laboratory (Boycott Testing Group, Edmonton, AB). The  
 108 Air-permeameter test was conducted at three new sites that are within 50 km radius from  
 109 TCPL-1 through TCPL-6 sites. Site average volumetric water content during the  
 110 permeameter test was 12, 10, and 6%, respectively at TCPL-6, TCPL-7, and TCPL-8  
 111 sites.

112  
 113 **Results and Discussion**  
 114 Tables 1 shows bulk density and volumetric water content at the upper subsoil (~30-40  
 115 cm depth from the surface) of the studied sites four to five months after subsoiling and  
 116 pellet injection. The SP treatment has significantly lowered (P<0.05) subsoil bulk density  
 117 at both K09 and W09 sites, and significantly increased (P<0.05) volumetric water content  
 118 at the W09 site Table 1). Relative to the C treatment, the SP has lowered subsoil bulk  
 119 density by 18% and 11% at the W09 and K09 sites, respectively. The effect of the SS  
 120 treatment was not apparent at both the K09 and W09 sites where both bulk density and  
 121 volumetric water content was not different from the C treatment.

122  
 123 **Table 1** Subsoil bulk density and volumetric water content of the three treatments at the  
 124 K09 and W09 sites (five months after subsoiling and pellet injection).

	<b>K09</b>	<b>W09</b>
-----BD (Mg m <sup>-3</sup> )-----		
<b>C</b> (n=6)	1.80 (0.08) <sup>†</sup> a <sup>‡</sup>	1.76 (0.07)a
<b>SS</b> (n=6)	1.89 (0.12)a	1.77 (0.08)ab
<b>SP</b> (n=6)	<b>1.59</b> (0.15)b	<b>1.44</b> (0.16)b
-----θ (cm <sup>3</sup> cm <sup>-3</sup> )-----		
<b>C</b> (n=4)	0.16	0.15 (0.04)a
<b>SS</b> (n=6)	0.17	0.10 (0.03)a
<b>SP</b> (n=6)	0.16	<b>0.22</b> (0.04)b

125 <sup>†</sup>95% Confidence interval; <sup>‡</sup>Values in a column followed by the same letter are not  
 126 significantly different (α = 0.05). A one-way ANOVA with Holm-sidak multiple comparisons  
 127 was used for statistical tests. C = Control; SS = Subsoiling; and SP = Subsoiling + pellets.  
 128

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

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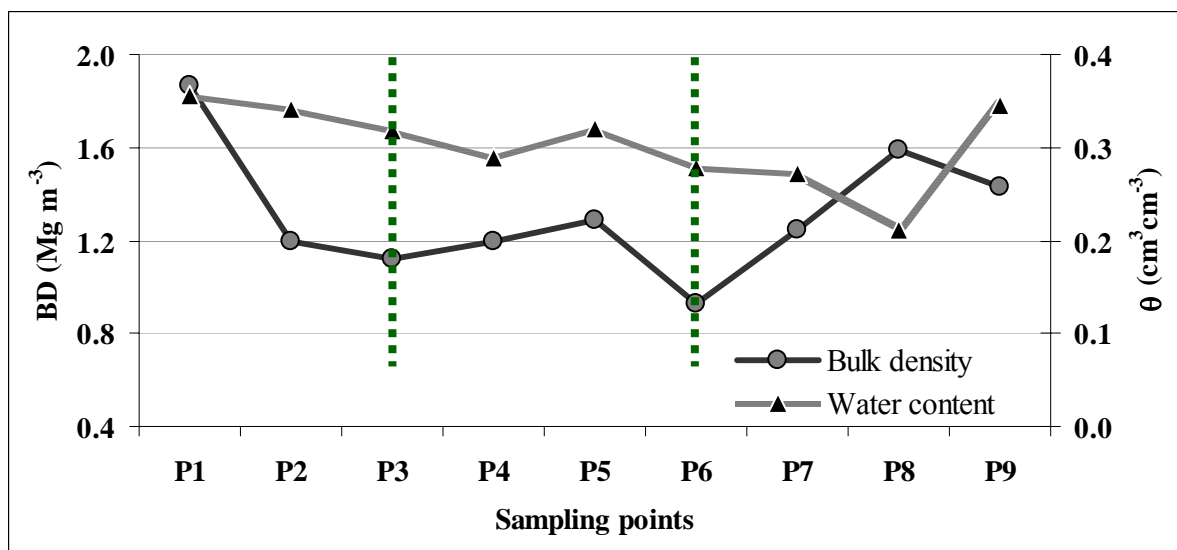
**Table 2** Subsoil bulk density and volumetric water content of the four treatments at the TCPL-1 through TCPL-4 sites (four months after subsoiling and pellet injection).

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

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

147

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

Available nutrients (NPK in mg Kg<sup>-1</sup> 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 <sup>-1</sup> )	Available P (mg Kg <sup>-1</sup> )	Available K (mg Kg <sup>-1</sup> )	OC (%)	N (%)
<b>W09 Site</b>					
Topsoil (0-20 cm)					
<b>C</b> (n=3)	7.3	58.7	279	1.68	0.16
<b>SS</b> (n=3)	3.7	47.7	165	1.31	0.12
<b>SP</b> (n=3)	6.7	52.7	275	1.52	0.14
Subsoil (20-40 cm)					

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

184 <sup>†</sup>Values in a column followed by the same letter are not significantly different ( $\alpha = 0.05$ ).  
 185 A one-way ANOVA with Holm-sidak multiple comparisons was used for statistical tests. C =  
 186 Control; SS = Subsoiling; and SP = Subsoiling + pellets.

187  
 188 Available nutrients (N, P, and K in mg Kg<sup>-1</sup> of soil), organic carbon and total nitrogen  
 189 data of TCPL sites are shown in Table 4. In the topsoil, the SS and SP treatments did not  
 190 show any significant effect on both available and total nutrient pools at all TCPL sites.  
 191 On the other hand, the C treatment, which was sampled mostly from the highly  
 192 compacted zones (closet to the pipeline centerline), has a slightly higher nutrient content  
 193 than the SS and SP treatments and the undisturbed adjacent land (Table 4). It appears that  
 194 organic amendments added in the past to encourage crop growth have masked effects  
 195 from the treatments. Owing to the high degree of subsoil compaction, this nutrient,  
 196 however, was not reflected in the vegetation performance or soil productivity.

197  
 198 The SP treatment showed significant (P<0.05) effect in the subsoil of TCPL-2 (for  
 199 organic carbon and total nitrogen) and in TCPL-4 (for all nutrients but nitrate N). The SS  
 200 treatment also showed significant (P<0.05) effect in the subsoil of TCPL-4 for all  
 201 nutrients levels. Relative to the C, the SP treatment increased OC and total N in the  
 202 subsoil of TCPL-2 by 39 and 50% and in the subsoil TCPL-4 by 67 and 33%,  
 203 respectively. Similarly, the SS treatment increased OC and total N in the subsoil of  
 204 TCPL-4 by 31 and 33%, respectively.

205  
 206 **Table 4** Soil nutrient status of the four treatments at the TCPL-1 through TCPL-4 sites  
 207 (four months after subsoiling and pellet injection)  
 208

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

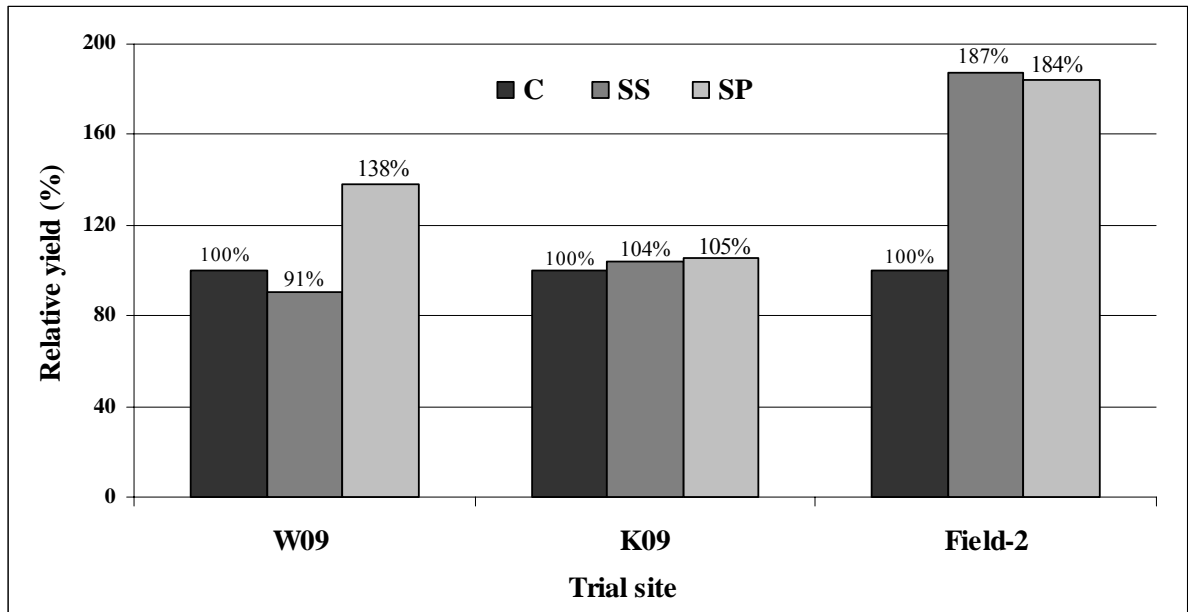
<b>SS</b> (n=3)	4.3	9.0	428	2.2	0.3
<b>SP</b> (n=3)	2.9	7.7	506	3.5	0.5
<b>UC</b> (n=3)	3.3	6.0	373	2.5	0.3
<hr/>					
<b>TCPL-2</b>			Topsoil (0-20 cm)		
<b>C</b> (n=3)	<b>5.3b</b>	6.3	569	<b>5.3b</b>	0.6
<b>SS</b> (n=3)	4.7a	5.6	468	3.0a	0.3
<b>SP</b> (n=3)	2.9a	7.7	568	4.2a	0.5
<b>UC</b> (n=3)	2.6a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

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

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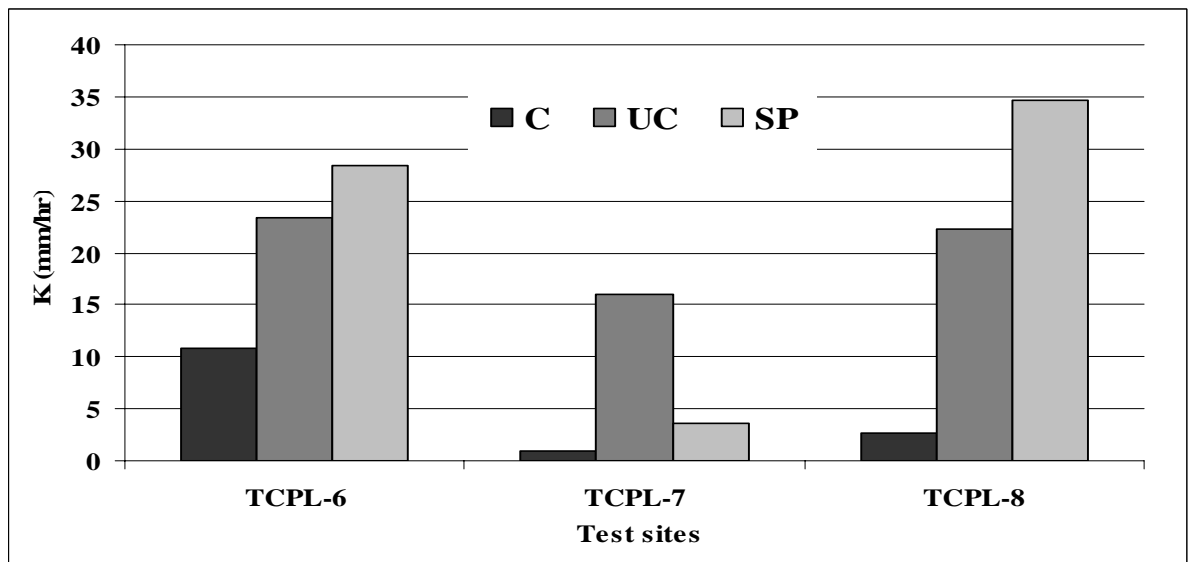
214 First season barley yield from three sites planted in spring of 2009 are presented in Figure  
215 2. In the two of the three sites, the SP treatment significantly increased yield over the C.  
216 The percentage increase in barley yield was 38 and 84%, respectively in the W09 and  
217 Field-2 sites.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

220 These benefits are expected to increase over next seasons as more nutrients become  
 221 available, and soil structure is improved.  
 222



223  
 224 **Figure 2** First season barley yield at the W09, K09, and Field-2 sites. Data is presented in  
 225 percent relative to the C treatment. Values are means of three replicates (n=3). C =  
 226 Control; SS = Subsoiling; and SP = Subsoiling + pellets.  
 227

228 Soil permeability rate, measured using an air-permeameter method is shown in Figure 3.  
 229 The SP treatment resulted in higher permeability than the C at all sites, and than the UC  
 230 treatment at two of the sites studied. Relative to C, SP treatment increased soil  
 231 permeability rate by 32, 17.7, and 2.5 mm/hr, respectively in TCPL-8, TCPL-6, and  
 232 TCPL-7 sites. The highest increase in permeability was observed in the site with sandy  
 233 loam texture.  
 234



235

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

242

### 243 **Summary**

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

254

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

267

268 Close examination of the result also showed that maximum benefit in bulk density (up to  
269 23% reduction) and nutrient content was observed for sites with finer soil texture and  
270 lowest initial nutrient content. It is also worth noting that the benefits observed in here  
271 will increase considerably in the near future as more nutrients become available and plant  
272 roots develop both laterally and vertically into the subsoil.

273

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278

279 **References**

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