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Subsoiling and surface tillage effects on soil  
physical properties and forage oat stand and yield

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**Aims and Scope.** This journal is concerned with the changes in the physical, chemical and biological parameters of the soil environment brought about by soil tillage and field traffic, their effects on both below and above ground environmental quality, crop establishment, root development and plant growth, and the interactions between these various effects.

This implies research on: characterization or modeling of tillage and field traffic effects on the soil environment; the selection, adaptation or development of tillage systems (including reduced cultivation and direct drilling) suitable for specific conditions of soil, climate, topography, irrigation and drainage, crops and crop rotations, intensities of fertilization, degree of mechanization, etc. and the appropriate use of tillage systems to maintain a balance between acceptable crop production, sustainability and minimum environmental impacts. In this context, papers on the characterization or modeling of tillage effects on: soil physical, chemical and biological properties, processes related to surface and subsurface ground-water quality, soil erosion, carbon and nutrient cycling and crop production, are most welcome. Papers on soil deformation processes, soil-working tools and traction devices, energy requirements and economic aspects of tillage are also considered. Attention will also be given to the role of tillage in weed, pest and disease control.

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# Subsoiling and surface tillage effects on soil physical properties and forage oat stand and yield

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## Abstract

Much of New Zealand's agriculture integrates animal and crop production on poorly drained, easily compacted soils. We hypothesized that soil properties affecting forage oat (*Avena sativa*, cv *Awapuni*) establishment on land compacted by 15 years of conventional cropping might be influenced by various subsoiling and surface tillage combinations. Plots on a Moutoa silty clay (Typic Haplaquoll) were paraplowed (P), deep subsoiled (V), shallow subsoiled (S), or were left as non-subsoiled controls (C). Subsequently, the surface 15 cm was surface-tilled (T) using a power rotary-tiller and firmed with a Cambridge roller or were not tilled (N). Oats were then sown with a cross-slot drill. Subsoiling greatly reduced soil strength. Cone indices showed disruption to 40 cm with P, 36 cm for V, and 30 cm for S. Approximately 60% of profile cone indices to a depth of 0.5 m from subsoiled treatments were less than 1.5 MPa, compared to approximately 30% for C. T slightly improved strength distribution in non-subsoiled controls but had little effect in subsoiled treatments. Subsoiling without T continued to show improved profile cone index cumulative frequency 233 days after subsoiling. Subsoiling after T in this high rainfall climate eliminated most of the separation in cumulative frequency of soil profile cone index values by two weeks after T. T reduced emergence from 142 to 113 plants per square meter and reduced yield from 5318 to 3679 kg ha<sup>-1</sup>. Forage yield increased from 3974 to 4674 kg ha<sup>-1</sup> with subsoiling. Soil porosity, saturated and slightly unsaturated hydraulic conductivities ( $K_{SAT}$  and  $K_{-40}$ ) and air permeability were highly variable but generally increased with subsoiling. Oxygen diffusion rate (ODR) (using Pt microelectrodes) was also variable, but N and C treatments had consistently lower ODRs than T or subsoiled treatments. Generally, subsoiling without T produced better soil

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conditions and oat crop performance than the prevailing New Zealand practice of T without subsoiling.

**Keywords:** No-till; Conservation tillage; Paraplow; Bulk density; Cone index; ODR; Soil aeration

## 1. Introduction

New Zealand's North Island supports intensive, integrated animal-crop agricultural systems. On alluvial, loessial, and humic soils, these systems often involve rotations that include three-five years of improved pasture. The cropping phase, which typically lasts 5-6 years, comprises spring-sown crops such as wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) or maize (*Zea mays*) and often an autumn-sown forage crop (e.g. oats or various brassicas).

Spring field cultivation for cereals often involves conventional tillage (plowing and/or heavy disking). Wet springs and autumns on New Zealand's typically imperfectly to poorly drained soils, often impair field operations, and lead to compaction and aeration problems. In some soils, reducing conditions can be severe enough to result in partial gleying and some mottling to within a centimeter of the surface. Subsoiling offers a potential management practice to combat these problems.

## 2. Relevant New Zealand subsoiling findings

There is growing acceptance of conservation tillage among New Zealand farmers, but questions remain as to its role in ameliorating degraded land. There has been little experience with combining conservation tillage and subsoiling. Among the key questions asked are: does subsoiling plus conservation tillage improve crop yields; what is the relative extent and duration of soil disturbance with the available subsoiling implements; does surface tillage affect subsoiling efficacy; and is there an aeration benefit from deep tillage?

Recent conservation tillage research from New Zealand has shown certain consistent effects on soil porosity and related properties (Ross and Hughes, 1985; Francis et al., 1987; Horne et al., 1992; Francis and Knight, 1993; Hermawan and Cameron, 1993). In the  $A_p$  horizon conservation tillage has generally been associated with higher bulk density, soil strength, aggregate stability, organic matter content, plant available water and earthworm population. Conservation tillage also reduced total porosity but it resulted in greater continuity between surface and subsurface pores. When assessed, tillage pans were found with conventional tillage but not with conservation tillage. There was no consistent effect on infiltration rate.

Chapman (1990) studied the effects of a vibrating subsoil shank in the Hamilton Basin of the North Island. Subsoiling improved soil physical conditions to a 45 cm depth, but was less effective at greater depths. In some cases, vibrating the subsoiling shank moved enough coarser soil from the surface horizon to the finer-textured subsoil that the  $A_p$  textural class was changed. Persistence of the subsoiling effect, as measured by plant response, penetration resistance and bulk density was one year for sandy soils and two years for silty or clayey soils.

Greenwood and Cameron (1990), working in the drier North Otago and Canterbury regions of the South Island (635 mm annual rainfall), found that subsoiling persistence was greater with paraplowing<sup>1</sup> to 35 cm than with less disruptive straight shanked units to the same depth. Yield and plant water status improvement in peas (*Pisum sativum*), wheat and barley were significant for one year with straight shank subsoiling and persisted for two years with paraplowing. In both cases, crop benefits were small when irrigation was optimized, but were appreciable under the supplemental irrigation strategies typically employed by farmers. Harrison et al. (1994) recorded improvements in soil physical conditions and pasture production from subsoiling at two depths (27 and 47 cm) in Canterbury.

Baker (1985) found that subsoiling of orchards on the South Island near Nelson initially increased infiltration and hydraulic conductivity. These effects persisted more than two years, but varied depending on soil, soil water content at the time of subsoiling, and subsequent management practices. Both Greenwood and Cameron (1990) and Chapman (1990) found the effects of subsoiling on soil properties were similar to findings of numerous other studies.

## 3. Related international findings

Depending on soil properties, water content at the time of tillage, and crop grown, the persistence of subsoiling effects can vary from one year (Hartge, 1981; Jager and Boersma, 1983) to between three and five years (Lindner, 1974; Schulte, 1974; Swain, 1975; Bokerman and Graichen, 1981; Kouwenhoven and Vulinck, 1983; Martinovic et al., 1983; Schulte-Karring, 1983) as soils vary from sandier to more clayey and/or more calcareous. Ide et al. (1987) found that cone index reduction and yield improvement in cereals and sugarbeet (*Beta vulgaris*) persist for three-five years.

Hipps and Hodgson (1988) working on a sandy clay loam, found that either paraplowing to 33 cm or moldboard plowing to 23 cm provided equal rooting for spring barley, and that paraplowing effects on soil strength were no longer identifiable from cone penetrometry after 20 months. Although direct drilling was a variable among deep tillage treatments, no effect of surface management on subsoiling was noted.

A great deal of subsoiling research has been done on the Ultisols of the US Southeast, where rainfall amounts are similar to those of New Zealand's North Island. Busscher et al. (1988) found different soil strength patterns on a sandy loam among implements compared. The differences were similar for cone indices measured at the prevailing soil water contents and for cone indices corrected to a reference soil water content. Generally, shattering patterns owing to subsoiling were more extensive for straight-shanked broad-shoed subsoilers or for the paraplow than for parabolically curved-narrow-shoed subsoilers. Busscher and Sojka (1987) noted that both shattering and shattering-persistence were affected by the subsoiler-surface tillage combination. These

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dissimilarities were thought to be related to differences in subsequent traffic patterns and crop water use between surface-tilled and no-tilled systems.

Sojka et al. (1990) concluded that persistence of subsoil disruption was dependent on the extent of the initial subsoil disruption and its resistance to reconsolidation with intense rainfall. For related soils, similar conclusions were made by Simmons and Cassel (1989), who examined subsoiling persistence at different hill-slope positions. Threadgill (1982) and Busscher et al. (1986) determined that although some evidence of subsoiling remained from one spring to the next, the profile strength reduction remaining in the second season was insufficient for crop response. Sojka et al. (1990) and Sojka et al. (1991) showed that where soil compaction was a limiting factor, maize and sunflower (*Helianthus annuus*) yields were highly correlated with mean profile cone indices to 0.6 m depth. Elkins and Hendrick (1983) proposed that narrow subsoil slits were as effective as extensive subsoil disruption if the slits could be stabilized with coarse roots resistant to decomposition. Karlen et al. (1991) suggested that two–three years of slit tillage could provide long term crop growth benefits without annual subsoiling once the network of stable slits was sufficiently extensive.

Duval et al. (1989) found that clay soil compaction was persistent, but that subsoiling benefits to soil aggregation could be identified for up to ten years if combined with traffic control. However, subsoiling effects on penetration resistance did not persist. Unger (1993) was unable to reliably identify persistence of deep profile disruption from paratilling on a clay loam soil using cone index and bulk density measurements. He attributed this to variations in soil water content at the time of initial subsoiling and secondary tillage operations.

In this study, we investigated the impact of three subsoiling and two surface-tillage methods on soil physical conditions important to the establishment of forage oats. The site was chosen for its intensive cropping history, compaction and poor soil structure. Results were expected to reflect the benefits and/or problems farmers might encounter when attempting to improve degraded land through tillage. Tillage impacts were evaluated through soil physical characterization and crop response.

#### 4. Materials and methods

##### 4.1. Field design and layout

The experimental site was located in New Zealand's Kairanga district, 10 km from Palmerston North. A detailed profile inspection (G. Shepherd, personal communication, 1993) revealed that the soil is a Moutoa silty clay, a typical Recent Gley Soil (N.Z. Soil Classification) or a Typic Haplaquoll (USDA Soil Classification). The  $A_p$  horizon (0–11 cm) is silty clay in texture with a weak, very coarse blocky structure and common, distinct mottles. Surface organic carbon content of this soil was 5.8%. The  $A_p$  horizon (11–25 cm) is silty clay with moderately developed coarse blocky structure and common, medium distinct mottles. The  $B_g$  horizon (25–36 cm) is silty clay loam with weakly developed blocky structure and common, distinct mottling (including Fe/Mn coatings). The  $B_g$  horizon (36–45 cm) is silt loam in texture with weakly developed medium blocky structure and many, distinct mottles. Soil beneath 45 cm

ranges from a fine sandy loam (45–60 cm) to a loamy fine sand (60–90 cm). This soil is poorly drained. The site had been continuously cultivated (cereals and row crops with no periods of pasture) for 15 years and was compacted and structurally degraded.

In mid-April 1992, eight treatments were established in  $6 \times 30$  m plots in a field that had been undisturbed since the harvest of spring melons the previous season. Weeds were cut and raked off the plot area to reduce the surface mulch and make it uniform over the plot area. Treatments were coded PN, PT, VN, VT, SN, ST, CN, and CT (where T is surface tillage, N is no tillage, P is paraploughing, V is deep subsoiling, S is shallow subsoiling, and C is non subsoiling). They consisted of subsoiling with three implements: P with a paraplow, which had laterally angled sheering plains 0.5 m deep; V with a deep vertical-leg subsoiler which had straight shanks to till 0.5 m deep; and S with a shallow subsoiler which had straight shanks that operated at 0.25 m deep; and a control. Effective spacing between the subsoiler shanks on each implement was 0.5, 0.5 and 0.45 m, respectively for P, V and S. These four treatments were either drilled without further seedbed preparation (N) using a "cross-slot" no-tillage drill (Baker and Choudhary, 1988) or power rotary-tilled to 15 cm and firmed with a Cambridge roller (T), and then drilled with the same drill. Seeding rate was  $120 \text{ kg ha}^{-1}$  at a sowing depth of 30 mm. The area was subsoiled and then sprayed with glyphosate ( $3.01 \text{ ha}^{-1}$ ) and  $0.36 \text{ kg ai per liter}$ ) from 14–16 April 1992. T and sowing of oats occurred on 1 May. No fertilizer was applied.

The experiment used a randomized complete block design with eight treatments and four replicates (i.e. 32 plots). Measured parameters were evaluated statistically employing SAS software to determine standard deviations, cumulative frequencies, or probability of treatment significance using analysis of variance, as appropriate to specific parameters.

##### 4.2. Soil physical properties

Soil profiles were characterized by core sampling at seeding and harvest for bulk density, saturated hydraulic conductivity ( $K_{SAT}$ ) and air permeability ( $K_a$ ), and at seeding only for slightly unsaturated (40 mm tension) hydraulic conductivity ( $K_{-40}$ ). Core samples were  $590 \text{ cm}^3$  (100 mm diameter  $\times$  75 mm) taken from the shank disruption path. Duplicate samples were collected from each of the trial plots, giving a total of eight replicates per tillage treatment. Sampling depths were centered on 5–15, 15–25, 30–40, and 40–45 cm depth increments. These core samples were used for  $K_{SAT}$ ,  $K_{-40}$ , air permeability, and bulk density determinations, giving eight replicates per measurement.

Sample  $K_{SAT}$  was measured by ponding water on presaturated cores whose upper 5 mm had been removed. The water level was maintained using a needle point reference until steady state flow was established, allowing application of Darcy's law. The  $K_{-40}$  methodology used a disk permeameter (Cook et al., 1993). Air permeability was measured at field soil water content using the Eijkelkamp air permeameter technique (Anonymous, 1983). Water contents at sampling are given in Table 1.

Field soil oxygen diffusion rate (ODR) was monitored using the platinum micro electrode technique (Stolzy and Letey, 1964) employing a Jensen Instruments "Model D" ODR meter and electrodes. Electrodes were aligned with the zone of maximum

Table 1

Profile soil gravimetric water contents (WC)  $\pm$  standard deviation (SD) for the surface-tilled control (CT) and the surface-tilled paraplow (PT) treatments samples on four days of the year (DOY)

DOY	Depth (cm)	Treatment <sup>a</sup>	
		CT	PT
116	0-10	0.35 $\pm$ 0.04a	0.38 $\pm$ 0.01
	10-20	0.39 $\pm$ 0.02	0.41 $\pm$ 0.01
	20-30	0.42 $\pm$ 0.03	0.43 $\pm$ 0.04
	30-40	0.43 $\pm$ 0.07	0.46 $\pm$ 0.07
	40-50	0.49 $\pm$ 0.08	0.49 $\pm$ 0.08
128	0-10	0.35 $\pm$ 0.02	0.36 $\pm$ 0.23
	10-20	0.38 $\pm$ 0.02	0.39 $\pm$ 0.01
	20-30	0.42 $\pm$ 0.03	0.45 $\pm$ 0.02
	30-40	0.49 $\pm$ 0.03	0.50 $\pm$ 0.03
	40-50	0.49 $\pm$ 0.02	0.51 $\pm$ 0.10
275	0-15	0.49 $\pm$ 0.02	0.50 $\pm$ 0.02
	15-30	0.48 $\pm$ 0.03	0.46 $\pm$ 0.06
	30-45	0.50 $\pm$ 0.12	0.50 $\pm$ 0.12
	0-10	0.43 $\pm$ 0.01	0.44 $\pm$ 0.02
	10-20	0.43 $\pm$ 0.01	0.44 $\pm$ 0.02
349	20-30	0.46 $\pm$ 0.01	0.45 $\pm$ 0.02
	30-45	0.49 $\pm$ 0.07	0.52 $\pm$ 0.06

<sup>a</sup> Gravimetric soil water contents ( $\text{kg kg}^{-1}$ ), mean  $\pm$  standard deviation.

subsoil disruption from subsoiling shanks (plot center for C treatment) at depths of 5, 10, 15, and 40 cm. Logistical considerations limited monitoring of soil ODR to four treatments, CN, CT, PN, and VN. Monitored treatments had duplicate electrodes for each depth in each plot replicate. This provided a treatment value consisting of the mean of eight field values for each treatment and depth reported.

Soil strength was assessed by determination of profile distribution of cone index values at field water content four times over the study period. Cone index was monitored using the Bush recording penetrometer with a standard ASAE 30° 12.8 mm cone. Readings were at depths of 1, 3, 5, 7, 9, 11, 13, 18, 23, 28, 33, 38, 43, and 48 cm. Six profile cone index readings were taken at 10 cm intervals on a 0.5 m lateral transect across the path of tillage, beginning at the point of maximum soil disruption (shank path), providing an array of 84 cone indices for each profile. A duplicate set of readings was made in each plot and averaged to provide a grid of cone indices for that plot. Means of grids from all four replicates were used for contour plotting of cone index isopleths and determination of cone index cumulative frequency in the 84 position grid, similar to the method of Sojka et al. (1990). Strength was determined four times: on day of year (DOY) 116 (between subsoiling, DOY 105 and seeding, DOY 121) and repeated on DOYs 128, 275, and 349. Gravimetric soil water content was measured on cone index sampling dates in treatments CT and PT, which were expected to represent the extremes of soil manipulation. Sampling depths were from 0-50 cm in 10 cm depth increments on DOY 116 and 128, 0-45 cm in 15 cm increments on DOY 275, and 0-30 cm in 10 cm increments plus a 30-45 cm sample on DOY 349.

Interpretation of soil strength was through examination of cone index cumulative frequency plots and two dimensional plots of cone index isopleths. Effects of profile soil water content changes on cone index were evident but were only considered qualitatively.

#### 4.3. Plant measurements

Crop establishment was measured on 5 June by counting the number of plants in 1 m of drill row. Final yield was measured on 28 October by cutting, drying (60°C) and weighing above ground dry matter in 1 m of drill row. This procedure was repeated six times per plot, representing a 0.9 m<sup>2</sup> sample per plot (15 cm drill row spacing). Areas of obvious sowing failure were skipped for stand and yield measurements, but noted for assessment of sowing performance.

#### 5. Results and discussion

Subsoiling is generally recommended as an autumn operation to take advantage of drier soil conditions to maximize profile loosening and crop response. Autumn of 1992 was wetter than normal, both before and during establishment of this experiment. Normal annual rainfall is 890 mm, while the total for 1992 was 1113 mm. Monthly totals in 1992 for the period May through November were 27.6, 74.8, 136.4, 110.4, 87.7, 85.7, and 60.8 mm respectively (583.4 mm for the seven months). Soil profiles in autumn were relatively dry compared to profiles during preceding months, but were not the driest period observed during the study (Table 1). Gravimetric soil water contents of the PT treatment tended to slightly exceed those of the CT treatment. These differences were more pronounced in the upper profile and diminished with depth. Volumetric values (not presented) showed little treatment difference, as the reduction of soil mass per unit volume in subsoiled plots (see below) cancelled the effects of increased water per unit mass of soil.

##### 5.1. Bulk density

Bulk density (Table 2) decreased only slightly in the A<sub>p</sub> horizon for T treatments. Subsoiling (P, V, and S) was somewhat more successful at lowering bulk density in the 15-40 cm depth compared with C plots. The textural shift and lower limit of tillage depth contributed to absence of subsoil loosening in the 40-50 cm zone as determined by bulk density. Bulk density was a relatively insensitive measurement of tillage effects. This has been noted by others. Treatment differences were small with high standard deviations. Nonetheless, there were some interesting trends in the bulk density values measured shortly after subsoiling and surface tillage. C bulk densities were reasonably consistent down the profile, with the greatest value in the 15-25 cm depth (Table 2). This depth was likely compacted by wheel and implement traffic during intensive cropping. Bulk densities also suggested that P and V generally loosened more of the profile than did S. The P and V treatments resulted in generally lower bulk densities ( $P < 0.05$ ) in the 5-25 and 15-40 cm zones, respectively, whereas bulk densities for S were only lower than controls in the 5-15 cm layer. The most thorough loosening, as

Table 2  
Profile bulk densities  $\pm$  standard deviation for subsoiling treatments and surface tillage treatments at sowing and at harvest

Depth (cm)	Subsoiling and surface tillage treatment <sup>a</sup>					
	Sampling time	Control	Paraplow	Shallow subsoiler	Vertical leg subsoiler	No surface tillage
5–15	Sowing	1.00 $\pm$ 0.07	0.97 $\pm$ 0.07	0.99 $\pm$ 0.02	0.98 $\pm$ 0.04	0.96b $\pm$ 0.04
	Harvest	1.03 $\pm$ 0.06	0.99 $\pm$ 0.05	1.00 $\pm$ 0.04	1.01 $\pm$ 0.05	0.98b $\pm$ 0.04
15–25	Sowing	1.06 $\pm$ 0.08	0.98 $\pm$ 0.10	1.01 $\pm$ 0.15	0.96 $\pm$ 0.09	0.99 $\pm$ 0.11
	Harvest	1.05 $\pm$ 0.03	1.02 $\pm$ 0.09	1.03 $\pm$ 0.07	1.06 $\pm$ 0.04	1.05 $\pm$ 0.06
30–40	Sowing	1.01a $\pm$ 0.16	0.99a $\pm$ 0.12	1.05a $\pm$ 0.10	0.83b $\pm$ 0.10	0.93 $\pm$ 0.15
	Harvest	0.98ab $\pm$ 0.07	0.93bc $\pm$ 0.08	1.03a $\pm$ 0.05	0.89c $\pm$ 0.08	0.97 $\pm$ 0.08
40–50	Sowing	1.04 $\pm$ 0.15	1.04 $\pm$ 0.14	1.13 $\pm$ 0.14	1.01 $\pm$ 0.10	1.07 $\pm$ 0.13
	Harvest	1.05 $\pm$ 0.15	1.05 $\pm$ 0.15	1.13 $\pm$ 0.14	1.01 $\pm$ 0.10	1.07 $\pm$ 0.13

<sup>a</sup> Bulk density at field water content ( $\text{Mg m}^{-3}$ ), mean  $\pm$  standard deviation.

Treatment bulk densities were compared by ANOVA for each depth on each sampling date. Differences by LSD ( $P < 0.05$ ) were only found among treatments for some depths and dates. These are expressed where means for a given depth and date are followed by different letters. No differences were found among those sampling dates or depths without letters. Note that surface tilled and no surface tillage regimes were tested separately from the subsoiling treatments.

measured by bulk density changes, was by V in the 30–40 cm depth. Yet, V did not thoroughly disrupt existing surface compaction. Compared with N, T tended to reduce the bulk density of the 5–15 cm depth. The reduction, however, was smaller than expected.

By harvest, bulk density reduction from subsoiling was no longer apparent except in V plots, and then only at the 30–40 cm depth. However, 5–15 cm depth bulk density of the T plots was still slightly lower than for N plots.

### 5.2. Saturated hydraulic conductivity ( $K_{SAT}$ )

Profile  $K_{SAT}$  values for 30 cm and deeper are low ( $(0.5–2.3) \times 10^{-4} \text{ m s}^{-1}$ ), indicating poor intrinsic subsoil hydraulic conductivity of the Moutoa soil (Table 3). Since none of the deep tillage implements penetrated below 45 cm, subsoiling would not be expected to significantly alter deep profile drainage in the absence of ancillary artificial drainage.

At sowing, the overall  $K_{SAT}$  range of the subsoiling treatment means, for all but P at 15–25 cm, was  $(0.6–7.8) \times 10^{-4} \text{ m s}^{-1}$ . Furthermore, the range of standard deviations within these data was  $(0.4–7.8) \times 10^{-4} \text{ m s}^{-1}$ . Thus, subsoiling had only limited effects on  $K_{SAT}$ . The exception to this observation was the increased  $K_{SAT}$  ( $14.0 \times 10^{-4} \text{ m s}^{-1}$ ) measured for P at 15–25 cm depth.

At harvest, the overall  $K_{SAT}$  range was  $(0.6–4.2) \times 10^{-4} \text{ m s}^{-1}$ , again with no particular treatment related differences. Even the P at 15–25 cm value had returned to the overall treatment range. There were no differences for T and N treatments, either at sowing or harvest. Others have also reported high  $K_{SAT}$  variances (Watt and Crouchley, 1985).

Table 3  
Saturated hydraulic conductivity ( $K_{SAT}$ ) for subsoiling and surface tillage treatments at sowing and harvest ( $\times 10^{-4} \text{ m s}^{-1}$ )

Depth (cm)	Subsoiling and surface tillage treatment <sup>a</sup>					
	Sampling time	Control	Paraplow	Shallow subsoiler	Vertical leg subsoiler	No surface tillage
5–15	Sowing	0.7 $\pm$ 4.2	2.1 $\pm$ 2.3	1.4 $\pm$ 1.4	2.9 $\pm$ 4.5	1.3 $\pm$ 1.8
	Harvest	1.6 $\pm$ 1.2	3.8 $\pm$ 3.2	4.2 $\pm$ 5.4	3.8 $\pm$ 4.1	2.8 $\pm$ 3.2
15–25	Sowing	5.8b $\pm$ 4.3	14.0a $\pm$ 6.5	5.0b $\pm$ 5.1	7.8b $\pm$ 6.5	8.8 $\pm$ 6.3
	Harvest	3.1 $\pm$ 4.0	1.8 $\pm$ 2.0	2.9 $\pm$ 3.1	1.3 $\pm$ 1.0	1.3 $\pm$ 1.7
30–40	Sowing	1.4 $\pm$ 3.0	1.0 $\pm$ 1.0	0.5 $\pm$ 0.4	2.3 $\pm$ 3.9	2.2a $\pm$ 3.1
	Harvest	1.4 $\pm$ 3.1	1.1 $\pm$ 1.1	1.3 $\pm$ 1.8	0.6 $\pm$ 0.7	0.7 $\pm$ 1.3
40–50	Sowing	0.7 $\pm$ 0.6	0.6 $\pm$ 0.5	1.1 $\pm$ 1.7	1.0 $\pm$ 1.1	0.7 $\pm$ 0.6
	Harvest	0.7 $\pm$ 0.6	0.6 $\pm$ 0.5	1.1 $\pm$ 1.7	1.0 $\pm$ 1.1	0.7 $\pm$ 0.6

<sup>a</sup> Saturated hydraulic conductivity ( $\times 10^{-4} \text{ m s}^{-1}$ ), mean  $\pm$  standard deviation.

Treatment saturated hydraulic conductivities ( $K_{SAT}$ ) were compared by ANOVA for each depth on each sampling date. Differences by LSD ( $P < 0.05$ ) were only found among treatments for some depths and dates. These are expressed where means for a given depth and date are followed by different letters. No differences were found among those sampling dates or depths without letters. Note that surface tilled and no surface tillage regimes were tested separately from the subsoiling treatments.

### 5.3. Unsaturated hydraulic conductivity ( $K_{-40}$ )

As with  $K_{SAT}$ , the range of overall  $K_{-40}$  treatment differences (Table 4), for both subsoiling and surface tillage comparisons, was small ( $(1.4–7.9) \times 10^{-7} \text{ m s}^{-1}$ ) and the range of standard deviation was high ( $(0.9–7.4) \times 10^{-7} \text{ m s}^{-1}$ ). Although the  $K_{-40}$  values for P and V were double the means of the other treatments, they also had standard deviations nearly equal to their means. No additional  $K_{-40}$  measurements were made at harvest because of high variability, lack of tillage differences for  $K_{-40}$  measurements made at seeding, and the three orders of magnitude difference between  $K_{SAT}$  and  $K_{-40}$ . The difference of three orders of magnitude between  $K_{SAT}$  and  $K_{-40}$  indicates that with normal rainfall rates (which typically exceed the  $K_{-40}$  values), water

Table 4  
Slightly unsaturated hydraulic conductivities ( $K_{-40}$ ) for subsoiling and surface tillage treatments at sowing ( $\times 10^{-7} \text{ m s}^{-1}$ )

Depth (cm)	Subsoiling and surface tillage treatment <sup>a</sup>					
	Control	Paraplow	Shallow subsoiler	Vertical leg subsoiler	Surface tilled	No surface tillage
5–15	2.7 $\pm$ 2.0	3.2 $\pm$ 2.5	2.4 $\pm$ 1.0	3.1 $\pm$ 1.6	3.0 $\pm$ 2.1	2.7 $\pm$ 1.6
15–25	1.7 $\pm$ 1.7	1.4 $\pm$ 1.0	2.0 $\pm$ 1.6	2.3 $\pm$ 0.9	1.5 $\pm$ 0.9	2.2 $\pm$ 1.6
30–40	2.8b $\pm$ 1.4	4.8ab $\pm$ 4.6	3.0b $\pm$ 2.8	7.9a $\pm$ 7.4	5.9 $\pm$ 6.4	3.3 $\pm$ 2.1
40–50	2.3 $\pm$ 1.9	3.0 $\pm$ 3.4	1.4 $\pm$ 0.9	2.8 $\pm$ 1.4	2.2 $\pm$ 2.6	2.6 $\pm$ 1.6

<sup>a</sup> Slightly unsaturated hydraulic conductivity ( $\times 10^{-7} \text{ m s}^{-1}$ ), mean  $\pm$  standard deviation.

Treatment unsaturated hydraulic conductivities ( $K_{-40}$ ) were compared by ANOVA for each depth on each sampling date. Differences by LSD ( $P < 0.05$ ) were only found among treatments for some depths and dates. These are expressed where means for a given depth and date are followed by different letters. No differences were found among those sampling dates or depths without letters. Note that surface tilled and no surface tillage regimes were tested separately from the subsoiling treatments.

Table 5

Intrinsic air permeability ( $k_a \times 10^{-7} \text{ m}^2$ ) at field water content for subsoiling and surface tillage treatment at sowing and at harvest.

Depth (cm)	Sampling time	Subsoiling and surface tillage treatment <sup>a</sup>			
		Control	Paraplow subsoiler	Vertical leg subsoiler	Surface tilled/No surface tillage
5-15	Sowing	3.6a ± 4.5	5.9a ± 2.9	3.4a ± 2.2	3.2 ± 2.4
	Harvest	1.0 ± 0.7	1.3 ± 0.8	0.9 ± 0.6	1.1 ± 0.8
15-25	Sowing	9.8b ± 4.7	17.6a ± 4.8	13.3ab ± 3.8	14.2 ± 4.6
	Harvest	0.8 ± 0.5	0.9 ± 0.7	0.5 ± 0.5	0.7 ± 0.5
30-40	Sowing	3.6b ± 3.8	4.6b ± 2.9	3.7b ± 2.0	6.3 ± 5.0
	Harvest	0.5 ± 0.4	0.7 ± 0.8	0.4 ± 0.3	0.5 ± 0.4
40-50	Sowing	3.8a ± 2.2	3.5a ± 1.6	3.8a ± 2.2	3.5 ± 1.7
	Harvest	0.5 ± 0.4	0.7 ± 0.8	0.4 ± 0.3	0.5 ± 0.4

<sup>a</sup> Intrinsic air permeability ( $\times 10^{-7} \text{ m}^2$ ) ± standard deviation.

Treatments  $k_a$  were compared by ANOVA for each depth on each sampling date. Differences by LSD ( $P < 0.05$ ) were found among subsoiling treatments for the sowing dates. These are expressed where means for a given depth are followed by different letters. No differences were found among the other treatments or sampling times. Note surface tilled and no tillage regimes were tested separately.

entry into the profile is mainly via preferential flow through cracks and fissures. The low  $K_{-40}$  values demonstrate that water entry via micropores is insignificant.

#### 5.4. Air permeability

At sowing, P and V subsoiling increased air permeability compared to C and S (Table 5) in the 15-40 cm depth zone, particularly in the 15-25 cm zone. In contrast, S did not substantially improve air permeability at any depth. This reflects the  $K_{SAT}$  trends at these depths, particularly for P. Likewise, the  $K_{SAT}$  and air permeability of V and S were also related, both being somewhat lower in the 5-15 cm zone. Although these values may not be significant in and of themselves, collectively they display a consistent pattern, indicating failure of V and S to disrupt pre-existing surface compaction as effectively as P. Little or no difference was noted between T and N.

At harvest there was a 5-10 fold drop in air permeability for all treatments. This is similar to the trends in  $K_{SAT}$  values and may relate to the overall increase in bulk density from sowing to harvest and the increase from 43.9 to 47.4% of the field gravimetric soil water content at which air permeabilities were determined. No treatment related air permeability differences remained at harvest. As with  $K_{SAT}$  and  $K_{-40}$ , air permeability was highly variable.

#### 5.5. Soil ODR

Soil ODR is strongly affected by soil water content. New Zealand is a high rainfall environment. The poorly drained soil in this study was near or above field capacity for most of the study period except DOY 230-250 and DOY 260-270. Even in this consistently wet regime, ODR decreased with depth for all treatments observed (Fig. 1) and fluctuated in response to rainfall. ODR also declined as water content rose following rainfall. On most measurement dates and depths, the non-subsoiled, non-surface tilled

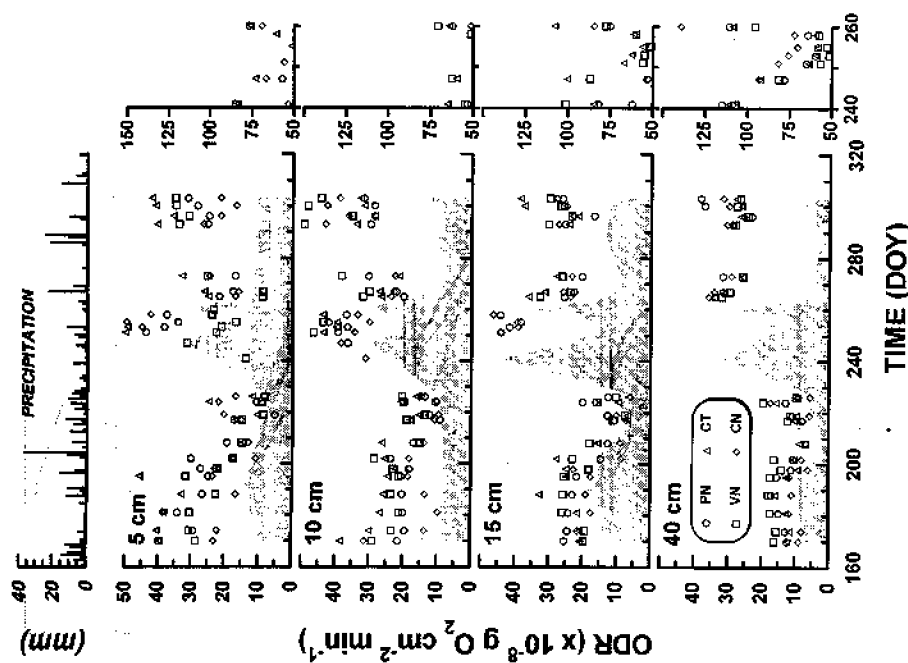


Fig. 1. Time course of profile soil oxygen diffusion rate (ODR) for paraplow, vertical leg subsoiler and control with no surface tillage (PN, VN and CN) and control with surface tillage (CT). Seasonal precipitation is presented as a histogram. ODR for days 240 through 260 are displayed separately to better discriminate their range. Shading indicates the mean standard deviation for each observation date.

control treatment (CN) ODR's were among the lowest values measured. T raised ODR in the 5, 10, and 15 cm depths, but had little or no effect at 40 cm. Essentially all subsoiling treatments increased ODR, although the degree of ODR increase from a given subsoiler varied through the season and on the various observation dates.

A brief dry period occurred at mid season, substantially raising ODR values. Although these values have been plotted in Fig. 1, a later study has suggested that incomplete water film coverage of the PT microelectrode begins to occur in this soil around an ODR value of  $(50-60) \times 10^{-8} \text{ g O}_2 \text{ cm}^{-2} \text{ min}^{-1}$ . Fig. 1 presents the ODR values above  $50 \times 10^{-8} \text{ g O}_2 \text{ cm}^{-2} \text{ min}^{-1}$  in a side-bar for DOY 240-260, in order to allow better graphical separation throughout the observation range of those data that are most certainly from water film-covered microelectrodes.



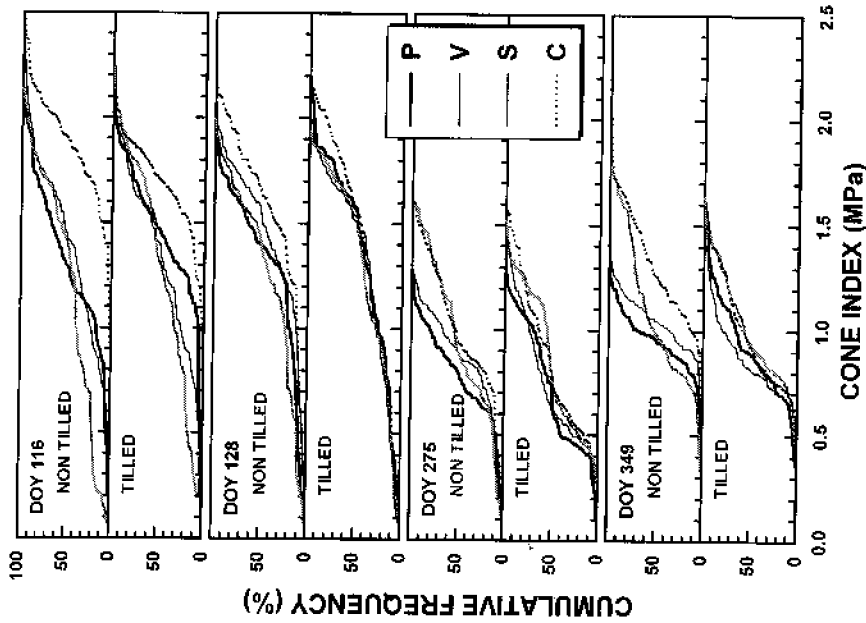


Fig. 2. Cumulative frequency of profile cone index readings for days 116, 128, 275, and 349 for paraplow (P), vertical leg subsoiler (V), shallow subsoiler (S) and non-subsoiled controls (C) as observed with surface tillage (T) or with no surface tillage (N).

ODR's of approximately  $20 \times 10^{-8} \text{ g O}_2 \text{ cm}^{-2} \text{ min}^{-1}$  or less are generally limiting to plant growth (Stolzy and Lacey, 1964). The only treatment monitored which consistently produced ODR's below this threshold at all depths was CN. The wet environment in which this study was conducted, provided an excellent means of determining the impact of deep tillage on soil aeration. One might speculate, however, that treatment differences could have been more pronounced or differently expressed if either natural or artificial drainage were available.

#### 5.6. Cone index cumulative frequency

Cumulative frequency of cone indices measured in a two-dimensional grid representing the soil profile provides a quantitative comparison of the fraction of the profile above or below a given cone index limit (Fig. 2). In order to increase sensitivity of upper profile characterization we used a grid with closer depth increments in the upper profile. Thus the cumulative frequency of cone indices is somewhat weighted toward conditions near the surface.

On DOY 116, immediately after tillage, but before drilling, both CT and CN had a greater frequency of high cone index values than P, V, or S (Fig. 2). However, T increased the frequency of low cone indices in C. Treatments CN and CT had 11.9 and 16.7% of their cone indices below 1.5 MPa respectively, and the cone indices above 1.5 MPa for subsoiled treatments averaged 57.4% of the readings. The T operation slightly increased the frequency of higher cone indices in P and S, indicating that T and the traffic associated with it caused more net profile reconsolidation than loosening. T did not appreciably change net cone index frequency distribution in the V plots. The SN and ST treatments resulted in the highest frequency of very low cone indices (less than 1.0 MPa). Above 1.0 MPa, SN and ST produced cone index frequency distributions similar to P and V treatments. This may be related to the slightly closer shank spacing and shallower shank operation of the S treatment compared to P and V.

On DOY 128, after drilling, the CN treatment had the lowest frequency of low cone indices throughout the entire cone index range. There were 34.5% of profile cone indices below 1.5 MPa for CN, compared to 64.3, 54.8, and 48.8% for PN, SN and VN, respectively. There were essentially no differences among treatments for T plots for cumulative frequency of cone indices up to 1.5 MPa. Above 1.5 MPa, PT, VT, and ST diverged more or less together from the strength distribution of the controls. An average of 75.8% of the profile's PT, VT, and ST readings were below 1.75 MPa compared to 61.9% for CT. The closer grouping of cumulative frequencies in the T treatments may reflect the recompaction of the loosened surface from the drilling operation.

On DOY 275 cumulative frequency of cone index in N plots was similar for PN, VN, SN, and CN through approximately 0.6 MPa, representing 11.9% of all profile readings. The CN and SN frequency accumulations from 0.6–1.5 MPa were similar with 92.3% of profile cone indices falling below 1.5 MPa compared to 72.7% of cone indices below 1.0 MPa for PN and VN, with PN showing consistently lower cone indices across this range of frequency accumulation. The N and T treatments behaved somewhat similarly above 1.0 MPa, but there was a generally greater frequency of lower cone indices for T treatments between 0.5 and 0.9 MPa. VT and PT cone indices had greater cumulative frequency through nearly the entire cone index range (indicating more low cone indices). Essentially all cone index distributions for DOY 275 reflected lower soil strengths than the previous two dates because of the wetter profile on DOY 275. The increase in profile soil water content on this date was probably also responsible for minimizing cone index cumulative frequency differences among subsoiling treatments, especially in T plots.

On DOY 349, CN profiles had appreciably fewer low cone indices across the range of cone indices than any of the subsoiled treatments. The SN treatment changes its pattern of cone index cumulative frequency relative to VN and PN as cone index increases. This is most obvious as the curves cross near the value of 1 MPa. Above 1.0 MPa, the SN treatment accumulated fewer low cone indices than either PN or VN. Cumulative frequencies of VT produced a higher frequency of low cone indices throughout the entire range of cone indices. The CT and ST patterns were similar, showing the lowest frequency of low cone indices, and PT was intermediate.

#### 5.7. Cone index profile isopleths

Profile soil strength patterns (Figs. 3 and 4) reveal the spatial distribution of subsurface soil disruption associated with each tillage practice. On DOY 116, the C

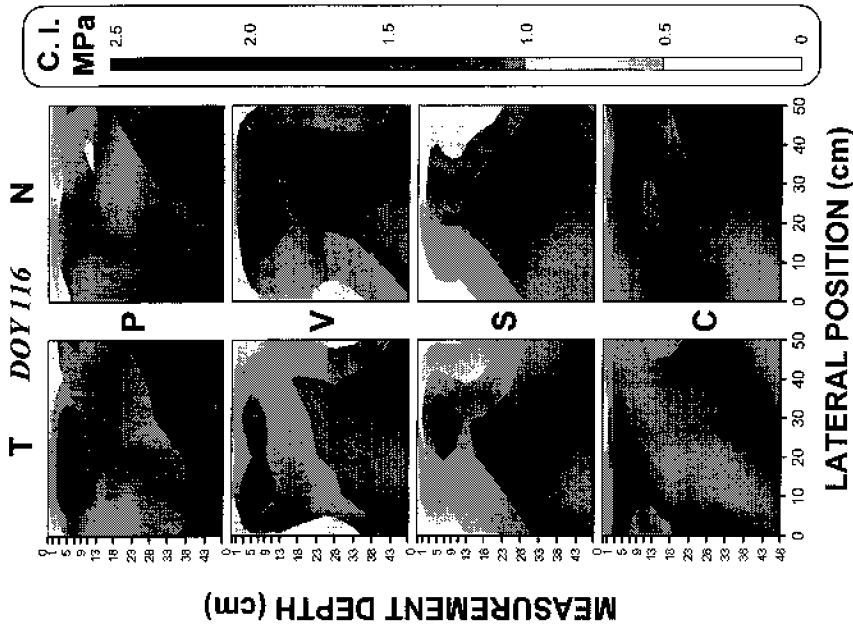


Fig. 3. Cone index (C.I.) profile isopleths for day 116 for all treatments for paraplow (P), vertical leg subsoiler (V), shallow subsoiler (S) and non-subsoiled controls (C) as observed with surface tillage (T) or with no surface tillage (N). Lateral position refers to distance from the subsoil shank (not applicable for C).

plots had the most extensive area of high cone index values near the surface of the profile (Fig. 3). Furthermore, the CN treatment had the most extensive profile cross-sectional area with cone index values exceeding the widely recognized critical value (for root growth restriction) of 2 MPa (Unger and Kaspar, 1994). CN, VN, VT, and PT all showed evidence of traffic compaction in the 3-10 cm zone. Disruption patterns for PN and PT show the greatest overall profile loosening to a depth of approximately 40 cm. Distinct disruption patterns associated with shank placement were evident in S (to 30 cm) and V (to 36 cm); however, the lateral extent of disruption was not as extensive as with P. In the top 10 cm, S produced more loosening than P or V.

On DOY 128, there was already evidence of reconsolidation in most plots, primarily as a result of traffic associated with sowing as illustrated by changes to VT and VN (Figs. 3 and 4a). Subsoiling persistence was more evident in N plots, suggesting that T accelerated profile reconsolidation.

On DOY 275, an overall reduction of cone indices throughout all profiles was evident

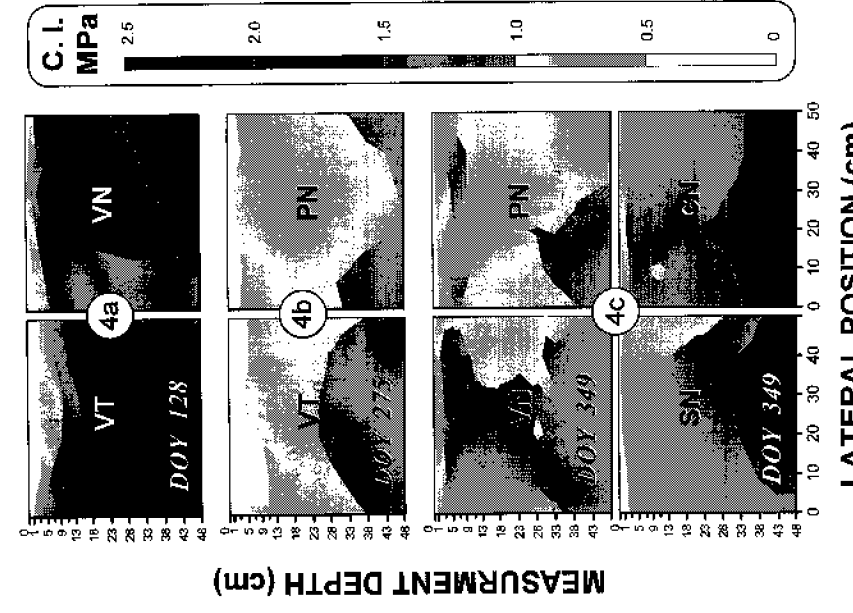


Fig. 4. Treatment mean cone index (C.I.) profile isopleths: a) for treatments VT and VN on DOY 128; b) for treatments VT and PN on DOY 275; and c) for treatments VN, PN, SN, and CN on DOY 349. Legend refers to paraplow (P), vertical leg subsoiler (V), shallow subsoiler (S) and non-subsoiled controls (C) as observed with surface tillage (T) or with no surface tillage (N). Lateral position refers to distance from the subsoil shank (not applicable for C).

(Fig. 4b). This was related to a higher profile water content (Table 1). P and V still showed evidence of lower cone indices at depth associated with subsoil shanks, however S treatments did not.

On DOY 349, soil water contents were less than DOY 275 but greater than DOY 128. At this intermediate water content, the disruption of SN was evident again, and subsoil shank patterns were still apparent in the P and V treatments (Fig. 4c). The reappearance of disruption patterns as the profile dried would be expected, given the non-linear relationship of soil cone index to soil water content.

Profile cone index treatment means and standard deviations (Table 6) demonstrate that the CN treatment had the highest overall cone indices throughout the study. The CT treatment cone indices were among the highest cone indices on all dates as well, but not always higher than some subsoiled treatments. No one subsoiled treatment consistently had the lowest profile cone index, however, on the last two observation dates (DOY 275

Table 6  
Profile cone index as measured on four days of the year (DOY).

Treatment	Cone index (MPa)			
	DOY 116	DOY 128	DOY 275	DOY 349
PT	1.46c ± 0.33	1.38cd ± 0.51	0.74e ± 0.31	0.93f ± 0.26
PN	1.34de ± 0.39	1.32ed ± 0.42	0.79d ± 0.23	0.96fe ± 0.15
VT	1.35de ± 0.43	1.33ed ± 0.51	0.76ed ± 0.32	0.88g ± 0.20
VN	1.41dc ± 0.46	1.45b ± 0.39	0.88c ± 0.25	1.05c ± 0.14
ST	1.30c ± 0.57	1.32ed ± 0.50	0.87c ± 0.35	1.02dc ± 0.27
SN	1.22f ± 0.62	1.27c ± 0.49	0.97b ± 0.40	1.09b ± 0.37
CT	1.68b ± 0.25	1.43cb ± 0.56	0.86c ± 0.36	0.99de ± 0.28
CN	1.87a ± 0.29	1.56a ± 0.44	1.01a ± 0.32	1.31a ± 0.27

Treatment cone index values (MPa, mean ± standard deviation) were compared by ANOVA for each depth on each sampling date. Differences by LSD ( $P < 0.05$ ) were found among some treatments for the same dates. These are expressed where means for a given date are followed by different letters. Treatment codes: C, control; P, paraplow; S, shallow subsoiler; V, vertical leg subsoiler; T, surface tilled; N, no surface tillage.

and 349), PT, PN, and VT showed a greater persistence of profile loosening than the other treatments.

### 5.8. Stand and yield

Plant response was reasonably reflective of the soil physical indices measured. Soil physical condition affected stand count which ultimately influenced yield (Table 7). Subsoiling increased stand from a mean of 98 to 137 plants per square meter. T interacted with subsoiling. The worst stand (68 plants per square meter) resulted from CT. The best stands (157 and 151 plants per square meter) resulted from P or S without T (PN and SN, respectively). All other treatment combinations were statistically intermediate for stand response. These results indicate the improvement in germination and stand establishment achievable with the cross slot drill in undisturbed soil versus seed placement in a somewhat cloddy loose seedbed when surface soil is dry. Once a stand is established, crop performance is further enhanced by reducing subsoil resistance to root growth.

Yield response followed nearly the same pattern. T reduced yields from 5318 to 3679 kg ha<sup>-1</sup>. C produced the lowest yield, 3974 kg ha<sup>-1</sup>, compared to an average of 4674 kg ha<sup>-1</sup> with subsoiling. P produced the highest yield (5063 kg ha<sup>-1</sup>). Although yield with P was not statistically different from the other forms of subsoiling, it was the only form of subsoiling resulting in significantly higher yields than C treatments. The advantage of all forms of subsoiling might have been better expressed had there been improved drainage. Subsoiling also interacted with T to affect yield, and the ranking was similar to that for stand. PN and SN produced the highest yields (6176 and 5413 kg ha<sup>-1</sup>, respectively) and CT produced the lowest yield (3222 kg ha<sup>-1</sup>). Other treatments resulted in statistically intermediate yields, with the four T combinations producing the four lowest yields.

T produced significantly lower mean stand counts and yields. T effects were actually more devastating than data in Table 6 indicate. This is because major drill skips were

Table 7  
Stand counts measured five weeks after sowing, and forage oat final yield as dry weight  
Stand counts (plants m<sup>-2</sup>) and forage yield (kg ha<sup>-1</sup>)

Subsoil treatment	Surface treatment	Stand		Yield		Mean	
		Count	Yield	Count	Yield	Count	Yield
Control	N	128ab	68c	157a	6176a	3222e	3974c
	T	128ab	68c	157a	6176a	3222e	3974c
Paraplow	N	151a	99bc	151a	5413ab	3950de	5063a
	T	151a	99bc	151a	5413ab	3950de	5063a
Shallow subsoiler	N	140a	131ab	145a	4415ab	3416e	4543ab
	T	140a	131ab	145a	4415ab	3416e	4543ab
Vertical leg subsoiler	N	146a	138a	146a	4129ecd	4129ecd	5318
	T	146a	138a	146a	4129ecd	4129ecd	5318

Mean values in the same row followed by the same letter are not significantly different as determined by LSD ( $P < 0.05$ ). Note, T and N are tested separately. Treatment codes: Control (C), Paraplow (P), Shallow subsoiler (S), Vertical leg subsoiler (V), Surface tilled (T) and No surface tillage (N).

avoided in both stand counts and yield samples. The rationale was to interpret soil influence on plant response, not machine response. However, drill skips in T plots affected 50% of plot area in some plots, and were nearly non-existent in N plots. Consequently net yields would have been substantially reduced on an entire-plot basis. Drill skips in this soil were exacerbated by the degree of pre-existing surface compaction, which produced highly resistant 5–10 cm diameter clods with T. This, coupled with a brief dry period after sowing, both delayed emergence and reduced ultimate stand with T. Under these conditions a disk opener may have had fewer problems in cloddy surface conditions.

The importance of uniform rapid stand establishment in the Manawatu district is well documented for these soils (Choudhary and Baker, 1994), and the conditions surrounding tillage and sowing time were typical of the region for this phase of the cropping sequence. When treatment yield was regressed against stand establishment the  $r^2$  of 0.47 verified that nearly half of the variation in yield was related to initial stand.

### 6. Additional observations

Because the original site was unavailable for continued observation, a related study was initiated in 1993 in an adjacent field. This area was under permanent pasture and had the same soil classification. The site was also severely compacted. This smaller investigation was comprised of a number of treatments, which, though not identical to the initial study, did include comparisons of paraplowing and controls. Each treatment was replicated four times in a randomised complete block design. The effect of autumn paraplowing on cone index, bulk density, ODR, air permeability and water content were measured as in the first year except that ODR readings were made only at the 100 mm depth.

In general, paraplowing affected soil properties in a similar fashion to the data presented in the initial study. The magnitude of soil loosening achieved by paraplowing, as measured by cone indices, was greater in the follow-up study. Mean cone index value to 480 mm in the control treatment was 2.05 MPa, compared to 1.68 MPa for the parapilled treatment and soil shattering (vertical and lateral) was more uniform than in the previous study. This is attributed to drier conditions in the Autumn of 1993.

A small but significant ( $P < 0.05$ ) increase in ODR at 100 mm depth was measured on the paraplowed plots. Unlike the original study, no ODR value less than the generally acknowledged  $20 \times 10^{-8} \text{ g O}_2 \text{ cm}^{-2} \text{ min}^{-1}$  threshold was recorded in the control treatment. The greater consistency of difference in readings between controls and subsoiled plots was again attributed to the drier conditions. Soil water contents in the 0–100 mm zone never exceeded  $0.4 \text{ g g}^{-1}$ . As in the first study, although bulk density,  $K_{SAT}$ , and air permeability tended to be more favourable in the subsoiled treatments, there were few significant differences.

### 7. Conclusions

The treatment which best reflected the conventional field preparation commonly used by local farmers to establish forage oats (i.e. CT), gave the poorest stand establishment

and produced the poorest performance for the cross slot drill. Subsoiling without T produced the best improvements in stand establishment and yield. The subsoiler that best served this end was the paraplow, although the closer-shanked shallow subsoiling unit performed nearly as well. The effect on oats establishment and yield generally reflected improvements in bulk density,  $K_{SAT}$ ,  $K_{40}$ , air permeability, cone index, and ODR. They generally improved with subsoiling (especially with P) but inconsistent or negative changes in these parameters often occurred with T.

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